Less (cars) is more:

how to go from new to sustainable mobility

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...to avoid a transport hell
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Executive Summary

Autonomous, electric, shared. According to some, these three technological revolutions are the epitome of the transformative wave impacting not only our mobility, but all of society.[i] Recent developments, from carmakers' massive investments in electric vehicles to the advances of artificial intelligence and automation confirm our mobility paradigm is at a crossroads. Add to that app-based services and disruptive business models offering a whole new range of flexible (micro)mobility options based on shared and on-demand access, and you get a mix that could revolutionise mobility, in particular urban mobility.

But technology alone won't make our mobility system more sustainable; and policy choices will be crucial in shaping future mobility revolutions. In particular, the European Union and the member states should lever these new developments to reach our climate objective of keeping emissions within well below the 2°C envelope and to make liveable cities. Risks are already visible today, as app-based ride sharing platforms such as Uber encourage new trips and lead to more kilometres driven, increasing emissions, and worsening congestion. In a scenario where such vehicles are automated, the cost of these services is expected to drop sharply (perhaps by more than 50%) and as a consequence, demand to sharply increase.

This paper shows through research and transport modelling the possible outcomes of the autonomous (and connected), electric, shared (new mobility), and *urban planning* revolutions. Based on the scenarios modelled, it issues recommendations to policy makers on steering these revolutions toward public-policy goals of reducing emissions and congestion.

Thanks to assumptions based on recent developments and announcements, it explores a range of possible futures: will automated vehicles be so cheap that they encourage people, or even vehicles without people in them, to travel more and for longer, causing more congestion and more car dominated cities, exacerbating the current mobility system's failings? Or will they be electric, shared and integrated holistically with other mobility options such as public transport and new (micro)mobility? We show with four scenarios the possible outcomes of these revolutions.

There has been significant investment and a scramble to secure more funding for the development of automated vehicles. These vehicles can be safer and allow us to use our time more productively on the move. But how quickly they come to market is highly uncertain. This report shows that allowing automated vehicles to come to market unregulated could mean greater dependence on cars, more traffic, and cars driving around empty. This could lead to a Europe where transport is provided for a single occupant of a heavy, fossil fuel guzzling, driverless car operated by tech giants. The resulting cumulative increase in emissions from 2018 to 2050 of between 0.5 and 5 Gt CO_2e, and a significant increase in vehicle kilometres, implying a peak hour that stretches across the whole day, and even into the night.

To mitigate the additional demand, automated vehicles need to be zero emission. But autonomous and electric (hence, zero emission) is not a given. The reality shows most players in the market currently trialling driverless cars that are conventional combustion engine cars. There is also a strong car and oil industry pressure to keep the internal combustion engine alive as long as possible. Regulations should therefore be adopted to ensure all automated cars are zero emission cars. This coupling could accelerate the uptake of electric vehicles in the European car fleet as a whole and would be beneficial to users and society thanks to zero exhaust emissions, lower maintenance costs, more durability, and reduced energy consumption. This however is not a panacea in and of itself, particularly in terms of liveable cities and resource utilisation efficiency.

An essential component of the sustainable transport revolution is sharing. With their higher upfront but much lower running costs, automated, electric vehicles (not just cars but also minibuses) are perfectly suited for sharing. Assuming automated vehicle sharing would take place on a large scale the number of cars required, as well as the space required to park them could drop dramatically. In very dense areas with lots of potential users a degree of sharing is likely to take place because of the reduced cost of shared trips and higher probability of two parties travelling from similar origins to similar destinations at the same time, compared to rural areas. As an example, a third of Lyft rides in major markets are booked as 'Shared rides' (with plans to increase that to 50% by the end of 2020)[ii] - however it is not clear how many of these rides were paired with other users. In New York City, about one fifth of their journeys are actually shared[iii]. But there is unlikely to be a trend towards full sharing in the absence of policy measures, such as road user charges, or additional taxes for non-shared rides.

Still, sharing cars and rides can only help reduce congestion to a certain extent. First because shared rides might be more efficient than solo-rides but they are much less efficient than train or bus rides. Second, even assuming shared rides mostly replace solo rides, road space in dense urban areas will remain extremely scarce and demand for it is virtually limitless. Any freeing up of road space through increased sharing would therefore likely be filled immediately by latent traffic, either additional cheap shared traffic or simply private drivers returning to less congested roads. For cities, the key therefore remains to adopt a holistic approach to mobility, effectively integrating car and ride sharing with existing public transport, active and micro-mobility (bike and e-scooter sharing) modes, strengthening overall urban mobility.

This is why a true new mobility revolution must be accompanied by reduced space for cars in cities. Mayors and city councils should proceed with plans to reduce parking and road space and introduce circulation plans to regulate private car flows across cities. If they do this shared, electric, and automated vehicles can fulfil their promise and help deliver more mobility much more efficiently than today. The benefits for Europe's cities would be spectacular, allowing them to achieve their climate objectives and vastly improve the quality of life for citizens, reducing air and noise pollution, traffic, and freeing up precious space for people.

To successfully and gradually lead this transformation, policies will require short term measures with long term vision, moving from a transport paradigm focusing on flows towards a mobility system revolving around people and places. This also implies a more reflexive approach to technology, involving stakeholders and citizens to ensure automated, connected, electric, and shared vehicles are steered by policies to deliver societal benefits.

Since ride hailing cars are the prime target for automation, regulators should begin by requiring that all new for hire vehicles operating in large cities are electric from 2025. Automated vehicles, or driverless cars, should be regulated to be electric drive - the implications of not regulating for this are dire consequences for the climate, as shown in this report. Automated vehicles should be designed and priced to encourage sharing to optimise research and transport efficiency. Cities should cut space, including parking, reserved for private cars and consider best case examples of new mobility roll-out and urban planning to ensure that emerging transport technologies complement existing public transport and are enablers for liveable cities. These findings are encapsulated in the results of our modelling. In a new mobility and urban planning revolution, car kilometres travelled could be reduced by 60%, while passenger transport in cars declines only 20%. Rather than travel in cars, people are not only encouraged but prefer to take public and active transport. The benefit for the climate is also clear, where this scenario could help reduce emissions to keep well within a 2°C-degree budget.

Metric in 2050	**Scenario**				
	Baseline	**Rapid automated**	**Slow automated**	**Slow automated & rapid Electric**	**New mobility & urban planning**
Mt CO_2	226	671	332	75	28
Mt CO_2 cumulative from 2018	13456	18538	14026	10306	9129
Cumulative emissions above (or below) 1.5°C/2°C EU car budget	+195% / +16%	+306% / +59%	+207% / +21%	+126% / -11%	+100% / -21%
Car vehicle km (G-vkm)	3989	9640	5868	5860	1622
Car passenger km (G-pkm)	6633	8920	7700	7696	5306

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1. Introduction

On Sunday evening 18 March 2018 in Arizona, Elaine Herzberg was struck and killed by an automated, soon to be driverless vehicle[iv]. The vehicle was an SUV carrying a single occupant charged with monitoring self-driving systems, operated by ride hailing service Uber. These vehicles are up to 2 tonnes, powered by diesel, petrol, or petrol plug-in hybrid drivetrains, and can consume up to 10.8 l/100 km.[v]

At the same time Uber and Lyft are now worth tens of billions and are adding new drivers and riders in cities across the world. These huge tech companies try to sell consumers, regulators and investors a story about ubiquitous, affordable and shared mobility, reduced congestion and reduced environmental impacts. But what's happening on the ground tells a very different story. Recent reports show Uber and Lyft are contributing to a big increase in congestion, creating new demand and competing directly with public transport[vi,vii].

"Do we envision a future of the sort where mobility is provided for a single occupant of a heavy, fossil fuel guzzling, driverless car operated by tech giants?"

These stories question our standard wisdom on the future of transport - our mobility. Where will the responsibility for the death of a pedestrian in such an incident lie? Do we envision a future of the sort where mobility is provided for a single occupant of a heavy, fossil fuel guzzling, driverless car operated by tech giants? The question of driverless cars appears to be no longer of *if* but *how quickly* - what does society want? Will zero emission electric cars come to market fast enough to stave off catastrophic climate change? Will we continue to buy cars, or will we share our rides? Will tomorrow's mobility mean better access to transport solutions and less exposure to noise and pollutants for all communities? These questions underline the ~~three~~ four revolutions of automated (and connected), electric, shared transport along with urban planning, coming soon to a street near you. Although these questions address the end goals, how we get there is of equal importance and will require a whole new revolution on urban planning and city design. How will the transport revolutions change mobility as we know it? How fast are they likely to roll out, and how will the revolutions interact? What are the policies required to guide or direct these revolutions in such a way that the future of mobility truly transforms the way people move around with positive environmental and equitable outcomes?

In this paper, we will investigate several potential futures of mobility and what their implications will be for passenger transport, the climate, public transport, and society.

1.1 Why this study?

This report draws inspiration from Fulton et al.'s *Three Revolutions in Urban Transportation* and the Joint Research Centre's *The Future of Road Transport*. We draw from the most recent developments and model the climate, energy, and congestion impacts, considering member state case studies. We also reflect on automated vehicles' (AVs') societal impacts along with the Collingridge dilemma on responsibility and accountability in innovation.[viii] This sector has been moving quickly, and a lot has changed in the last couple of years. There has also been a wave of studies that have looked into the future of mobility, each offering a different view on the speed of technological progress that will help drive this change. This begs the question: what value does this report add? In short, this report will

- Focus on climate impacts for the EU, with the Paris Agreement targets as the key metric.
- Collate the most important findings and issues from a broad range of research and reports.
- Hone in on the EU context with some insights on European cities.
- Address the EU specific policy requirements through T&E's policy expertise.

1.2 EU climate targets for 2050

The latest plan from the European Commission setting out long term climate targets is in the *Clean Planet For All* report[ix], which contains several scenarios for decarbonisation. Only those scenarios that aim to achieve net zero greenhouse gas emissions in 2050 are closer to compliance with the objectives of the Paris Agreement. The key metric to consider here is the carbon budget, that is, how much can the EU emit and contribute to a pathway which keeps the average rise in global temperatures to well below 2°C, or ideally, 1.5°C. Using a grandfathering approach as per the T&E long term strategy[x] to allocate carbon budgets to sectors of the economy would mean that from 2016 cars would have a budget of 4.6 Gt CO_2e for 1.5°C, and 11.6 Gt CO_2e for 2°C . Considering annual emissions of around 550 Mt CO_2, if emissions were to remain constant, the 1.5°C budget for cars will be used up in the year 2026, 7 years from now. In T&E's decarbonisation strategy, in a scenario with a rapid electrification of the passenger vehicle fleet (last ICE sold in 2035) coupled with significant modal shift, the 2°C budget is just about met. There is no room for inaction or increasing emissions. With this in mind, how can new mobility be levered to help the EU reach its climate targets?

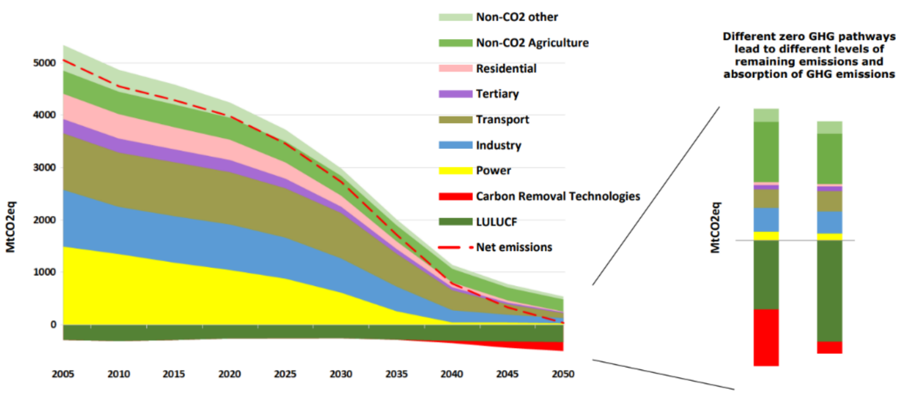

Figure 1: *Clean Planet for All* net zero scenarios

1.3 The scope of this study

We will calculate the impacts on greenhouse gas emissions and energy using our in-house European transportation roadmap model, the EUTRM[xi]. The key challenges of modelling the four revolutions are: the problem of scale (balance between micro bottom-up data vs high level trends) the unknown change in travel preferences of emerging technologies[xii], and the interaction of cars with other modes (and transport with other sectors). Details of the transport model and the complexities of modelling are discussed in Appendix 1 and Appendix 2, respectively.

In short, this paper presents research and gathers data, evidence, and trends of the four revolutions of transport to model their effect on activity at a vehicle (or passenger) level in several scenarios. The inputs are fed into the EUTRM to obtain regional outputs that create a broader picture for the EU. Below are some of the key studies that are used:

- Three Revolutions - Steering Automated, Shared, and Electric Vehicles to a Better Future, by Dan Sperling, is a main source of inspiration for this report and is the authoritative text in the field.[xiii]
- The Future of Road Transport, from the Joint Research Centre (JRC)[xiv], presents both a broad and in depth analysis from a technical and policy standpoint with a particular focus on Europe, however it doesn't directly model energy, emissions, or passenger activity changes.
- Fulton et al. 2017[xv] study, showing a global outlook of energy, emissions but with Europe as one region.
- International Transport Forum (ITF) studies that investigate several cities including Lisbon, Helsinki and Dublin[xvi], presenting a best case scenario based on optimising a reduction in energy and passenger waiting time.
- Lyons et al., which applies a thorough econometric analysis of automated vehicles from a UK perspective[xvii].
- Additionally, RethinkX[xviii] looks at stranded assets, envisages a transition that is extremely aggressive; the BNEF BEV 2019 Outlook refers to the 3Rs but is more pessimistic; Revolution in the Driver's Seat, from Boston Consulting Group[xix] has something in between.

INFO BOX: Freight transport

Electrification and automation coupled with intelligent freight forwarding may come at a faster rate than for passenger transport. It will no doubt have profound effects on the way goods are transported within Europe and across the world; from heavy duty long haul trucks delivering between warehouses to delivery vans being replaced by bots or drones. In the case of the latter, the Belgian region of Flanders plans to use drones for packet delivery between two hospitals[1]. This is beyond the scope of this study and may be subject to future T&E analysis, but we note three potential limitations in its exclusion: with the advent of ever faster and cheaper delivery, will a significant portion of car journeys be made redundant? On the other hand, to what extent will delivery services add to congestion and slow overall traffic flows? Will there be public acceptance of swarms of drones delivering parcels, and what will be the energy requirements?

1.4 Comparing European and US cities

Compared to the US, 'European cities are densely populated, highly walkable, and closer in proximity to one another than are cities in the United States. They are often better served by public transit… [and] … as a result, a culture of shared transportation is more prevalent in Europe than it is in the United States'.[xx] Add to that the higher price of fuel, taxes, and parking, and the case for Europeans to abandon their privately owned car may prove easier to make than in the US, but not necessarily for an automated ride. For the moment, there is indeed a stronger culture of public transport and active modes. In general, Europe has more metro capacity and a more effective public transport systems, leading to a higher modal share in buses and metros than the US[xxi]. Additionally, the systems of the wealthy Western Europe will have different responses to automated, electric and shared vehicles.

1.5 How will the transport revolutions unfold? Some general considerations

The three transport revolutions may fundamentally change how we move ourselves around the continent and turn the sector on its head. We certainly are moving towards these transport revolutions, but how fast will they come to market? And what is needed at the system level to extract the most benefits? These points will be investigated further in the following chapters; below is a summary of the current and projected state of play.

Electrification: In Europe, perhaps the easiest revolution to predict is electrification. The post-2020 light duty standards will require manufacturers to sell cars that emit, on average, 37.5% less CO2 per kilometre than those sold in 2021[xxii]. Although sales amount to around a 2% share today, latest production plans indicate over 200 plug-in models will be available by 2021, with sales likely to rise to around 20% and 40% in 2025 and 2030 respectively[xxiii] (models that include pure battery electric or hydrogen fuel cell)[xxiv]. Beyond 2030, several countries have announced internal combustion engine (ICE) passenger vehicle sales bans, ranging from 2030 to 2040. Charging infrastructure will be a challenge, but upcoming EU and national regulations and funding should help roll it out faster, especially at home and workplace for cars and across main roads for commercial vehicles. Aside from the push from legislation, manufacturers have made announcements that indicate their global production in terms of models will enable them to meet, and perhaps exceed the 2030 targets. Similarly, lithium battery production is finally ramping up in Europe, reducing the potential supply risks from relying on Asian manufacturers only. The immediate future of vehicle electrification is clear: strong signals for wide scale uptake to comply with the EU's emission targets, but the longer term outlook will depend on whether car makers embrace electrification or continue to treat it as a necessary evil to comply with regulations.

Automation: Driverless cars have been an object of sci-fi and of research for much of the 20th century[xxv] - will the 21st century be the age of automation? Vehicles on the road today already employ technologies that significantly or completely take over the role of driving, including automatic parking, adaptive cruise control, and lane keeping[xxvi,xxvii]. Automated cars and minibuses have been operating for a couple of years in controlled areas. The success of automated vehicles will also likely be dependent on them being 'connected', able to find the fastest route considering real-time traffic and infrastructure conditions, and optimising traffic flows[xxviii]. Many players are eyeing the automation market as a way to add value to the existing private car ownership model, while others are approaching it from an angle of the cannibalisation of private car ownership, offering automated mobility as a service. If we believe the companies who have invested significant amounts of money into the technology, it is only a matter of years away and ready to sweep aside cars with steering wheels by the 2030s. Other analysts are more cautious[xxix,xxx]. Legislation is currently regional or targeted at pilot projects, and many uncertainties remain regarding their regulation, ethics, and public acceptance. In particular, automated vehicles (AVs) raise questions related to tech governance and society's role in designing innovation. The power asymmetry between the industry, regulators, and citizens could lead to technological determinism and de-politicisation of the issue, preventing alternative forms of mobility from emerging. In this context, ensuring responsible innovation - as defined by Collingridge[xxxi] - in the field of vehicle automation will be key to secure public acceptance. This means focusing more on inclusion, openness, incrementalism, flexibility and reversibility in the innovation process. This also implies that AV technology must comply with the key principles of trustworthy artificial intelligence (AI) identified by the European Commission's high level expert group on artificial intelligence[xxxii]: it should be lawful, ethical, and robust. The impact of automated vehicles on job is also likely to upset the labour market. Low-skilled workers, among them taxi and Transportation Network Companies (TNC) drivers, will be most exposed to the transition to AV. Given that most jobs created by automation will relate to engineering, it is unlikely that a mere retraining of the existing workforce will be sufficient to mitigate job losses. Finding a sustainable employment alternative for existing low-skilled workers will be crucial to a just transition to autonomous vehicles. Beyond these considerations, the cost of fully automated vehicles may also pose an insurmountable hurdle for widespread uptake, particularly as a new market entrant. After all the hype of the last few years that the technology is imminent, are we now heading towards the Gartner Hype Cycle's trough of disillusionment?[xxxiii]

INFO BOX: Driverless cars: Automated or Autonomous?

Some may consider this semantical hair splitting, where others may consider it fundamental. We tend to prefer Daniel Sperling's usage - cars will be *automated* as they will follow the trip requests of users, they will not decide our destination for us, as what may be implied by *autonomous*. That being said, autonomous is by far the most common parlance, and we will interchange freely between both in this report.

Sharing: In terms of motorised transport, shared rides in buses and trains dominated the transportation sector up until the mid-20th century. In Europe in 2016, 82% of passenger transport activity is by car, or 71% if aviation is included[xxxiv]. The speed, convenience, and status of the private car for its cost will make any transition back to a sharing model difficult. Sharing vehicles should be the easiest aspect, and many business models of short term car rental (car sharing) have cropped up in recent years. This is an important first step to pricing people away from owning their own car, freeing up parking spaces and making more efficient use of resources. As data on Uber and Lyft ride pooling services in New York City illustrate, only about 20% of rides are shared.[xxxv] The real challenge will be to get people to share their ride - reaping the benefits and flexibility of the car combined with high utilisation. Fiscal measures or incentives may not be enough for people to give up their private space to share the cost with several strangers, or worse, one other. Sharing is the crux of the future of mobility, but how accepting are we of such a change?

New mobility and urban planning: This is not quite a revolution as it requires a long term, planned transition to enable and foster new mobility (encompassing micro-mobility & shared automated and electric passenger cars), however it will require a revolutionary change of mindset. Already in 1961, in her seminal work *The Death and Life of Great American Cities*[xxxvi], Jane Jacobs questioned the urban planning orthodoxy and insisted on the importance of walkable spaces and parks as places of social interactions. Today's technological revolutions give a renewed enthusiasm to revisit these key principles of lively cities; and the climate and air quality crisis add a much needed sense of urgency to implement these changes. In fact, cities are already taking action to limit traffic flows in strategic locations: Madrid and Paris have adopted plans to make their city centres more lively by restricting access of the most polluting vehicles (Madrid low emission zone, pedestrianisation of Paris embankment); London has introduced a charging scheme for polluting vehicles on top of the existing congestion charge (so-called ultra-low emission zone); the Belgian city of Ghent introduced a car free area, pedestrian zone of about 35 Ha, resulting in less car trips in the city as a whole.[xxxvii]

1.6 A Europe without transport revolutions

In the previous section, we summarised the revolutions and what their implications on transport may be. In order to quantify their potential impacts, we define here a baseline case of emission projections in which to compare them to. If the revolutions were suppressed, through lack of policy, investment, technology development, or any other reason, and historical trends were to continue, car transport in Europe will reach new levels of congestion as motorisation and wealth spur more passenger activity (Figure 2). Diesel sales will stabilise, and plug-in hybrids will likely taper off as pure zero emission vehicles will improve in range and charging speed, and be cheaper[xxxviii].

Passenger activity in Europe is projected to increase by about a third from now until 2050. Although some Western European countries have reached peak car[xxxix], some of this rise is due to transportation network companies (TNCs). Tank-to-wheel (TTW) emissions in 2050 are only reduced by around two thirds compared to 2005. This gives cumulative emissions from 2018 to 2050 of 13.4 Gt CO_2e, exceeding the 2°C budget by 1.8 Gt CO_2e and still far from zero emissions by mid century.

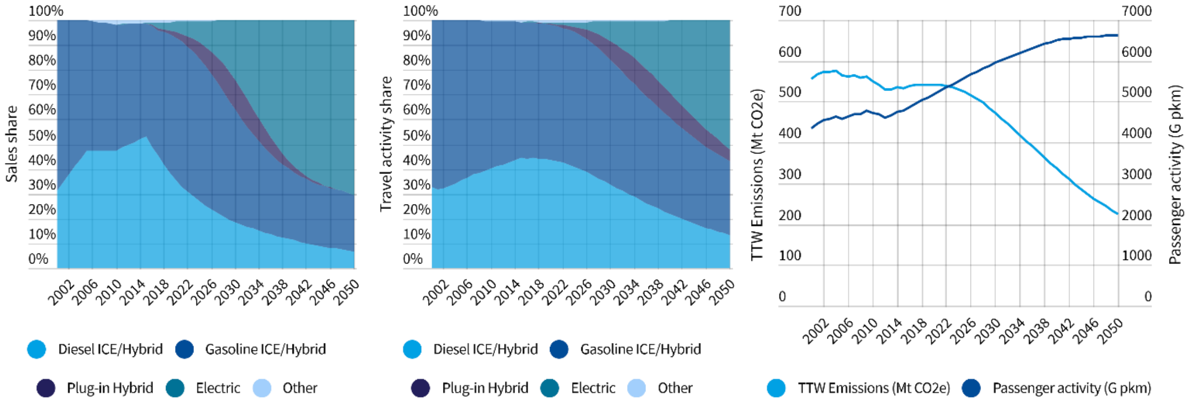

Figure 2: Stifled revolutions combined with European 2030 LDV CO_2 regulations. Note that electric here implies vehicles which are either directly electrified (battery electric vehicles) or indirectly electrified (hydrogen fuel cell vehicles, where the hydrogen is produced by electrolysis).

2. Automated Revolution

INFO BOX: Levels of automation			
Level 0	No automation	The human driver does all the driving.	OEDR: Driver ODD: Not Applicable
Level 1	Driver assistance	An advanced driver assistance system (ADAS) on the vehicle can sometimes assist the human driver with either steering or braking/accelerating, but not both simultaneously.	OEDR: Driver ODD: Limited (e.g. highway) Example: adaptive cruise control (ACC)
Level 2	Partial automation	An advanced driver assistance system (ADAS) on the vehicle can itself actually control both steering and braking /accelerating simultaneously under some circumstances. The human driver must continue to pay full attention (“monitor the driving environment”) at all times and perform the rest of the driving task.	OEDR: Driver ODD: Limited (eg.highway) Example: ACC with lane keeping, reverse park assist
Level 3	Conditional automation	An Automated Driving System (ADS) on the vehicle can itself perform all aspects of the driving task under some circumstances. In those circumstances, the human driver must be ready to take back control at any time when the ADS requests the human driver to do so. In all other circumstances, the human driver performs the driving task.	OEDR: System ODD: Limited Example: Traffic Jam Pilot[1]
Level 4	High automation	An Automated Driving System (ADS) on the vehicle can itself perform all driving tasks and monitor the driving environment – essentially, do all the driving – in certain circumstances. The human need not pay attention in those circumstances.	OEDR: System ODD: Limited (e.g. geofenced areas, good weather) Example: Navya Shuttle[1]
Level 5	Full automation	An Automated Driving System (ADS) on the vehicle can do all the driving in all circumstances. The human occupants are just passengers and need never be involved in driving.	OEDR: System ODD: unlimited Example: None
Autonomy as per the NHTSA[2] and operational design domain (ODD) and Object and Event Detection and Response (OEDR) as per Traficom[3]. OEMS are saying that they should skip level 3 automation, as it could be a risk to drivers. Level 1 and Level 2 automation can offer significant safety benefits; however, level 2 can lead to drivers to think the car has more control than it does. For level 2, proper monitoring of the driver is required to ensure full attention to the road for OEDR.			

2.1 An introduction to automated vehicles

Automation already exists in the broader transport system. The autopilot is doing most of the flying on a commercial jet, outside of take-off and the final stages of landing. New metro lines increasingly tend to have driverless trains that can enable higher train density and increased punctuality[xl]. The world's first driverless tram was launched late 2018 in Potsdam[xli]. The challenges of automating these sectors are different to cars, but in the case of rail, automated systems have been around for decades. Progress in rail automation is typically limited by lack of potential financial gains and a strongly unionised workforce[xlii].

The technological pursuit of automated cars is compelling for the potential they have in reducing road fatalities. 90% of road fatalities in Europe are due to human error[xliii] (this statistic bellies the unequal distribution across countries[xliv]) a figure that advocates for driverless cars claim could go to zero in a full fleet of autonomous vehicles, citing the current improvement of automated technology. This is certainly something to strive for, in and of itself. However there is a lot of evidence that counters this conclusion[xlv,xlvi] and a growing debate about what level of improvement should be legislated. Regardless of how much the fatality rate could be reduced, the public's acceptance of what will likely appear to be preventable deaths will be put into question[xlvii]. Accidents will continue to happen, but they may be due to a misinterpretation of input signals that humans would normally have no problem misinterpreting, for example the '45 mph stop sign'[xlviii] or vehicles mistaking trucks for overhead road signs[xlix]. Aside from data interpretation errors, there is also the risk of complete software failure[l]. Accidents and incidents of this nature will severely dent confidence in the technology, and hinder its uptake.

Autonomous vehicles may have benefits beyond safety: for one, there could be reduced need for heavy crash protection and high performance, allowing for greater energy efficiency. It could also be that occupants better utilise their time rather than driving; up to 11% of drivers admit that they text or use their smartphone while driving today. But being a passenger in a vehicle that is navigating around a city means that visual and vestibular[li] stimuli don't match, inducing motion sickness[lii]. Solving this problem will be key for realising the opportunity costs which may make or break the economics of automated vehicles[liii]. On the other hand, driverless cars could be entrusted to drive faster on highways, allow a change of design that could increase entertainment features built into the vehicle, and tap into a large market that currently has limited or restricted access to vehicles, such as the elderly, disabled or young. The seminal paper by Wadud[liv] shows the potential energy consumption implications in these cases at the vehicle and system level (Figure 3). Besides these impacts, there will be a significant amount of computing power required to manage a fleet of automated connected vehicles, but this is not considered in this analysis.

Z. Wadud et al./Transportation Research Part A 86 (2016) 1–18

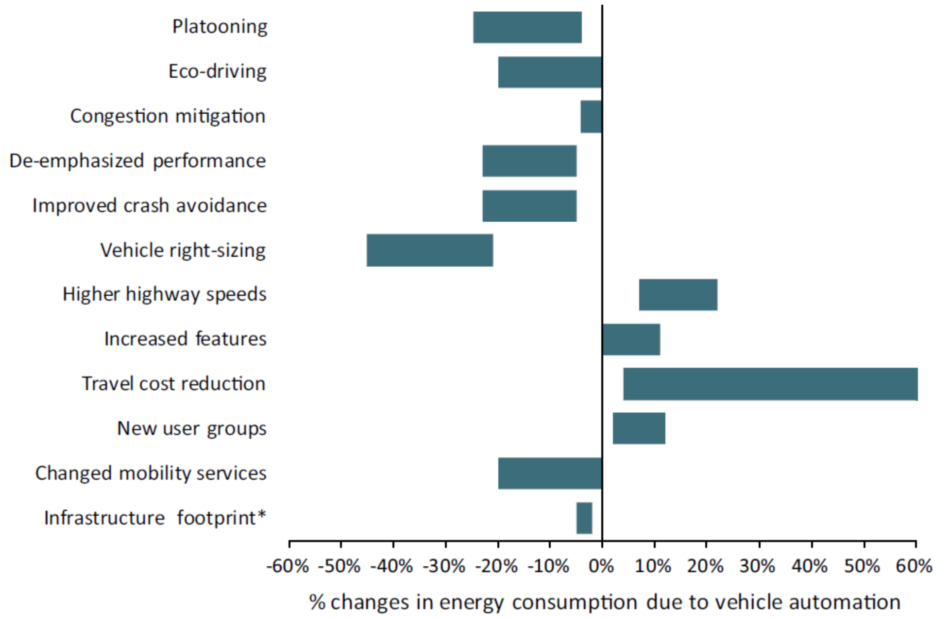

Figure 3: How automated vehicles may influence passenger vehicles energy consumption.

INFO BOX: The Zahavi (or Marchetti) constant

A key metric to consider when dealing with a surge of automated vehicles is the amount of time on average people are willing to travel. The Zahavi (more commonly referred to as the Marchetti) 'constant' has been observed over the course of the 20th century and before[4,5], and is a metric still used by transport modellers (e.g. Bleijenberg[6]). The underlying principle is that people travel further only because travel speeds increase, as we seem to limit ourselves to an average amount of travel time budget, which is around 1.1 hours per day. In urban areas in peak hour, the average speed of vehicles has not improved significantly compared to the horse and carriage. This essentially puts a limit on the maximum growth of activity bound by the length of a road network. Some argue that automated vehicles will break the Marchetti constant, as travelling in an AV will not be the same - drivers will become passengers, and they could be in an environment comfortable enough to be productive with their time, or enable rest. Some data suggest this could lead to overall longer travel times[7]

We assume that automated vehicles will have to reach a NHTSA level 5 for widespread uptake to occur. Level 3 automation requires full driver concentration, which has been shown to be difficult to maintain without being fully engaged in the driving activity. Worse still, as drivers 'drive' less, they become less equipped to deal with or anticipate emergency situations, as has been seen in the airline industry[lv]. Many OEMs have stated that they will skip level 3 altogether. Level 4 would likely be suitable for a wide range of operational situations on most days, but if a part of the car fleet were to stop because of a snow or rain storm, heavy fog, or something as simple as the sun setting straight ahead impairing the on-board cameras, this loss of utility may be too great for consumers to make the final leap away from cars with drivers. We accept the hypothesis of Lyons[lvi] that there is no great distinction between level 4 and level 5 automated vehicles in terms of general user acceptance (of being driven without a driver) and hardware requirements (and thus cost). But for large scale uptake and hence an overhauling effect on the transport system, we argue that level 5 autonomy will be required.

Manufacturers are gambling on combinations of Lidar, radar, and/or cameras. As described in Mosquet *et al.*,[lvii] before any technology is rolled out, it will need to be proven secure to cyber-attack, affordable (which often implies sold in high volumes), and user friendly. At present there is no framework or industry standard of which companies can compare their performance. Claims of safety or performance will need to be standardised during type approval.

2.2 AV market today and OEM announcements

It's difficult to know how much money has been invested into driverless car technology (whether it be hardware or software), but some estimates put the figure at $100 billion across the industry[lviii]. Table 1 shows some of the key players, and their progress reflected through kilometres driven and kilometres per disengagement; the difference between best and worst on the latter metric is startling (Waymo at 17 800 km, Uber at 0.6 km). Comparing these figures like-for-like however can lead to some misinterpretation, as it is unclear what kind of roads or weather conditions the testing took place in were. The investments column doesn't include all historical or planned/current investments, only recent publications of the current state of play. Most companies have reported investments that exceed USD 1 billion.

Table 1: †[lix] Key players, their investments, and their progress in the race to automation. Hyphens indicate no data found.

Company	Reported Investments	Kilometres driven	Kilometres per disengagement[lx]	AV Technology	Drivetrain
Uber	USD 1.1 bln[lxi]	5 bln	0.6	Lidar, cameras	PHEV
Waymo	USD >1.1 bln	16 bln†	17 800	Lidar, cameras, radar	HEV (Chrysler Pacifica)
Tesla[lxii]	'hundreds of millions of dollars'[lxiii]	1.6 bln[lxiv]	N/A	Cameras, ultrasonic sensors and radar	Battery electric vehicle (BEV)
SMMT UK	--	--	N/A	Lidar, cameras, radar	ICE
GM	USD > 1.1 bln[lxv]	--	8 330	--	--
Baidu[lxvi]	USD > 1.5 bln[lxvii]	2 mln[lxviii]	330	Lidar, cameras, radar[lxix]	BEV, PHEV, ICE
Mercedes & BMW[lxx]	USD > 1 bln	--	2.5	Lidar, cameras, radar	Hydrogen fuel cell

Aside from the companies above, which include a mix of traditional car OEMs, technology giants, and a TNC, NVIDIA is perhaps *the* key player for AVs[lxxi]. Originally a graphics card producer for computers, their high performance cards are perfectly suited to processing the huge amounts of data that the cars sensors gather. They are providing hardware to Tesla, Uber, Volkswagen, and Baidu[lxxii], and are also developing a simulation program where automated vehicle software can be rigorously tested, without endangering lives.

INFO BOX: Automated vehicles - what are the other risks

Primary and secondary effects. Primary effects are mentioned here, and they include luring passengers away from public transport, as seen by ride hailing services[8], and even public transport development and deployment as public authorities may worry about stranded investments. Furthermore, there is a risk that AVs will impact longer distance travel, both for more efficient modes (trains and coaches) and more polluting modes (short-haul flights). Other risks are greater urban sprawl[9] with a significant shifting of real estate values from central to greater-urban areas[10]; this is countered by the possibility that automated vehicles could be hotels on wheels, significantly cheaper than current rental or hotel prices[11]. These issues are not treated further in this study.

2.3 Cost and social impacts

Fulton, RethinkX, and many other analysts conclude that by taking away the costs of drivers, automated vehicles will significantly lower the cost per kilometre for the consumer compared to current ride hailing or private vehicle ownership - according to RethinkX costs could be a factor of 2 to 8 times cheaper[lxxiii]. Cheaper prices would be expected to lead to much higher demand. Uber and Lyft claim to take no more than 25% of the fare, with the rest going to the driver but in reality, it is at least 30% and up to 50% for shorter trips[lxxiv]. So this means fares could reduce by at least 50%, all else being equal, without the driver. These companies would also start to take the financial burden of cleaning, servicing, and fuelling of the vehicles, as well as paying for depreciation.

On the other hand, Nunes and Hernandez[lxxv] argue that without sharing, automated vehicles would not be a profitable business proposition compared to privately owned vehicles, particularly if the consumers don't take into account opportunity costs (i.e., using their time productively during a trip). The paper suggests that the price per kilometre for automated vehicles to break even would be twice that of private cars[lxxvi]. Uber is also currently running at significant losses, to the tune of $4 billion over 2017 and 2018[lxxvii]. The second quarter of 2019 results showed a $5 billion loss, with questions about a path to profitability mounting[lxxviii]. Removing the driver certainly help the business case of ride hailing companies, but the balance of providing enough vehicles to offer a reliable service but without having to over invest in automated cars will be a fine balance.

In terms of additional cost, Lyons[lxxix] gives prices for Level 4 AVs of around €5500 today, decreasing to around €3400 in 2035. The reduction in price depends largely on a learning rate, provided by Mosquet et al.[lxxx], so a delay in technological or societal readiness for autonomous vehicles may push these savings further into the future. In any case, the hardware represents a >20% premium on the current average purchasing price of about €20 000[lxxxi]. For a fleet of automated ride hailing vehicles, this cost would foreseeably be averaged over more than 100 000 km; this would tend to push the technology to these sectors or to premium car segments only.

In Europe, there are around 5 million people employed as drivers, of which 2 million in passenger transport[lxxxii]. These drivers are split across taxis and private hire vehicles operations. Among EU member states, there is a large difference between the proportion of drivers split between these two segments, and there is a large difference across Europe in terms of drivers per population (in the UK, 36 drivers per 10 000 inhabitants compared to France with 3.8 drivers per 10 000 inhabitants). Although this revolution has been touted to create new high tech jobs (particularly in hardware and software development), displaced drivers will not be able to find equivalent jobs in terms of skills and pay, which will vary from technical (fleet supervision) to low-skilled (fleet cleaning). Recently, new market entrants (Lyft, Uber) have changed the business case of passenger transport. There is evidence that drivers for these platforms have less or no social protection (such as minimum wage and pension contributions), while upper management become eye-wateringly wealthy[lxxxiii]. These trends must be addressed if Europe is to reduce inequality and a just transition to a clean economy.

2.4 Unregulated automated hell

The previous sections have highlighted the levels of uncertainty of automated vehicles. We explore two uptake options to investigate the effects on emissions and activity (Figure 4). Here, we assume that the automated vehicle fleet has the same makeup as the fleet average, in terms of number of PHEVs, ZEVs, and ICEs. These two uptakes show a scenario where policy has failed, and there is a mix of ride hailing automated vehicles, but also privately owned vehicles that often run around empty, so load factors of the car fleet actually decreases, representing an overall loss of efficiency of vehicles moving people. Worse, additional passengers are lured from public transport. Buses are caught in the traffic jams, where the have-nots who cannot afford the extra premium for a private automated ride are most affected. Although automated rides are more expensive than public transit, it is cheaper than a regular taxi service or privately owned vehicle because road charging was not politically palatable. Finally, because of the rapid and uncoordinated roll-out, the vehicles are not connected, either to each other or to infrastructure. Key modelling inputs are shown in Table 2.

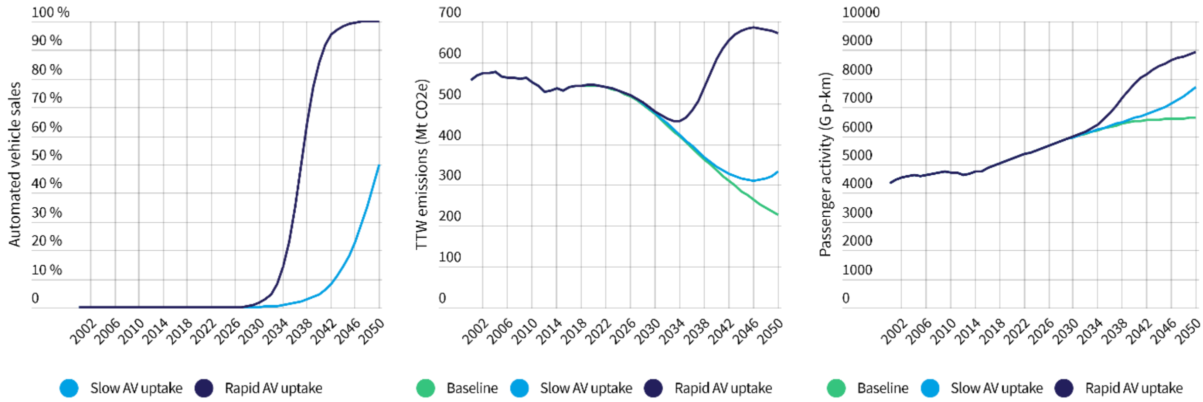

Figure 4: Two uptake scenarios of automated vehicles and the effect on emissions and passenger activity, for the EU. (left) Sales of Autonomous vehicles, (middle) slow uptake results and (right) rapid uptake results.

Table 2: Key input parameters for an unregulated automated vehicle revolution, T&E assumptions

Automated vehicle Metric	**Change from base case or existing fleet**	**Comments**
Vkm driven	4x fleet average	Automated vehicles will be essentially able to drive all day, rather than being parked for 95% of the time - although with a strong share of privately owned vehicles, a lot of them will still be underutilised. Note that vehicles are also assumed to survive and have import/export flows across Europe equivalent to the current fleet.
Induced passenger demand	+40%	The affordability and availability of automated vehicles to existing and new user groups mean that travel demand increases compared to the baseline. These passengers also come from public transport and active modes, which can't compete with price, speed, convenience.
Per vehicle energy demand	No change for slow uptake, 10% increase for fast	It is assumed that automated vehicles will follow EU standards to 2030 and general EV uptake. In the rapid uptake, we assume that the potential energy savings through light-weighting and lower speeds are not offset by the processing power

		for the AAV technology or additional entertainment systems in the vehicle, unlike for the slow uptake case where these effects are assumed to offset each other.
Load factor	-50%	Owing to the affordability of automated rides, there is no incentive to share rides, and there is a greater share of empty miles as vehicles look for new rides.

The results show that both emissions and passenger activity are set to greatly exceed the baseline scenario. Emissions under both scenarios see a relative increase, and the total GHG emitted from 2018 to 2050 ranges from 14.0 Gt CO_2e to 18.5 Gt CO_2e. This shows that by not anticipating the arrival of automated vehicles, Europeans could find themselves not only still stuck in a car dominated society, but one that has become significantly worse than what we see on our roads today. The distribution of these emissions across European regions are also not equal: in the EU15 countries, emissions will increase by up to 21% compared to 2005, while in the EU13, they will increase by 43% in the rapid uptake scenario.[lxxxiv]

For the remainder of this report, we assume that the most likely uptake of automated vehicles will be closer to the slow uptake curve, even when the economics of electrifying early on in the uptake are considered (see next section). This chapter has shown that there has been a lot of investment in this field, where companies losing money today are relying on automated vehicles to turn around their fortunes. Indeed, (over) selling this potential is in the interest of companies to secure investment. We side with the analysts who show more caution here. That said, if proven wrong, policies must be in place early in order to avoid the scenarios described above. See the Policy Recommendations section for more.

3. Electromobility revolution

Transport & Environment, among many others, have critically analysed historical and expected development of electromobility in Europe. The advantage of EVs over conventional cars is clear: they emit less over their lifetime[lxxxv,lxxxvi], they are cheaper to run[lxxxvii] and rapidly becoming upfront cost competitive as battery prices plummet[lxxxviii] and the technology improves[lxxxix], most EU member states are fulfilling their charging infrastructure requirements[xc], and they will play a key role in decarbonising the sector[xci]. This section looks at electric vehicles in a new light: how will they be integrated into autonomous vehicles.

3.1 Electric and automated, the perfect match?

Electric vehicles have drivetrains with 90% fewer moving parts compared to traditional internal combustion engines. Electric vehicles have regenerative braking, which reduces wear on brake pads. Studies[xcii] and anecdotal cases[xciii] tend to show that this results in significantly lower maintenance costs for electric vehicles. Battery performance is dependent on the manufacturer, but the data show that Tesla batteries tend to remain above 80% after 220 000km[xciv] or more[xcv], and Nissan claims up to 22 years of usable life[xcvi]. Battery technology and management will only continue to improve, so battery state of health for high mileage vehicles, what one may expect from a fleet of automated vehicles, will also improve. Electric vehicles also save considerable amounts in terms of cost of fuel, as electric powertrains are much more efficient than internal combustion engines. These cost advantages make electrified autonomous vehicles compelling, and Bloomberg New Energy Finance predicts that electric vehicles in some segments (e.g. medium) will even achieve purchase price parity with conventional models by 2024[xcvii].

Fears of insufficient raw material availability with the uptake of electric vehicles have been largely put to rest, so long as manufacturers have timely strategic plans to ensure supply[xcviii] and are required to effectively recycle all batteries reaching end of life. However, an exponential increase in size and battery capacity of electric vehicles is not sustainable, so whether automated or not, cars will have to be rightly sized for their use in the future. Member States may need to take into account the reduced ability of these electric vehicles for grid balancing, as their utilisation will be far greater than a privately owned vehicle and may not be able to operate as a "battery on wheels"[xcix]. There will be an even greater need for smart grids and smart charging in order to manage and integrate electric vehicles into the electricity system, particularly as the transition to decarbonised electricity production will rely heavily on solar and wind energy.

3.2 Electric - Automated vehicle potential

The upfront cost of electric vehicles are predicted to reach cost parity with ICE vehicles for some segments at around 2022, with other segments following soon after[c]. EVs equipped with automated vehicle technology will however be more expensive. The running costs of EVs however are favourable compared to ICEs today, and for fleet operators, taxi companies, and transportation network companies (TNCs) whose vehicles travel many more kilometres a year than a privately owned car[ci]. Predicting the exact increase in this demand is a difficult proposition; for the low uptake of automated vehicles is shown in Figure 5. This scenario shows a Europe where automated vehicles were regulated to be zero emission, and that aimed to achieve its zero emission 2050 target. This leads to further ICE bans, particularly in Western Europe in 2030 to 2040[1], which created more market certainty for an even greater push for zero emission vehicles.

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[1] In 2030, Sweden, Netherlands, Ireland, Slovenia, Denmark; Scotland in 2032; the UK and France in 2040. https://www.transportenvironment.org/news/uk-and-france-end-diesel-petrol-car-sales-2040

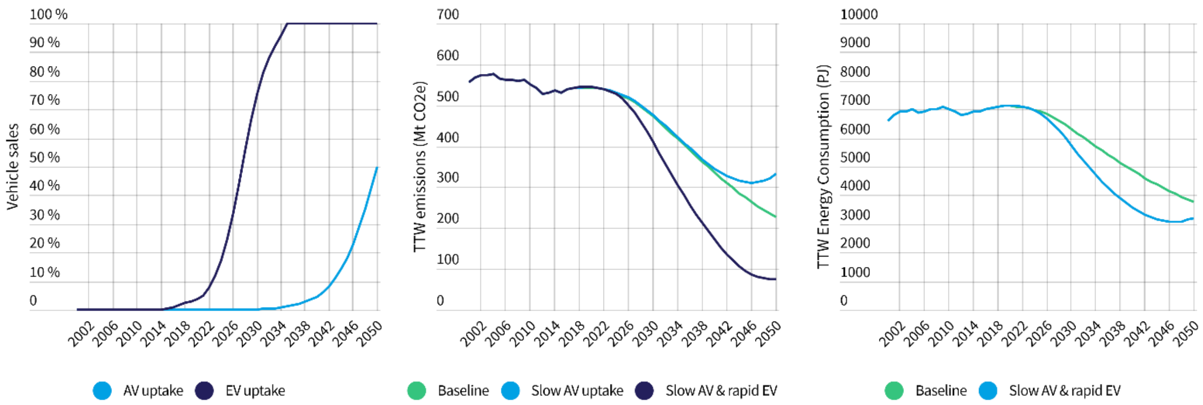


Figure 5: Scenario with rapid electric vehicle uptake followed by a slow automated uptake.

The results show zero emissions are only part of the solution. From a climate perspective, the total GHG emissions from 2018 to 2050 is 10.3 Gt CO_2e. This means that the 2 degree budget is only just met by 2050, but as emissions are not at zero, a policy to remove the existing ICE fleet of vehicles is needed, as discussed in other studies[cii]. However, in terms of vehicle kilometres travelled, and the slow degradation of public transportation services that push ever more people into cars means that cars stay dominant, journey times go up, vehicle kilometres go up, and energy usage is much higher than what would have been the case if the electric vehicles were also not automated. This includes car use in the existing fleet, explaining the slight plateauing of emissions after 2045, which is only due to the existing fleet. The reduction in emissions in EU15 countries is projected to be 90%, while in EU13 countries the reduction is 60%, compared to 2005. The key modelling parameters are presented in Table 3.

Table 3: Key input parameters for an unregulated automated but electrified vehicle revolution

Automated vehicle Metric	**Change from automated case**	**Comments**
ZEV sales	100% in 2035, see Figure 5 for sales uptake.	The 2030 targets are over achieved through a range of government incentives beyond EU regulations, including ICE phase-outs and the uptake continues until 2035, when the last ICE is sold. All automated vehicles sold are electric.
Per vehicle energy demand	Electric vehicle energy demand	All automated vehicles are electric, and thus have a lower energy consumption and zero emissions.

4. Sharing and new mobility revolution

4.1 Limited city space and urbanisation make sharing a necessity

The UN[ciii] expects the world population to increase to 9.8 billion by 2050, while urbanisation is likely to further increase in coming years, with 68% of the world population living in cities by this date, compared to 55% today. In Europe, 83% of the population will live in urban areas by 2050, from 74% today.[civ]

In this context, car ownership rates similar to the current ones in Italy, Germany, or Poland of more than 500 cars per 1000 inhabitants[cv] (EU28 average: 505 cars per 1000 inhabitants) cannot be sustainable in the long term simply because of cities' physical limitations, especially regarding space allocation in a context of increasing demand for affordable housing and improving quality of life. Limiting and eventually reducing congestion while preserving citizens' quality of life will require us to move away from owning cars towards sharing vehicles - and ultimately sharing rides - in combination with public transport and other flexible mobility options.

INFO BOX: The value of space

Space is expensive. Housing prices in Europe grew 15% from 2015 to 2018[12]. The price per square metre for living space can vary significantly across cities, from nearly €12 000/m^2 in London to €1100/m^2 in Sofia[13]. The population weighted average price paid by residents in Europe's capitals is €5411/m^2. Needless to say, land comes at a premium. Street-side parking for residents however can be much cheaper. It is a rate often set by the local council district. In Tower Hamlet in London, parking ranges from £10/year to £186/year depending on car category[14]; in Brussels prices are around €15/year[15]. If we consider that a typical car spot is 11.5m^2 [16], then the price per square metre for a car in central London is €18/m^2/year, or between 20 to 60 times less than the value of rented residential real estate[17]. In an effort to highlight this disparity, a pilot program in the Netherlands allowed residents to use their parking spots however they like (such as to have a small garden bed) in a bid to promote shared cars and active mobility, but it reportedly had a lot of criticism from many residents and only low uptake[18]. As will be discussed in the policy discussion, this large imbalance on the value of space must be addressed to avoid cities being ever crippled by the burden of the car.

This transition will require a substantial adaptation of existing urban planning. Space utilisation for instance will have to be optimised as population density increases, if we are to avoid urban sprawl. The transition to shared mobility will support this evolution, if managed well and complemented by sound urban planning. This involves a redistribution of public space, with more road space devoted to active modes, and whole areas repurposed to benefit social interactions. In particular, limiting space allocated to car parking is crucial. Reducing the number of parking spaces of personal cars, or increasing their cost through parking price policies, impacts travel choices. Freeing up kerbside parking also frees up space in urban areas that should be allocated to active modes, public transport, and housing. A 2013 assessment from the European Parking Association (EPA) indicates that there were 47.1 million regulated parking spaces in Europe. More than a third of these were on-street parking spaces.[cvi] The EPA also notes that there are a lot of unregulated kerbside parking places, which are estimated at over 190 million spaces[cvii]: at 11.5m^2 per spot, this amounts to 2 200 km^2, not far off the surface area of Luxembourg.

In addition, measures such as access restriction and road pricing could further incentivise shared vehicle use. These measures are complementary to the objective of tackling air quality problems in cities, e.g. through low and zero emission zones.

4.2 Existing sharing business models

There is an ever increasing offer of new mobility solutions, and fortunately many of the business models promote or are centred on shared infrastructure or rides. This section looks at the key players in Europe to provide insight into what the future may hold for urban transport. Although we do not include or describe it in this section, public transport (i.e. trips by bus, tram, metro, or regional trains) will be the backbone of the various models described below. A dedicated T&E publication on the future of public transport in Europe will investigate this aspect in more details. This section provides an overview of the most popular sharing models being offered in Europe. Interestingly, and as illustrated below, their pricing models make shared mobility services in general more expensive than public transport services, but still attractive when compared to the costs of owning a car in cities.

4.2.1 Transportation Network Companies

INFO BOX: What are Transportation Network Companies?

Companies such as Uber are often alternatively referred to as Transportation Network Companies (TNCs), Private Hire Vehicles (PHVs), ride-sharing, or ride-hailing. Below is a quick overview of these typologies:

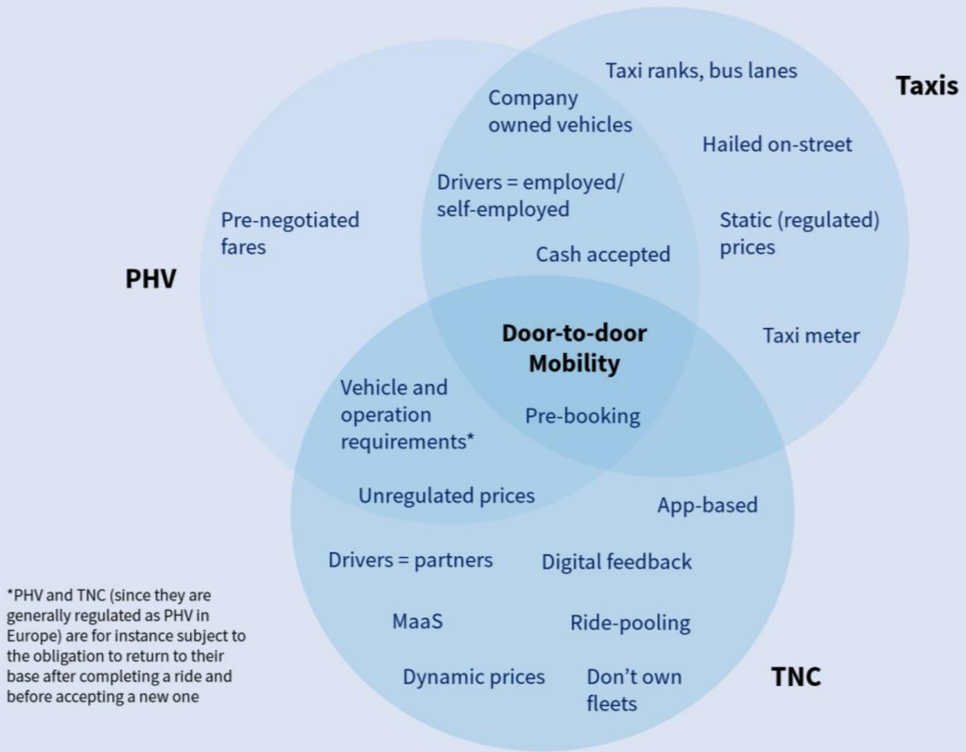
TNCs provide pre-arranged transportation services for compensation using an online-enabled application or platform (such as smartphone apps) to connect drivers using their personal vehicles with passengers[19], while a PHV means a vehicle constructed or adapted to seat fewer than nine passengers which is made available with a driver for hire for the purpose of carrying passengers, other than a licensed taxi or a public service vehicle.[20]

Ride-sharing is an arrangement in which a passenger travels in a private vehicle driven by its owner, for free or for a fee, especially as arranged by means of a website or app'.[21] The term 'ride-sharing' can be confusing when designing a single-occupancy ride; ride-sharing can be synonymous with carpooling when conducted by a TNC. Ride-hailing is the activity of asking for a car and driver to come immediately and take you somewhere, or a service that lets you do this.[22]

In our view, TNC is the most accurate to describe the reality of businesses such as Uber or Lyft as it:

- Indicates these companies are providing transportation services
- Encompasses the notion of network, which captures the role of online technology in intermediation between drivers and riders.
- Clearly indicates that these services are provided by companies (implies the notion of profit, as opposed to some forms of free carpooling)

INFO BOX: What are Transportation Network Companies?



In the literature, TNCs have often been assimilated with ride-sharing. It should be noted, however, that some countries (e.g. Sweden) do not view TNCs as ride-sharing companies, but classify them as “on-demand taxi services”[2]. This distinction makes sense given that the majority of rides are not shared: Uber estimated back in 2016 that their shared-ride service UberPool represents around 20% of their total rides, but it was not disclosed how many of those rides resulted in another passenger sharing the ride.[cviii] DiDi’s 2018 annual report revealed that 1.6% of vehicle kilometres were shared rides[cix].

The global TNC market is dominated by few players, mainly companies such as Uber and Lyft (US) and Didi Chuxing (China) that were founded around a decade ago. As of May 2019, Uber was available across 600 cities in 65 countries. It had 3.9 million drivers worldwide and claimed 14 million rides per day.[cx] Uber was valued at USD 75.46 billion on the day of its first day of trading on the New York Stock Exchange, on 10 May 2019. Lyft operates exclusively in the North-American market, in 350 cities in the US and in Canada (Toronto and Ottawa), with a market share reported to be between 29% to 35%.[cxi] As of 31 December 2018, Didi was operating in more than 1000 cities worldwide. With 31 million drivers providing 30 million rides daily, it is Uber’s biggest rival globally.[cxii]

[2] In Europe, TNC mobile applications matching riders with drivers are considered a transport service. The European Court of Justice ruled in December 2017 that a service whose purpose was "to connect, by means of a smartphone application and for remuneration, non-professional drivers using their own vehicle with persons who wish to make urban journeys" must be classified as "a service in the field of transport" in EU law. TNC drivers therefore have to comply with a range of obligations applying to transport service providers.

In Europe, Uber operations are limited by the different regulations at national and local level, which may impose more or less stringent requirements on drivers. For example, in Belgium cars need to have a purchase price over €30 000 and have taxi number plates; in several countries including France, Germany, Austria, drivers need to return to their base of operation each time they complete a ride, and before accepting another. In July 2019 Uber was available in 123 European cities and regions.[cxiii] Other important TNC in Europe include Bolt (formerly taxify), and Cabify. Launched in Estonia in 2013, Bolt now operates in 50 cities and 30 countries worldwide (with a focus on emerging countries), and count 500 000 drivers worldwide.[cxiv] Other, smaller TNC include Via, Ola, Kabbee, Berlkönig, but their availability varies greatly from country to country. Pricing varies depending on business models. For instance in Paris, Bolt has a €1.20 base fee, and charges €1.10 per kilometer + €0.25 cents per minute. The minimum price has to be €6.[cxv] For Berlkönig in Berlin, the basic price in €1.50 - a premium can apply during peak hours - and the minimum ride price is €4.[cxvi]

In parallel, traditional OEMs have backed TNCs such as Moia (mini-bus ride sharing, backed by Volkswagen) or taxi apps like Mytaxi (Daimler), now rebranded FREE NOW following a partnership with BMW. In Europe, FREE NOW operates in 100 cities, with 14 million passengers and around 250 000 drivers at the time of writing.[cxvii]

There has been increasing evidence that ride hailing services, despite offering pooled or shared rides, have not resulted in the expected or desired outcomes of reducing congestion or complementing public transport. On the contrary, case studies in the US show that congestion has increased as public transport utilisation has decreased[cxviii,cxix]. In the case of San Francisco traffic congestion – measured in journey times – increased by 62%, and at least half of that increase was attributable to Uber and Lyft.

4.2.2 Long-distance ride-sharing

A form of ride-sharing with longer history in Europe is the approach of sharing a car on a longer journey to increase vehicle occupancy and share costs. Various companies operate to facilitate this via websites that match drivers to passengers. The largest of these is BlaBlaCar, based in Paris, with 70 million users worldwide in 2019. BlaBlaCar displays fixed prices per passenger and operates by charging a commission on bookings. The company has avoided some of the issues faced by companies such as Uber, as drivers are formally not allowed to make a profit, instead charges are based on the cost of the journey together with an allowance for wear and tear. They therefore do not have to pay tax or change their insurance. This sharing method is not, however, without controversy, with concerns surrounding competition with more established services. In 2015, BlaBlaCar was sued (unsuccessfully) by Spanish bus companies that claimed its drivers should be considered as commercial enterprises.[cxx]

4.2.3 Peer to Peer (P2P) car sharing

These car-sharing schemes allow owners to hire out their car when they are not using it. Car-owners make money on a car that they are not using, drivers are able to rent vehicles at a lower price than a traditional hire car. Some of the larger schemes include US companies Getaround and Turo. As of July 2019, Turo is available in the US, Canada, the UK, and Germany; it gathers 10 million members, and 350,000 vehicles. People are free to price their cars as they want, and the platform takes a share of the trip price. Sometimes dubbed the 'Airbnb of cars', these alternatives are mostly competing with the car rental industry.

4.2.4 Car club car sharing

A growing number of car manufacturers and car rental companies are seeking to enter the shared mobility market, through car sharing or car clubs. With over a million members and access to more than 12 000 vehicles across more than 500 cities, ZipCar is the largest provider worldwide.[cxxi] The company is a subsidiary of Avis Budget Group and provides both station-based and one-way (or 'free floating') car sharing.

Station-based: These schemes allow customers to pick up a car from any dedicated parking station and return the vehicle to the same place. Stations are generally found at transport hubs, for example train and bus stations, allowing customers to continue their journey with public transport. In Germany, Flinkster (Deutsche Bahn car sharing) has deployed 4000 vehicles.

Free floating (flexible): Free floating schemes allow customers to pick up a car from one location and leave it at another, using allocated parking spaces. While still relatively new in Europe, the free floating car sharing market has boomed in recent years. Biggest companies include for instance Sharenow (7,400 cars in Germany[cxxii], backed by Daimler and BMW), Maven (GM), or WeShare (Volkswagen), which recently deployed its full electric service in Berlin, with 1,500 e-Golfs.

Typically, costs for services such as WeShare and ShareNow depend on different options and packages. In the case of DriveNow Germany[cxxiii] (part of ShareNow) in addition to a registration fee of 29€ and a 1€ fixed-fee per rental, costs per minute are around 33 cents, and vary from 20 cents to 36 cents depending on the vehicle. Other packages exist depending on the length of the rental. WeShare (only available in Berlin as July 2019) charges 1€ fixed fee per rental, and 19 cents per minute.[cxxiv]

4.2.5 Bike and e-scooter sharing

The multiplication of bike sharing schemes in major European cities over the last decade clearly indicates citizens' appetite to use shared bikes as their daily transport mode. In many big cities, cycling is actually the quickest way to commute, as data from millions of cyclists' journeys shows.[cxxv] Many European countries and cities have a strong cycling culture, dominating lists of cycle friendly cities[cxxvi]. In parallel, technology-enabled improvements such as dockless bikes - where shared bikes can be picked up or dropped off in designated areas and not at a specific station - and the multiplication of electric bike sharing offer the opportunity to reach out to more users.

The dockless bike sharing business worldwide has grown rapidly over the past few years. This has been illustrated by the rapid expansion of Chinese company Mobike, which eventually reached 200 million users in over 200 cities across 15 countries.[cxxvii] Even if the roll-out of these bikes raised a number of regulatory concerns, it clearly shows that citizens are ready to cycle more when they are offered flexible and affordable options to do so, and that bike sharing schemes can encourage modal shift from cars to public and active transport. Docked bikes typically have a yearly subscription of around €50 with rental prices increasing in 30 minute increments (where the first time band is free). Dockless bikes typically have a rental fee of €1 and a per minute charge in the order of €0.15.

More recently, several companies such as Bird and Lime have started rolling out electric kick scooters in more than 100 cities worldwide. Created in 2017, both companies experienced rapid growth, being valued each at around USD 2 billion[cxxviii]. Bird reached 10 million scooter rides one year after its launch, while as of February 2019 Lime totalled 34 million rides globally for all its micro-mobility services (bike, e-bike, e-scooter sharing).[cxxix] Following their success, over 30 scooter start-ups have been created, which makes up for a very dynamic, but also chaotic market that will likely consolidate in the future. Similar to other new mobility services, the impact of micro-mobility on cities still needs to be further researched. E-scooter pricing models are very similar to dockless bike sharing: in addition to the rental fee of €1, the per minute charge is €0.15. [cxxx]

According to a US survey commissioned by Lime, around a third of all Lime rides have replaced car trips[cxxxi] - this was corroborated by data from a pilot in Portland[cxxxii]; on the contrary, French consulting company 6T comes to very different conclusions about Paris, finding that only 8% e-scooter trips replaced car trips.[cxxxiii] This suggests that the impact might vary locally depending on the quality of the existing public transport network, the convenience of car use, and the shape of the city. Beyond their impact on urban mobility, e-scooters raise important sustainability concerns. One study from Louisville in Kentucky estimates at 28 days the average life expectancy of an e-scooter.[cxxxiv] This is mainly because of vandalism (many stories report scooters being dumped) and rapid material depreciation due to intensive use (average of 5 to 6 trips per day of around 2km for bird scooters[cxxxv]). E-scooters are priced similarly to dockless bikes, with a rent fee of €1 and a charge of €0.15 to €0.25 per minute.

4.2.6 Mobility as a service

In addition to the above mobility schemes, mobility as a service (MaaS) is the integration of end-to-end trip planning, booking, electronic ticketing, and payment services across all modes of transportation, public or private. Central to any scheme is the need for a digital platform that enables all transport options to be reviewed, booked and paid for in a single step. One of the best examples in Europe is the app Whim[cxxxvi], which has been in operation since 2016, aiming to make sharing so convenient for users to get around that they opt to give up their personal vehicles for city commuting: Whim's first activity report indicates that their users in Helsinki use public transport more than twice the average, and use individual cars less than other inhabitants.[cxxxvii] In Finland, Whim proposes several packages, from pay as you go to unlimited access public transport, city bikes, taxis, and car rentals (under conditions) for €499 per month.[cxxxviii,cxxxix]

MaaS is still at an early stage of development, and while it holds strong promises to make car ownership 'a thing of the past', some risks associated to it should not be overlooked. Designed as a user-centric mobility hub, MaaS offers unrestricted door-to-door mobility for customers subscribing to unlimited packages; on a larger scale, this could lead to worsened congestion in case of high demand at peak hours. Besides, the convenience of trip booking and the subscription model might encourage people to privilege motorised trips over active modes.[cxl]

INFO BOX: Rule of the road - Braess' Paradox.

It has almost become an old adage: if you build a road, cars will come to use it. This is the rule of the road, otherwise known as Braess' Paradox or induced demand. From 2006 to 2016, car passenger activity in Europe grew 6% while the motorway network grew 20% and all other types of roads grew 5%. Motorways facilitate intercity car travel, where the car is then assumedly used within the city limits to the final destination, contributing to congestion - this correlation is no coincidence[23]. When road networks are reduced, there is evidence that the journeys made by cars also reduce[24]. The reasoning is simple, if a new lane is added to a segment of the road network, travel here will improve, but that in turn improves the speed and convenience of driving. This encourages more trips until the congestion reaches the same point, or a Nash equilibrium. In a world where trips are shared, this will reduce the number of cars required to fulfill the passenger activity demand, but likewise free up the network and encourage more cars. As car sharing and ride sharing begin to change the transport system, it is crucial that the infrastructure dedicated to driving convenience adapts instep with it. Street side parking should slowly be reduced, speed limits reduced, connectivity by cars reduced, as has been shown in both a small city like Ghent[25] and a large city like London[26]. Copenhagen also offers a positive example through integrated urban planning to reduce parking spaces for cars[27].

4.3 Making sharing more attractive than ownership

In combination with public transport networks, the scope of the technology-driven change in the mobility sector offers new solutions for first and last mile services, ensuring both round the clock availability and proper accessibility. Still, in order to thrive, shared mobility providers will have to find joint solutions with local and national authorities to several challenges.

4.3.1 Ridesharing

Making all alternatives to car ownership attractive is key to succeeding in the mobility transition. Regulation plays an important role in managing the attractiveness of ridesharing, through a range of different obligations. Because of higher mileage and potential impact on emissions, these services - along with taxis - should be required to operate with emission free vehicles by 2025 at the latest in big European cities, and by 2030 across the EU. However, some requirements are not justified by any environmental or social consideration and make shared rides less attractive to users. These can be divided into three broad categories:

Mandatory car equipment: technology (for example app-based booking and price information) makes traditional taxi equipment such as tachographs or taximeters redundant. Such requirements make the service artificially more expensive, and less attractive to potential users.

Restriction of service: the obligation for private hire vehicle (PHV) drivers to return to their base (so-called 'return to garage' obligation) contradicts the efficiency gains that should be achieved with shared mobility, as it adds empty kilometres driven on the road, causing extra emissions and congestion.

Vehicle requirements: while regulation should ensure taxi and PHV services comply with safety and environmental standards, setting minimum vehicle requirements regarding price, size, or engine power incentivize the use of bigger, more powerful and polluting vehicles. On the contrary, regulation should mandate taxi and PHV services to transition to zero-emission vehicles by 2030 at the latest.

Finland's Act on Transport[cxli] that entered into force in Finland in July 2018 provides a good example of balanced regulation for ridesharing. Mainly, it opens the market for new mobility services through “more efficient arrangement of publicly subsidised passenger transport by utilising digitalisation, combined transport and different fleet types.”[cxlii] This increases the transport offer available, also through policies regarding the sharing of data and digitisation of services. However, the transport act led to price deregulation and a surge in taxi prices.[cxliii]

In parallel, cities can enact local regulation to manage the negative impacts of TNC on congestion and emissions. In New York for instance, the city introduced a TNC-specific congestion charge in Manhattan on top of the existing charge. It will also introduce a cap on time TNC drivers can spend without a rider in the vehicle: TNCs will be fined if drivers spend more than 31% of their time cruising in the congestion zone (starting August 2020).[cxliv]

Beyond enabling ridesharing, it is key to ensure PHV and taxi fleets electrify in the next years. Major ridesharing companies such as Uber have launched electrification programmes[cxlv], but these initiatives should be scaled up to all cities and flanked by supporting policies (i.e. dedicated fast charging stations). Drivers for ridesharing and taxi companies should be incentivised to buy EVs, for instance with a lower registration tax for these vehicles, and with in-kind benefits such as special parking and stopping privileges at airports or railway stations. A dedicated fund to support drivers should also be explored.

4.3.2 Bike and scooter sharing

To effectively reduce car ownership in cities, users need to be able to choose from a range of flexible, on-demand alternative mobility options that efficiently cover their mobility needs. These include bike and scooter sharing.

To avoid having too many shared bikes on offer, and to best manage public spaces, cities could adapt the supply of shared bikes and scooters in function of the actual demand. This would ensure equal development of the service across the city, as the number of shared bikes and scooters deployed would be set according to use rates.

Cities should clearly define parking areas for shared bikes and scooters to avoid irresponsible parking behaviour, as is already happening in Lisbon for example. The city has identified no-parking zones (where streets are particularly narrow and competition for space is high), and people are encouraged to park in micro-mobility parking hubs, which also serve as deployment locations for e-scooter providers. Depending on the success of micro-mobility offers, the number of parking hubs could be gradually increased to improve users’ first and last mile connectivity. This space could be reclaimed on existing on-street car parking slots - which already necessitate a lot of public space (see section 4.1.) - but should not be taken at the expense of clean transport options such as EVs or shared EVs.

4.3.3 Carsharing

Sharing cars allow users to access them only when needed, and have the potential to improve the transport system efficiency and reducing the need for private cars. For example in Bremen, a northern German city of about 500,000 inhabitants, the deployment of 344 car sharing vehicles led to a reduction of nearly 5,000 privately-owned cars.[cxlvi]

In addition, electric car sharing helps roll out emobility infrastructures in cities, ensuring minimum use of charging points, while giving users the opportunity to progressively get familiar with EVs. Since shared cars do more mileage than the average vehicle fleet, there's a natural synergy with deployment of charging infrastructure for electric vehicles, whose profitability depends on high use rate. For instance, in Germany, 10% of vehicles that are part of car sharing schemes are electric models, compared to 1% in the whole country's car fleet.[cxlvii] This share is expected to grow in the future thanks to commitments of car sharing companies such as ShareNow (plans to increase the proportion of EVs in their European fleet to 26 per cent by the end of 2019[cxlviii]) or WeShare (EV only car sharing service[cxlix]).

A sufficient availability of charging points is of course a very important precondition to ensure convenient use of shared electric vehicles. As identified in a paper co-signed by the German car sharing association and by consumer organisation VZBV, interoperability of payment solutions, charging point visibility, and price transparency are key enablers to boost consumer uptake of (shared) EVs[cl]. Deploying charging hubs in the outskirts of cities near public transport stations (and underutilised power connectors) is also a good means for cities to address charging needs for several vehicles at once, including shared EVs. Such charging hubs[cli] can combine multiple smart charging solutions to answer the needs of all; from slow chargers for park & ride to fast charging for travellers and topping-up. This would limit the incentive for drivers to enter often congested city centres.

Studies show that about 30% of all city traffic is search traffic[clii], making it a main cause of congestion (road congestion costs Europe 1% of GDP every year[cliii]). Charging hubs at easily accessible locations, with reserved parking slots for shared vehicles, would facilitate charging operations and relieve cities from part of the congestion resulting from parking space search. More generally, reserved street parking spaces for shared vehicles constitute a strong incentive for people to share.

Finally, with a predictable and continuous high demand for charging, the business case becomes clear from the very start. This has already been done in China, where several large charging stations serve the needs of various vehicle modes. For example the Qian Hai charging station can charge 60 vehicles simultaneously (maximum capacity of 3 200 kW), the charging station is populated by taxis (50%), LCVs (30%), passenger cars (10%) and buses (10%), highlighting the diversified use of the chargers.[cliv]

4.4 Beyond sharing: urban planning and a new approach to the city

The transition to shared and new mobility on its own won't be sufficient to significantly reduce congestion, if at all. This is dictated by the rule of the road. Automated vehicles that are connected and shared could lead to increased fluidity of transport flows, but this will also make travelling by car cheaper (through high speed and reduced cost). New mobility options such as shared bikes and e-scooters may help facilitate a move away from cars to public transport, but that also increases capacity to cars. If there is no structural change (i.e. if the road networks, parking places, and accessibility stay the same), cars will fill the capacity and congestion will reach equilibrium levels.

It is therefore crucial that the transformation to new and shared mobility encompasses urban space as a whole, in which city planning policies have a defining role. As the examples mentioned in part 4.1 on parking policies illustrate, there is increasing pressure and competition for public space in cities, including road side on-street parking. To curb demand for transport in cities, urban spaces need to be approached from a new, integrated perspective. Planning principles should be guided by the objectives to build liveable and sustainable cities, ensuring community participation through consultations and feedback mechanisms.

INFO BOX: A city modelled around people, not cars: Pontevedra, Spain.

In Pontevedra, a Spanish city of more than 80 000 inhabitants, 300 000 square meters of space in the centre were converted into a pedestrian area. City officials stopped the flow of more than 10 000 cars per day going through one of the main streets, and removed all parking spaces in that zone. Progressively, they extended the car-free zone and put in place a 30km/h traffic calming zone around it. The change didn't come about without any opposition. Main concerns related to insufficient parking spaces and increased congestion outside the zone. Still, benefits for the city are manifold. Traffic fatalities have been divided by ten, CO_2 emissions have reduced by 70%, and almost three quarters of trips are active mode trips (cycling or walking). The city is safer for children, and encourages social interactions.[28]

Rethinking urban planning and mobility involves reconsidering urban planning from an analytical perspective based on vehicle flows to one revolving around place-making. This also implies a more even distribution of functional areas within cities to avoid clusterisation, increased housing density to limit urban sprawl, and restrictive parking management to discourage private car use.

4.5 A new mobility heaven

Achieving a new mobility heaven will require planning, policy, and design, as described in the sections above. The privately owned passenger car has become the dominant form of transport in Europe. Combining technological advances and new business models into a policy framework that gradually reduces access and parking and increases cost for single occupancy vehicles while designing and building infrastructure for active modes of transport may be the only way to end this domination and meet climate targets, while still levering the great societal benefits that shared autonomous cars could bring. The equitable improvement to the quality of life of all European citizens is inextricably linked to achieving this goal.

Figure 6 shows how this future could look. The assumptions shown in Table 4 should be seen as both what could be possible and what needs to be achieved, in order to transform the transport system. The sustainable transport revolution could allow for complete decarbonisation before 2050, if policies are implemented to stop ICEs from driving. From the trajectory of emissions in this scenario, the last ICE to be allowed to drive on European roads could be in the mid-2040s. This policy will play a larger role in EU13, as while the EU15 is projected in these scenarios to reduce car emissions by 97% compared to 2005, it is only 77% for EU13. The results also show that the amount of energy required to power the fleet compared to 2005 is significantly (85%) less.

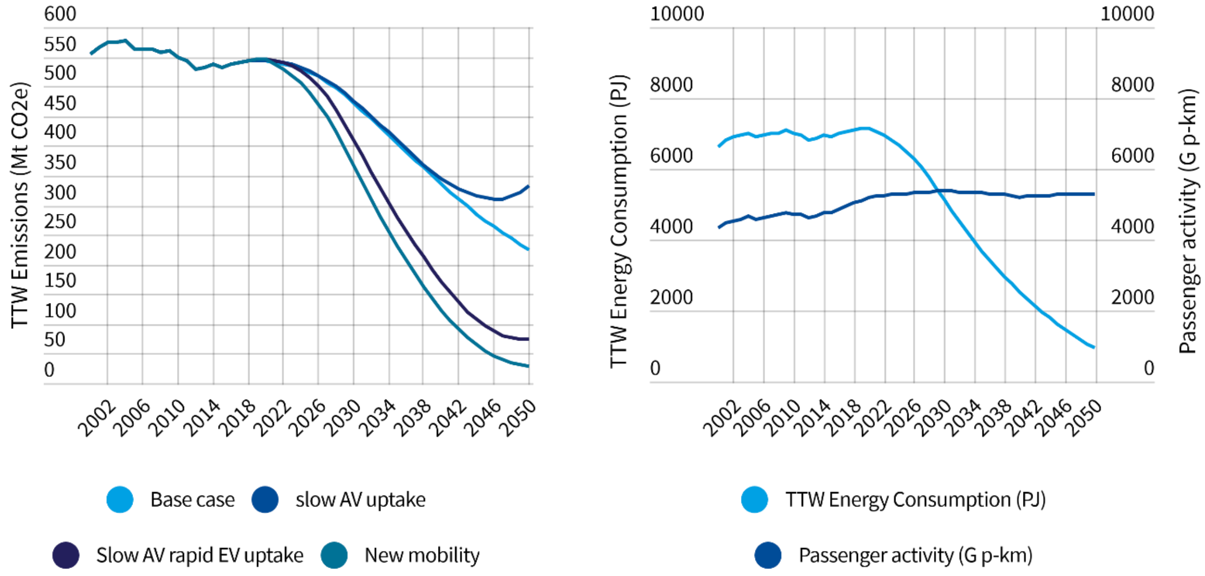


Figure 6: New mobility revolution, with modal shift to public transit and active modes, and a strategically rolled out fleet of automated (and connected), electric, and shared (in terms of vehicles and rides) vehicles.

Table 4: Key input parameters for a new mobility and urban planning revolution

Metric	Change from base case	Comments
Induced passenger demand	0%	Automated vehicles are electric, and they are integrated into public transport systems, supporting last mile journeys from core networks, or transport from underserviced areas to transport hubs; demand does not increase as per an unregulated uptake of automated vehicles.
Modal shift from passenger cars	20%	Public transport and active modes of transport are improved dramatically and integrated into cities' long term vision - policies are in place and this transition occurs from 2020 to 2040, or 1% per year.
Load factors of automated vehicles	+250%	Automated electric vehicles are integrated into the public transport system, including right-sized vehicles (such as mini-vans or rob taxis)
ZEV sales	100% in 2035	The 2030 targets are over achieved through a range of government incentives beyond EU incentives, and the uptake continues until 2035, when the last ICE is sold. All automated vehicles are electric.
Energy demand	Electric vehicle energy demand	All automated vehicles are electric, and thus have a lower energy consumption and zero emissions.

5. Summary of results and conclusion

This paper has shown that there are many divergent views on the future of mobility. While many companies are racing for funding to develop their automated vehicle ambitions of which they are dogmatically insisting are just around the corner, some analysts are inclined to pour cold water on the idea. This has all been happening in an environment where there has been no discourse with civil society and consumers about whether this technology is something they want. If these vehicles aren't zero emissions, Europe will likely fall well short of its climate targets and obligations. Zero emission automated vehicles will not improve quality of life in cities, and people may spend even longer in vehicles, stuck in perpetual traffic jams. If these vehicles are shared, this problem is likely to persist, as the rule of the road dictates that the reduction in vehicle kilometres will be temporary, as the rebound effect of less cars and less traffic will induce traffic to pre-sharing levels.

The future of mobility and the ability of Europe to improve the quality of life in cities and to achieve its climate targets in the transport sector will depend on a holistic change to the transport system. It will require reducing space for cars (in terms of lanes and parking) to allow space for buses, cycling and walking, improving the mobility as a service offerings which allow shared bikes or e-scooters to complement public transport connections. The future of transport has an opportunity to make cities connected, liveable, and green (with more trees, parks and squares). Table 5 summarises some of the key metrics.

Table 5: Summary of key metrics from scenarios for trips made in cars. The 1.5°C & 2°C EU car budget for is 4565 Mt CO_2e and 11628 Mt CO_2e respectively

Metric in 2050	Scenario				
	Baseline	**Rapid automated**	**Slow automated**	**Slow automated & rapid Electric**	**New mobility & urban planning**
Mt CO_2	226	671	332	75	28
Mt CO_2 cumulative from 2018	13456	18538	14026	10306	9129
Cumulative emissions above (or below) 1.5°C/2°C EU car budget	+195% / +16%	+306% / +59%	+207% / +21%	+126% / -11%	+100% / -21%
Car vehicle km (G-vkm)	3989	9640	5868	5860	1622
Car passenger km (G-pkm)	6633	8920	7700	7696	5306

6. Policy recommendations

In order to achieve mobility heaven, we identify policies that are required at the EU, national and city levels. We split these into recommendations for each revolution, and general recommendations pertaining to all revolutions.

6.1 EU policies:

Automated vehicles must be zero emission: Europe cannot allow a situation where fossil fuel consuming autonomous cars are introduced to the fleet. Regulating this will ensure at the very least that automated vehicles have non tailpipe emissions, meaning battery electric or hydrogen drivetrains. The upcoming EU regulations on connected and autonomous vehicles should mandate all new autonomous cars, vans and trucks to have zero tailpipe CO2 emissions.

Common framework for AV testing data: Europe must ensure that companies vying to offer automated vehicles and their technologies have a harmonised and transparent method of reporting their development. Thus, the testing and type approval of automated vehicles must be strengthened. The US currently has a fragmented system that has incompatible datasets between states. Not all automated kilometres are equal, and should not be treated as such. Therefore, Europe should ensure that OEMs provide data such as:

1. automated kilometres driven, differentiated by
    a. Highway, rural, & urban kilometres
    b. Day, night, twilight times of day
    c. Sunny, cloudy, rain, snow conditions
2. Automated kilometres driven before intervention, for each sub category above
3. Reporting of intervention reasons

Approval can be granted based on these data and licensing could be restricted if safety criteria are not met in certain situations, for example, not allowing driving in snowy conditions.

Industry standard for simulations: Europe should agree minimum simulation standards with key stakeholders to ensure that simulated automated kilometres are consistent between OEMs and allow a consistent testing of technologies.

Automated vehicles must have minimum cyber security standards: Europe should propose or legislate for minimum level security of the vehicles from cyber attacks. Cars may also require an override switch from within the car that stops and unlocks the car.

Minimum data sharing criteria: Uneven data sharing between different mobility providers currently limits the attractiveness of multimodal transport options. To accelerate the integration of shared and flexible mobility offers with public transport and enable (cross-border) integrated ticketing, the EU should define minimum data sharing criteria, as identified in the study on 'Remaining challenges for EU-wide integrated ticketing and payment systems.'[clv] Providers of passenger mobility services in the EU shall ensure that essential, up-to-date data on their services are freely available from an information system (open interface) in a standard, easy to edit, and computer-readable format. Data collection and processing must at least comply with the General Data Protection Regulation.

6.2 National policies:

At national level, **taxation policy** has to complement the transition to shared and electric mobility. For instance, car ownership should not be incentivised through company car schemes. Less taxation on labour, or alternatively the introduction of a mobility budget for employees.

Private hire vehicles and taxi regulations should require these services to be zero-emission in cities by 2025, and across the whole territory by 2030. Allowing fair operations of ridesharing companies is a first necessary step toward increasing their attractiveness. But as shown in this study, moving away from car ownership will lead to significant congestion and pollution reduction in cities only if rides are pooled and electric.[clvi] Besides, studies show that this can be implemented at all levels and is economically sound for early adoption[clvii]

Automated vehicles should be shared: Private ownership of AVs should be discouraged through taxation or through medallions. AVs should be part of an integrated transport network, complementing existing or new mass transit options, which requires less valuable space in cities.

Speed limits must be retained or reduced: Particularly on highways, automated vehicles should not be able to exceed current speed limits, or they should be reduced in some places. This would result in decreased energy demand (renewable electricity) and would reduce competition with intercity rail or coach, which are much more energy efficient.

Fast chargers: Install a minimum number of fast charging solutions above 50 kW that are either dedicated to shared vehicles, or allow shared vehicles to fast charge at a cheaper price than conventionally owned ones (this would mean fast chargers can act as a driver for wider EV uptake). This could be achieved through taxation.

6.3 Local policies:

Road pricing in combination with (U)-LEZ are needed to manage the vehicle kilometres driven. As the analysis has shown, road pricing is a key measure to limit transport flows and regulate demand for mobility, especially to mitigate possible rebound effects resulting from AV uptake. A TNC-specific congestion charge, as has been introduced in New York, together with a cap on kilometres driven by TNC without a rider, can help further limit their negative impact on congestion and pollution.

Parking policy, regulation of curb use, and street design guidelines[clviii] should take into account new forms of mobility - including micro-mobility - and reconsider the space allocated to private cars to the benefit of public places and housing. The amount of parking space available for private cars should be reduced each year and be made available for other new mobility services. Regular exchange between city regulators and mobility providers should be sought (see section 4.2.3 for more details).

In a scenario where AVs' uptake is significant (e.g. more than half the total vehicle fleet), introduce a cap on the number of licenses for private cars, like in Singapore or Chinese cities such as Beijing or Shanghai.

Clear operation rules for micro mobility in order to ensure availability of shared bikes and scooters and proper public space management. This includes dedicated micro mobility parking spots, public-private data sharing agreements, city coverage requirements, and an adapted supply of vehicles according to actual demand and use rate.

Appendix 1: Methodology and the EUTRM

The analysis undertaken in this report was undertaken with T&E's European passenger car stock model, an updated version of the EUTRM[clix]. The EUCSM is a bottom-up demand driven model that computes passenger car GHG emissions in yearly intervals. This type of model is also referred to as an ASIF model:

Emissions = **A**ctivity * Modal **S**hare * Energy **I**ntensity * **F**uel Carbon Intensity * Load factor

Transport demand is based on purchasing power parity (PPP) adjusted GDP, which is determined by historical and projected gross domestic product (GDP), population, and fuel price for each country. All transport demand is then met with the required transport capacity through the sales of passenger cars. All else being equal, an increase of per capita GDP over time will result in an increase of demand for transport. In the absence of policy, this new demand is only met by increasing the fleet size with new vehicle sales.

The EUCSM is initialised and calibrated with historical data from member state reporting to the UNFCCC. Vehicle renewal is based on retirement curves. Policy and technical assumptions can change the trajectory of car activity and emissions. For example, passenger activity can be shifted to buses and to walking and cycling, and demand can be reduced through fuel or congestion taxes. Regarding the four revolutions of transport presented here, the ingress of autonomous vehicles into the fleet and how it disrupts the system is analysed. Autonomous vehicles enter the fleet separately, and have characteristics as determined by the input factors presented in each chapter. More information can be found online.

Appendix 2: Modelling the new mobility revolution

Scale refers to the level of detail required to obtain meaningful results. At one end of the spectrum there are full agent based models[clx] (such as the ITF approach); on the other large regional based studies (such as Fulton et al.). Scaling agent based models up to European coverage is impractical, and the uncertainty of travel preferences has not necessarily been addressed. On the other hand, Fulton et al.'s study looked at intra-urban transport and considered large global regions using more aggregated data, where a trade-off of granularity allows for an analysis of the transition of the three revolutions along with regional energy and climate implications. Our approach tends to follow that of Fulton.

While the uptake of technologies themselves have been addressed in the corresponding chapters, it is largely inseparable from modal shift. Needless to say, each country and city has a different topography, demography, population density, existing transport network, wealth, and culture. How that influences the success or failure of public transport that will be in direct competition with automated vehicles. This is also true of longer distance travel, where without the burden of actually driving, automated vehicles may offer relaxing, flexible, cheap and reliable transport, directly competing with high speed trains and short haul flight[clxi]. We make use of Eurostat data to gain an appreciation of historical and current modal shift, both urban and intra-urban, to evaluate how automated vehicles may impact them. The transport system should be treated holistically, and this is reflected in our modelling approach.

In Europe, passenger kilometres in cars had a share of around 80% of land transport activity; modal share doesn't correlate with motorisation rates, the size or population of countries or fuel taxes. Passenger activity does correlate with wealth, as does vehicle activity[clxii]. In most cities and countries in Europe, the car is the most convenient form of transport, not bound by timetables or infrastructure, and offers in the most case door to door solutions. This underlines a difficulty of determining preferences for transport mode. Do people take the car if there is a cheap and relatively direct public transport route? It depends on the reliability, speed, and affordability of the service, which in large part will be driven by policy.

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