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Effects of the Digital Transition in Passenger Transport - an Analysis of Energy Consumption Scenarios in Europe

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Summary

The transport sector has rarely seen disruptive evolutions after the diffusion of the internal combustion engine, and today the European mobility is still heavily relying on oil derivates and on private cars. However, there is a significant push in cities towards more sustainable mobility paradigms, and digital technologies are playing a major role in unleashing possible alternatives to a car- and fossil-based mobility. Three major digital trends can be highlighted, with different levels of maturity and some potential synergies among them: Mobility as a Service, Shared Mobility and Autonomous Vehicles. The effects of these trends are also related to the strong push towards electric mobility, which currently appears as the most supported solution by companies and regulators to decarbonize the transport sector.

This working paper discusses an investigation of the potential effects of digital transition, by means of a data-driven model for the calculation of the impacts of mobility demand in Europe in terms of primary energy consumption and CO_2 emissions. The results show that digitalization may have a positive effect on energy consumption and CO_2 emissions for passenger transport, given the strong efficiency improvements expected by technological development in the vehicles powertrains. The benefits are maximized if digital technologies are used towards a collective optimization, by increasing the share of available mobility options. Conversely, if digital technologies are limited to increase the quality of private mobility, the environmental benefits will likely remain very limited. Thus, there is a need of tailored policies supporting the right mobility models to fully exploit the potential benefits of digitalization.

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Abstract

The transport sector has rarely seen disruptive evolutions after the diffusion of the internal combustion engine, and today the European mobility is still heavily relying on oil derivates and on private cars. However, there is a significant push in cities towards more sustainable mobility paradigms, and digital technologies are playing a major role in unleashing possible alternatives to a car- and fossil-based mobility. Three major digital trends can be highlighted, with different levels of maturity and some potential synergies among them: Mobility as a Service, Shared Mobility and Autonomous Vehicles. The effects of these trends are also related to the strong push towards electric mobility, which currently appears as the most supported solution by companies and regulators to decarbonize the transport sector.

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1 - Introduction

The transport sector includes different human activities that show different behaviours, patterns, priorities and drivers. To fully understand its heterogeneity, multiple categorizations can be considered, as each perspective gives specific insights on the transport behaviours. Transport can be subset considering passenger and freight, transport modes, distance, purpose, fuel, etc. A brief description of the main categorizations can help to highlight the most significant aspects that have an impact on the Energy and Transport nexus.

A first categorization, which is usually applied in energy statistics and social sciences, draws a major separation between passenger transport and freight transport. These two categories show huge differences in demand patterns, transport modes, stakeholders, energy sources, priorities and time distribution. While passenger transport is usually aimed at providing access to opportunities in a timely and flexible way, freight delivery has usually less stringent requirements of speed and comfort, but efficiency and cost become a priority. Two additional objects can be included in this categorization: energy and information. Energy transport is generally included into the sector, although it represents a marginal share with respect to passengers and goods. Energy carriers are usually moved by means of different solutions depending on their physical states: solid fuels need ships, trains or trucks, while liquid and gaseous fuels can also be moved through pipelines, and electricity is supplied by power lines. The last element of this categorization is rarely considered in the transport sector, as the supply of information has traditionally been limited in significance and included in other sectors (e.g. telecommunications, mail, etc.). However, the rise of the Internet has driven a major escalation of demand of virtual services worldwide, and consequently a new energy demand to support this infrastructure. In most cases, this virtual demand has substituted traditional goods (videos vs DVDs, e-books vs books, etc.) or services (online courses, travel planning, e-commerce). Data traffic is expected to increase with an exponential pace, as multiple technologies will need to be supported by a reliable and extended network for the transport of information (including Internet of Things, Mobility as a Service, Autonomous Vehicles, etc.)

A second major classification is related to the transport modes that are used. A first classification is done between land, air and water. The latter is mostly dedicated to freight transport on long distances, while some short-distance passenger services are provided for islands nearby the mainland or for inland waters. Air transport, on the other hand, is mostly dedicated to passenger travel, due to the higher costs associated to its very high speed and specific energy consumption. But the largest share of transport demand worldwide is related to land transport, and it includes multiple modes, that can have a common infrastructure (i.e. roads are generally shared between cars, trucks, buses, motorbikes, bikes and pedestrians) or a dedicated infrastructure (mainly trains and underground transit). The modal distribution can significantly vary among regions: while private car is currently predominant in Europe and North America, East Asia heavily relies on two-wheels vehicles, and Africa on buses and mini-buses.

A third categorization that can explain the transport demand is related to the distance of the travel. Usually three major distinctions are performed: at urban scale, country/regional scale and international scale. The travel distance has an influence on available modes, priorities, as well as on the number of users and the predictability of the patterns. Urban scale

people mobility is mostly related to commuting, while international trips are usually less regular and related to occasional business trips or tourism. The purpose of the travel is a significant parameter to be considered in evaluating the future trends of mobility demand.

Each of these classifications can explain specific patterns in transport demand, as all these aspects have a role in how people and goods are moved. At the same time, it is difficult to gain access to data with a high degree of disaggregation for large areas. Measuring transport is difficult, especially for passengers, for two main reasons. Firstly, there is no easily quantifiable indicator that can be measured, such as the GDP of a country or the total oil production. Transport demand is usually measured in passenger-kilometre, which is the result of a double approximation that is based on multiple hypotheses and estimations. The second reason is strictly related to this aspect, as there is a lack of standard procedures for quantifying transport demand, and therefore the same number calculated in different countries can lead to non-comparable results.

A focused look on urban transport

Urban transport is a significant share of the total demand, accounting for 24.8 trillion passenger-kilometres worldwide, one half of total passenger demand (ITF, 2017b). Moreover, world population is moving towards cities at a pace of 75 million per year, and cities are estimated to account for 70% of world population by 2050. The urban mobility demand is estimated to reach 48.3 trillion passenger-kilometre by 2050 according to ITF baseline scenario (ITF, 2017a), i.e. doubling the current levels. The challenge in urban transport is becoming to shift the planning approach towards providing an equitable access to opportunities for people, rather than to be limited to offer mobility services. This challenging target requires an integrated urban planning, in which the transport planning needs to be addressed together with the space distribution into the city.

Each city has a unique history, which reflects the evolution of its transport infrastructures and patterns driven by geographical, economic, social and political aspects. However, the city is usually influenced by cultural contexts, and usually cities in the same country or region show some common aspects. For this reason, although it is not possible to apply the very same solution to different cities, common approaches can be defined as a base for an efficient and sustainable planning of urban mobility.

Main transport modes and their characteristics

An important aspect to be considered in urban transport is the opportunity of exploiting multiple transport modes depending on the specific needs of each trip. Each mode has its own strengths and limitations, and thus mastering them allows both the policy makers and the final users to benefit from the advantages of an optimized urban mobility system. The largest competition is usually between private and public transport, that represent two opposite paradigms of mobility.

Private vehicles allow a higher flexibility and independence, but at the same time they have a higher cost and a lower efficiency. The flexibility is seldom compatible with an optimized organization of the transport. An additional aspect is that private cars are usually sized to face a large variety of mobility needs of a family (e.g. long trips, space for passengers/suitcases, etc.) but for most of the time they are used for single-person commuting during the week.

Consequently, the vehicles are almost always oversized with respect to the actual needs, resulting in very low efficiency compared to alternative solutions. This problem is less relevant for two-wheelers and for bicycles, which in turn allow for lower flexibility in some contexts (e.g. long trips, carrying capacity).
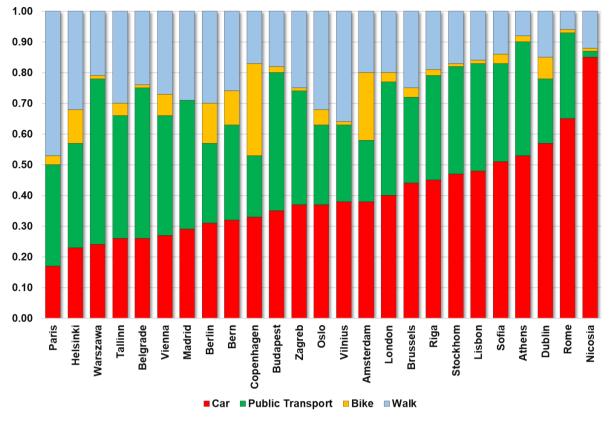
On the other side stand the public vehicles, which offer a lower flexibility but generally at a lower cost and with a higher efficiency. An additional advantage is the possibility of performing other activities while travelling, an aspect that is increasing in importance with digital technologies supporting a wide range of activities through the improved connectivity of smartphones, tablets and laptops. A key point for the quality of public transport is the reliability of the service, which is a result of the frequency of the passages on a stop and the predictability of the time required to perform the trip. Among the factors affecting reliability is the presence of a dedicated infrastructure, like for trains and subway, or the need of sharing the same infrastructure with private vehicles, as it happens for buses and coaches on roads. Dedicated track lanes often limit this issue, but without reaching the level of a dedicated infrastructure.

A third paradigm that is emerging in between these two approaches is the so-called sharing mobility, which includes two different concepts: the possibility of sharing a private car for a specific trip (often referred as car-pooling) or the possibility of using a vehicle "on demand", without the need of owning it. This last model is not limited to car sharing, many cities are successfully offering bike sharing solutions, and other options are being investigated (e.g. electric mopeds, etc.). These two approaches have dramatically different consequences on mobility, as will be better described in the next sections.

Drivers for the choice of modes

The drivers of the choice of transport modes emerge from an equilibrium between the demand of the users and the mobility supply that is offered, which is related to the interests of other stakeholders. External factors include local impacts (e.g. air quality and noise) that need to be tackled by local authorities, limitation of the infrastructures that may lead to congestions, as well as the quality of the service that can include both technology availability and maintenance strategies. The choice of a transport mode for any user is the result of multiple aspects, which are both rational and emotional, informed or perceived. Users want a travel experience to be safe, comfortable, fast and cheap. The balance of these four aspects may vary from user to user, but each of them has an impact on the choice of the preferred transport mode. Other aspects may have a role, such as the environmental impact of the travel, which is becoming a concern for certain users. It is important to note that often the choice is based on uncomplete knowledge of available options, and therefore the user may not be able to perform the optimal choice based on his optimization goal.

From a system perspective, the optimization of the transport system leads to consider other aspects with a higher priority. Local authorities are in charge of mobility policies, that should guarantee an economically (and environmentally) sustainable transport system, with the aim of allowing an equitable access to opportunities and services for each citizen. An optimal transport system needs to deal with limited space availability, air pollution, congestions and peak demands over time. An impactful transport planning should be tailored to each city specifically and analyse all the possible transport modes to find an optimal balance to supply access to opportunities.

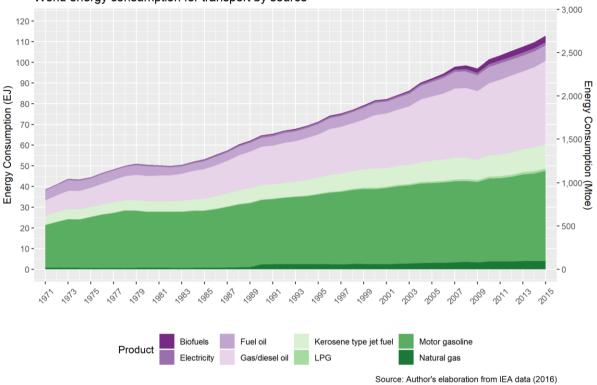*Figure 1 – Modal shares in selected European Capitals. Author's elaboration on data from* (EPOMM, 2018)*.*

Modal shares can show a significant variability from a city to another, as it is clear from Figure 1, where the estimated shares for some selected European capitals are illustrated. These data must however be read by remembering that modal share is often estimated from surveys, and the results can vary from year to year. The data on which Figure 1 is based have been collected over multiple years and with different methods, resulting in different levels of detail. However, the plot provides an idea on the heterogeneity of the modal distribution in Europe.

Energy consumption of passenger transport

A significant impact of transport is connected to its energy consumption, which is both related to non-renewable primary energy consumption, and to several emissions with a global or local impact on the environment.

Due to the complexity of the transport system, it is difficult to provide a global picture of its evolution over time. A starting point, although it shows only a part of the picture, can be the evolution of the energy consumption related to transport. The International Energy Agency provides an interesting database of worldwide statistics on different energy sectors. There are some additional details of some modes (Road, rail, aviation and shipping), but no information about passenger and freight transport, nor among urban and non-urban transport.

Energy consumption for transport has seen a continuous increase in last decades, with almost a three-fold increase from 1971 to 2015, higher than industry consumption (around +80% increase) or residential consumption (roughly +90%). The transport sector is largely powered by fossil fuels, mostly oil products, with a slight development during the last years of biofuels, electricity and natural gas (see Figure 2).
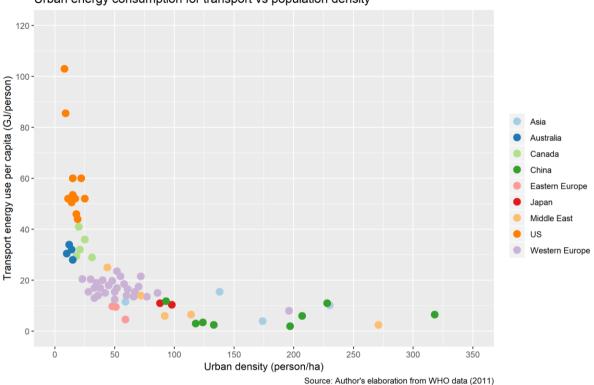

Figure 2 – World energy consumption for transport by fuel. Author's elaboration from (IEA, 2017).

The total energy demand in transport for 2015 reaches around 112 EJ (2,686 Mtoe), with motor gasoline and diesel oil accounting for 38.5% and 35.4% respectively. Other oil products represent 18.4%, while the remainder is made up by natural gas (3.6%), biofuels (2.8%) and electricity (1.3%). These numbers suggest that the path towards a low-carbon transport is still long, although in the last decade biofuels and electricity showed a significant increase.

In particular, due to the complexity of the transport solutions, as already discussed in the previous section, the data availability is often limited to some regions of the world. A coherent and organic picture is thus not available, and it will probably still be missing in the next future.

Moreover, there are few data specifically related to urban transport at world scale, although for some cities it is possible to estimate their energy consumption. Figure 3 shows an estimation of transport energy consumption per person in cities related to the population density (author's elaboration from (WHO, 2011)). Although the data are not updated, the hyperbolic relation among these two quantities appears very clearly. An interesting aspect is the strong dependence on the region, which in turn can be correlated to multiple factors including political, economic, cultural and social behaviours. US cities show a generalized low density coupled with the highest per-capita energy consumption, which is mostly caused by

the diffused use of single-passenger car and low use of public transport. Western European cities stay in the middle, while the bottom-right part of the chart is showing mainly high-density cities, whose low per-capita energy consumption is a result both of relatively low transport needs due to higher density and low income of the citizens leading to lower access to opportunities. In fact, this plot should be corrected by considering the actual GDP of such cities, which can be a hidden driver for transport consumption.

Figure 3 – Urban transport energy per capita vs population density. Author's elaboration from (WHO, 2011).

Main energy sources for passenger transport

The transport modes described above can be powered by multiple energy sources, which are the result of different drivers including cost, availability, regulations, technological and social aspects. While some modes have always been relying on an integrated electricity infrastructure (subway, trams and some trains), the road traffic is almost totally dependent on liquid oil-derived fuels. The two big competitors are gasoline and diesel, showing different performances with respect to energy efficiency and environmental impact, and having traditionally very different shares depending on the specific country and its choice related to oil products management. However, during last years, there is an interest of moving towards alternative fuels, including natural gas, biofuels, electricity and hydrogen. While some technologies are mature and reaching competitive costs (although sometimes still subsidized), others still need to face significant challenges before getting to a full market maturity.

Oil fuels have dominated the automotive sector from the invention of the car, representing today about 94% of the road transport worldwide (IEA, 2017). Their high energy

density, relatively high availability and easiness of transport have led to a large distribution network that is now well developed worldwide. Diesel and gasoline are the major fuels for road transportation, as heavy fuels have been banned worldwide due to excessive pollution and LPG is still limited to a marginal share of the market. The share of gasoline and diesel for urban transport has had several variations over time for different regions. While the US have historically been favourable to gasoline, in Europe diesel has been seen with more interest, although with differences among countries. Diesel is generally preferred for freight transport and for vehicles used for long mileages, thanks to its use in engines with a higher efficiency with respect to gasoline, which in turn offers greater power performances. Their price varies greatly from country to country as a significant share is represented by taxes. Thus, the push towards one fuel or another is often the result of policies rather than production cost. Oil fuels are leading to significant environmental impacts both at a global and a local scale. Their high carbon content lead to CO_2 emissions during their combustion, and further compounds including NO_X, particulate and CO represent a major threat to air quality in large cities. Diesel has been at the centre of a major scandal during the last years. Due to the issue of particulate emissions leading to major pollution problems in large cities, diesel is seeing a large decrease in some regions. Major European cities are currently limiting the access to city centre for older diesel cars, and some car manufacturers have declared a diesel phase out by 2020-2022 (Campbell, 2018). For these reasons an interest towards alternative fuels is emerging.

One of the most diffused alternatives to oil fuels are bio-fuels, mainly biodiesel and bioethanol, which are being supported in multiple countries worldwide to shift to a carbon-neutral paradigm. Biofuels show interesting advantages, including the possibility of local production resulting in lower geo-political dependence from oil-exporting countries, and their direct use without the need of major modifications of existing engines (although in some cases they need to be mixed to traditional fuels to avoid technical problems). However, while bio-fuels can support the fight against climate change, they still produce local pollutants and generate other problems: one which is often mentioned is the potential competition with food production. For this reason, 2nd and 3rd generation biofuels have been developed or proposed: they rely on biomass sources that are not directly in competition with food production (e.g. lignocellulosic crops, agricultural residues, algae). Biofuels have been widely supported in the European Union by the Energy and Climate Package, to reach a target of 10% renewable share in transport sector by 2020. Worldwide biofuels production has risen from 18 billion litres in 2000 to 129 billion litres in 2016 (WBA, 2017), mostly from the USA (58.6 billion litres), Brazil (29.4) and the EU-28 (19.3). The feedstock varies, with corn bioethanol dominating in the USA and sugarcane bioethanol in Brazil. In the EU-28, biodiesel reaches 75% of the total biofuels production.

Another fuel that is being considered in different countries is natural gas, which provides an interesting alternative to lower the carbon intensity of the sector, although not representing a carbon neutral alternative. Natural gas also provides a cleaner combustion in the engine, resulting in lower emissions of pollutants. This energy source is being used especially in countries that have a well-developed distribution network that is used for other purposes (e.g. heating and power generation). Italy is the only country in the European Union with a noticeable market share of natural-gas-powered cars, with annual shares of natural-gas powered new cars sales between 5% and 20% in the last 10 years (ICCT, 2017a). However, most of the traditional fuel stations are far from natural gas networks, and they often need to

use alternative supply solutions. Some trucks are experimenting the use of liquified natural gas (LNG) instead of compressed natural gas (CNG), with some advantages related to storage and distribution. Natural gas has the potential of including a part of renewable energy if it is produced by biogas or alternative synthesis processes that use renewable electricity. The production of biomethane from biogas requires a cleaning and upgrading process, which removes other compounds from biogas to reach the standard quality required by natural gas standards. Current biomethane production is still in its infancy compared to biogas, but there are already 500 plants in the EU, mostly connected to the natural gas network (GIE-EBA, 2018).

However, the most promising solution to address both the global and local emissions problems appears to be the use of electricity. Electrification will be further analysed in this research work as its development is strictly related to digital technologies. Electricity is already supporting a non-marginal share of urban mobility (rail, tram, subway), but the largest hopes are related to the possibility of impacting the road transport. The transition towards electric vehicles is more than a simple fuel switch, as it has the opportunity of developing a new paradigm for mobility. In fact, electric vehicles could provide a range of services that goes beyond the simple transport of people or goods, through the so called V2X ("Vehicle to everything") model. The possibility of exploiting the electric storage of the vehicles to provide energy and power services to the electricity network is an interesting opportunity for the development of unprogrammable RES for power generation. However, although many manufacturers are already producing electric cars (both hybrid and full-electric) and their market is increasing, there are still a number of issues to be solved before reaching a mature acceptance by the potential customers. Major concerns are related to the maximum range of electric cars, which is limited by the battery potential. Current technologies do not guarantee comparable performances with traditional cars, but manufacturers are investing in R&D to improve this bottleneck. The vehicle cost is still higher than traditional cars with comparable performance, although in some countries the total cost over ten years is comparable to, or lower than, diesel cars (Energy & Strategy Group, 2018). Moreover, some studies highlight that the higher weight of the cars leads to higher particulate emissions from wheels and braking (Timmers & Achten, 2016), and these potential impacts should be carefully evaluated. An additional aspect, that will be considered in detail, is the electricity production and distribution pathway: although electric cars are not causing local emissions, the electricity production may have other de-localized environmental impacts, especially if produced by fossil fuels. Focused studies are needed to promote synergies between EVs and a proper electricity generation from local RES (Bellocchi, Gambini, Manno, Stilo, & Vellini, 2018).

A final solution that has similar benefits than electricity is hydrogen. It ensures no local pollutants emissions, but just water, and it can help decarbonizing the transport sector by being produced from renewables. However, just like electricity, its production requires multiple transformations, lowering the total "well-to-wheel" efficiency of the system. Moreover, when producing energy from renewables, a necessary step is the electricity generation, so that electric cars would require fewer conversion steps. Hydrogen generation from electrolysis is currently showing a relatively low efficiency, which leads to higher costs compared to other production technologies. For this reason, the current industrial production of hydrogen is largely based on Steam Methane Reforming (SMR), in which high temperature steam is used to produce hydrogen from a methane source, usually natural gas. Compared to electricity,

hydrogen shows a better potential for storage, although some technological and economic limits still need to be fully solved. Hydrogen has been seen as a breakthrough technology at the beginning of this century, allowing for a diffused and carbon-free energy system (Rifkin, 2003). But since then there has been little technological evolution, both for some technical limits not yet fully solved, and for the worldwide financial crisis that has moved investors interest towards more mature technologies (Balat & Kirtay, 2010).

The potential of digital technologies in mobility

Urban centres are facing worldwide a transition in different fields: technology developments are pushing towards optimized, connected and sustainable cities, often referred as "smart cities". This concept involves multiple domains at multiple levels, and this digital transition is quickly modifying several aspects in disruptive and unexpected ways.

Transport is among the sectors that are involved in this transition, and urban mobility is already seeing different applications of digital technologies. Three major trends are emerging, with different potentials and level of maturity: (1) Mobility as a Service, (2) Shared Mobility and (3) Autonomous Vehicles. These three aspects, together with Electric Vehicles, will be used in this study to evaluate the impact of digital technologies in passenger transport, by analysing their impact on energy consumption and CO_2 emissions.

Mobility as a Service

Mobility as a Service, MaaS for short, is a new paradigm to support multimodal transport, by providing to the users an integrated travel experience in which different modes are combined and organized to provide at each time the best solution based on the user's needs (e.g. fastest, cheapest, most comfortable, etc.). MaaS is strongly based on public transport solutions, but often the user can also rely on car-, ride- and bike-sharing systems, or even to taxi. The strength of this approach is the possibility for the user to interact with a single interface that takes care of comparing multiple solutions, providing live updates based on the actual timing of each system. The final development of MaaS, which is already in operation in some cities, is the possibility of paying a single monthly fee for all those services, which is calculated on the level of service required by each user.

The development of a MaaS platform requires reliable and up-to-date information from different transport systems, which need to exchange information over a common protocol. Public transport companies in large cities are already publishing live data on their services, to allow other players providing additional services to the users. The availability of solutions for fast route planning and re-routing in case of delays or congestions is a powerful driver for increasing the users of public transport. The higher the complexity of the network, the higher the need of complex online optimization models that are continuously updated with information from traffic sensors around the city.

The full development of MaaS will be aimed at providing to the user a comprehensive service, with an all-in-one monthly fee for all the mobility services together. This new business model is in line with other trends for which the customer prefers to pay for a service rather than to own an asset. From smartphones to cars, the users are willing to pay for the services they need, rather than to buy a tool that can allow them to independently fulfil their needs. The same concept is applied to shared mobility, as it will be discussed below.

A notable example of MaaS, which is currently the most advanced application of this concept, is the private-owned platform Whim, based in the city of Helsinki. While there are significant expectations, this business model is still at an early stage, and probably more improvements are needed to unleash its full potential (Zipper, 2018). In particular, two aspects are at the base of the success of MaaS as well as on the consequences of urban mobility's sustainability. The interaction of private platforms with municipal transit service companies is crucial, as their willingness to be included in external networks may compete with the marketing strategies of last years. Specific regulations may be required to address this specific aspect, as it happened in Finland in early 2018, when a law has obliged the transit company in Helsinki to provide to third parties the possibility of selling their tickets. On the other hand, the development of MaaS (affordable) flat rate plans that include infinite taxi trips may shift a significant share of users from public transport to taxis, leading to increasing problems of congestion, local pollution as well as global emissions.

The potential of MaaS is the optimization of the mobility system of a given city, both from the user and the community point of view. While to the single user this model provides the fast and cheapest travel solution, the live optimization should allow an optimal sizing of the public transport for the effective mobility demand. However, an equilibrium between flexibility and efficiency will require to account for regular patterns (i.e. commuting) but also for occasional mobility demand (e.g. tourism, business trips, shopping, etc.). The real challenge that MaaS is facing is to provide enough flexibility and reliability to lower the modal share of individual car to public transport, or to shared mobility systems. In this vision, a tight collaboration with shared mobility organization will be a key aspect to reach this challenging goal.

Shared mobility

One of the results of the digital technologies, and in particular the enhanced mobile connectivity through the internet, is the development of the so-called sharing economy. The basic idea is the possibility of "sharing" (which often means renting) an unused asset to optimize its use over time. This novel business model has led to the development of online platforms with the only aim of organizing the dialogue between the demand and the supply. In fact, these platforms are now becoming significant players in different sectors (Airbnb for hosting, Uber for mobility, Deliveroo for food delivery, just to name a few). The opinions on sharing economy are various and often in contrast, but undoubtedly this trend is dramatically changing different markets, including mobility.

Sharing mobility can be divided into two main behaviours: the "shared" use of a single vehicle (a car, a bike, a motorcycle) at different times, or the simultaneous use of a vehicle (mainly a car) for the same trip that is in common for different users. These two aspects have some common features, but at the same time they represent different risks and opportunities for the mobility market.

Sharing a vehicle usually does not lead to a better energy efficiency (i.e. the energy needed to provide a specific transport service, such as moving a passenger for 1 km) compared to the private vehicle, but it lowers the travel costs and promotes the access for more people. Some advantages of car sharing against private cars could be a faster renovation of the vehicle fleet (lower age is related to better technology and lower impacts), and in some cases a more profitable use of electric cars instead of traditional fossil-fuelled

vehicles compared to private owners. Regulators and policy makers should define a careful planning of these business models to avoid rebound effects: the simple share of the asset could lead to a decrease of the cost, moving some users from a more efficient transport mode (bus, rail) to a less efficient (one-passenger car). This is already happening in some cities, where the availability of car sharing is not having a significant impact on car owners, but rather on public transport users (including university students).

On the other hand, optimizing the vehicle load by sharing the same trip (often named "carpooling") is an effective way for a significant increase of the efficiency of the car and to reduce congestions during peak hours. Like for car sharing, a better effect is obtained if the users switch from single car use rather than from public transport modes. The regulation of carpooling transport fares is crucial, since an excessive level of income for the drivers could lead to an illegal competition with taxis, that are regulated by precise limits. For this reason, some carpooling platforms (such as Blablacar, which is limited to extra-urban trips) have set an upper limit to carpooling fares, based on the idea that the actual cost of the travel (including fuel, tolls, vehicle O&M and capital depreciation) is being shared between the passengers. Both car sharing and carpooling are currently gaining momentum worldwide, with multiple companies targeting specific market shares or world regions.

An additional application of shared mobility in cities, which can bring significant advantages for lowering congestions and increasing air quality, is the bike sharing. In the last decade bike sharing systems have successfully been installed in several cities worldwide, providing an alternative solution for the last-mile mobility and increasing the use of bike for commuting and occasional trips. At the end of 2017, there were more than 10 million shared bikes worldwide, from 1.27 million in 2015, with Chinese cities representing the major market for number of bikes, with 9.3 million bikes in 430 cities across the country (Roland Berger, 2018). Different business models have been developed, and after a massive rise of de-regulated business models during the last years, especially due to the strong competition between multiple Chinese firms, the system is oriented towards a cooperation between municipalities and bike-sharing companies. Cities are requesting a collaboration both during the planning phase (e.g. number of bikes, position of the stations, etc.) and especially during the operation phase, as the availability of live data for the integration with other transport modes is a significant advantage for a better monitoring of the city mobility patterns.

Autonomous vehicles

Of the three digital trends considered in this study, Autonomous Vehicles (AVs) are the less mature. There are multiple projects worldwide in a testing phase, but very few commercial applications already in operation. However, R&D resources allocated on this technology are massive, and both major automotive and ICT companies are strongly involved in this sector. The challenge appears significant, but the potential of developing driverless cars could lead to one of the most significant evolutions in the automotive sector.

Autonomous vehicles have the potential of providing a better travel experience, as without the need of driving, people can focus on other activities, while at the same time increasing the safety, optimizing the transport efficiency, removing the need of parking lots nearby the city centres and significantly reduce congestions. A major diffusion of AVs would

lead to drastic changes in urban design, as mobility spaces will be redesigned based on different logics than the current ones.

On the other hand, major challenges still need to be faced. While a reduction of parking lots will allow for a significant amount of space to be relocated, pick-up and drop-off areas will still need to be present nearby the points of interest. Moreover, in the case of private AVs, the parking outside city centre will result in increased car mileage. On the other hand, in the case of shared AVs, the need of providing quick available travel solutions in each point of the city without parking would require many AVs always in motion. In both cases, there will be the need to deal with peak/off-peak demand patterns to optimize the total number of vehicles. The increased efficiency obtained from platooning (the reduction of spaces between cars to avoid air resistance) could be an improvement on high speed roads, but it would have a minor effect in an urban context where speed would be necessarily limited. Finally, a significant ICT infrastructure needs to be built to allow for the necessary communication between vehicles (Vehicle to vehicle, V2V) and with the surroundings (Vehicle to network, V2N) to allow a correct operation. A specific legislation should be defined for the management of accidents: although with a lower probability of occurrence, it is not yet clear who will be responsible for possible failures.

Moreover, while a mobility scenario related on AVs only presents the challenges described above, the transition phase in which AVs and normal cars will need to share existing roads will lead to even more challenges. Also, it is not clear if human drivers will need to disappear to fully develop the potential of AVs, or if a coexistence of these two approaches is foreseeable. An additional challenge, particularly relevant for urban context, is the interaction with pedestrian and bikers. The potential need of separated infrastructures would lead do a major increase of investment costs and layout designs.

2 – Methodology

Transport Model

The transport model that has been built in this work is able to connect the demand for transport with its energy consumption and other impacts (e.g. CO_2 emissions). A given transport demand can be matched by multiple modes, that are in turn operating on different fuels, with specific energy consumption and average loads. All these parameters can vary in time and space, and are affected by other drivers, including economic, social and technological aspects.
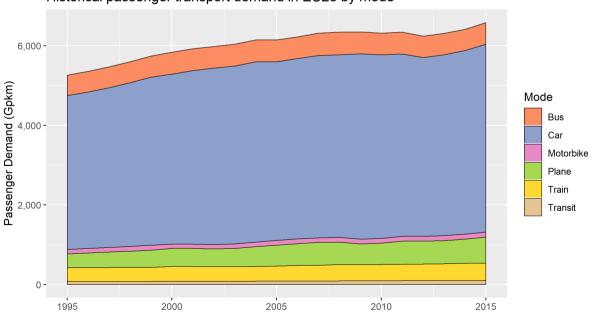
The model is deterministic, and its purpose is the linear calculation of the impact of the transport given its demand. Through the definition of proper parameters, multiple indicators can be calculated, including primary energy consumption, CO_2 emissions, share of renewable energy sources, other pollutants emissions, etc. The transport demand is an input to the model, and its future trends can be defined by external scenarios or by considering some main drivers that have been proved to influence transport patterns (e.g. population and GDP).

The first application of this model, which is the object of this working paper, is the estimation of the effects of digital technologies on the passenger transport. European Union is used as case study, to evaluate the effects of the main digitalization trends on a relatively homogeneous macro-region. The scenarios horizon is set both at 2030 and 2050, in accordance with other scenarios and roadmaps from different sources that will be discussed in detail in the following sections.

Future developments of this model will extend to other world regions with different features, and potentially the freight transport can be included into the analysis to provide a complete figure. This model is also able to handle different levels of aggregation and, based on the availability and reliability of input data, a bottom-up approach can be used to integrate information at multiple levels.

Historical Evolution

The currently available information for passenger demand is available from European statistics (expressed in "passenger km", or pkm) divided per transport mode at country level (EU-Eurostat, 2017). Figure 4 shows the distribution of the total transport demand by mode, with passenger cars reaching 71.5% of the European passenger transport demand in 2015, followed by planes (9.8%), buses (8.2%) and trains (6.7%). The evolution in the last decades shows a slight increase, from 5.3 trillion pkm in 1995 to 6.6 trillion pkm in 2015. Considering the average passenger transport demand per capita, each citizen of the EU had travelled an average of 11,000 km in 1995 and 13,000 km in 2015. There is additional information at country level for some modes, but the differences in national statistics methods lead to non-comparable results.

Historical passenger transport demand in EU28 by mode

Source: Author's elaboration on EU data (2017)

Figure 4 – Passenger transport demand in EU28 by mode. Author's elaboration from (EU-Eurostat, 2017).

Moreover, there is no information on the bike and walk mobility demand, which is seldom represented in international statistics. However, when considering urban demand these modes can have a significant share in some cities (see Figure 1), especially for the so-called "last mile" mobility. Moreover, these mobility modes, often referred as "active mobility" due to the importance of the energy provided by the user itself, will be a key aspect for an optimization and decarbonization of transport in cities. Some information can be retrieved by (Castro, Kahlmeier, & Gotschi, 2018), where estimated cycling data is available for almost all EU countries, and walking data is available for around ten countries. The total demand supplied by cycling in the EU28 area can be considered equal to 124.6 billion pkm, and an approximated value of 134.4 billion pkm has been estimated from the values presented in (Castro et al., 2018). Unfortunately, there is no historical evolution for these values, and therefore they will be used as a constant value for past years.

A further issue lays in the definition of the share of fuel use for each mode. The most updated information available for road transport refers to 2015 (ACEA, 2017), where a split by fuel for passenger cars and medium and heavy commercial vehicles (including buses) is provided for each EU28 Country. Cars run primarily on gasoline (55.6%), followed by diesel (41.2%), although in some countries this figure is reversed (e.g. France, Spain and Belgium). The remainder is distributed among LPG/natural gas (2.2%), hybrid (0.4%), electric (0.1%) and others (0.4%). These data are available for 2015, while past data have been estimated by building a trend based on different sources for market share by fuel and fuel consumption over the years (Fuels Europe, 2017; ICCT, 2017a). It has to be highlighted that electric cars are gaining momentum, and updated statistics show a significant increase in the very last years: 287,000 electric vehicles have been sold in Europe in 2017 (+39% on 2016), being the second market worldwide after China (Energy & Strategy Group, 2018). Considering heavy vehicles, diesel outstands all the other fuels with a share of 95.5%, although trucks are probably counting more than buses in this category. No detailed information is available for the other transport modes, but 2-wheelers (i.e. motorbikes and mopeds) have been totally allocated to gasoline, and transit (metro and trams) has been considered as fully electrified. The fuel share for passenger trains has been set 85% on electricity and 15% on diesel, in accordance with data from (UIC-CER, 2015) that provides similar figures for aggregated passenger and freight railways in Europe.

A specific focus needs to be performed for bio-fuels, which are mainly bio-diesel and bio-ethanol in Europe. Since they are generally used in traditional fossil-based engines, they do not result from statistical data on vehicle fleet and market shares. For this reason, the biofuels consumption has been allocated to gasoline and diesel-powered vehicles (excluding trains) by considering their average European share over the years obtained from official Eurostat data (Eurostat, 2018b).

A further requirement is the definition of a representative specific fuel consumption, which is a challenging task considering the need of estimating an average value for a very broad range of vehicles for each category. However, given the need of providing simplified values and the relatively low availability of detailed data, some reference values from literature have been considered in the model. The fuel consumption has been considered both as final energy consumption and as a primary energy consumption, to compare the impact of different fuels on the energy supply chain. However, no life cycle approach has been considered, nor the energy required for the building and maintenance of the vehicles. Further improvements of the model may include also this aspect. For electricity, an average EU28 primary energy

factor has been considered in the calculation, based on the evolution of the electricity mix over the years. In 2015 the average EU28 primary energy factor for electricity was equal to 2.21, down from a value of 2.53 calculated for 1995. The CO_2 emission factor for electricity shows a similar trend, decreasing from 467 g/kWh in 1995 to 323 g/kWh in 2015. These trends are caused both by a significant increase of RES in the electricity mix and by a generalized improvement of fossil-fueled power plants' efficiency, but with a larger contribution of the former aspect. These values are however limited to the operation of the power plants, while a more correct approach would require including the effect of the supply chains. These values will be described with greater detail in the following sections (see Table 2).

Finally, an average load factor has been included, to obtain a specific fuel consumption for each passenger and each km of travel. The load factor is based on average data from different sources, and it is a crucial parameter for the assessment of the effectiveness of vehicles in their usage. The higher the load factor, the better the usage of a given vehicle, which should be used at its full capacity for an optimal operation of the entire system. Car pooling is based on this very same assumption, as passenger cars are being shared both to improve efficiency (and especially cost) and to reduce congestions.

The application of these aspects leads to the calculation of the energy consumption for passenger mobility in EU28 (see Figure 5). Fossil fuels are currently representing the most significant share in passenger transport final energy consumption. The main reason is the dominance of private car in the modal share (see Figure 4), where oil-based fossil fuels are currently representing more than 95% of the market. Moreover, the lower efficiency of fossil-fuel-powered engines in comparison to electric engines (which are currently relevant for trains and transit but will be increasingly used in cars) increases their weight in the total energy balance of the transport sector.
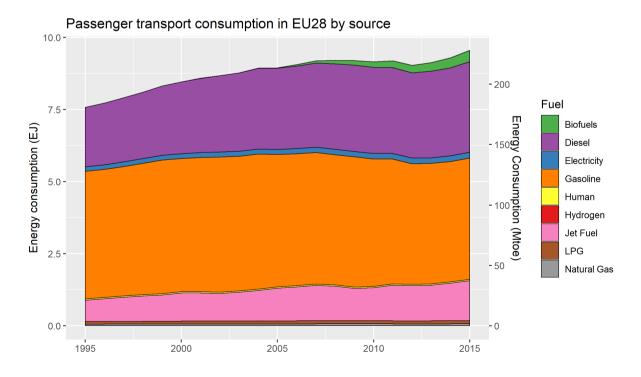

Figure 5 – Calculated transport consumption in EU28 by source. Author's elaboration from multiple sources (as described in the text).

A slight difference could emerge when considering primary energy consumption, depending on the characteristics of electricity production: while final energy consumption is lower for electricity, a low conversion efficiency of the entire supply chain could lead to a larger consumption of primary energy in comparison with fossil fuels. However, other aspects should be considered in such a comparison, including local pollutants emissions, CO_2 emissions as well as the share of renewable energy sources. These aspects will be described in detail in the following sections.

Future trends and drivers for passenger demand

The evolution of transport demand has been modelled by different authors by considering multiple exogenous drivers that are usually correlated with the users' need and willingness to travel. Such drivers generally include population, to account for the number of potential users that have access to mobility services, and GDP to consider the economic possibilities of those users. Since the focus of this work is on urban mobility, an additional driver that needs to be consider is the urbanization rate, which provides information on the share of the total population that is concentrated in urban areas.

The Shared Socioeconomic Pathway 2 (Fricko et al., 2017) has been considered as the baseline scenario for the trend of population, urbanization share and GDP in the European Union. The complete trends are reported in Table 1, obtained by aggregating the data for the EU28 countries.

Table 1 – Evolution of population, urbanization share and GDP according to SSP2. Source: Author's elaboration on (Fricko et al., 2017).
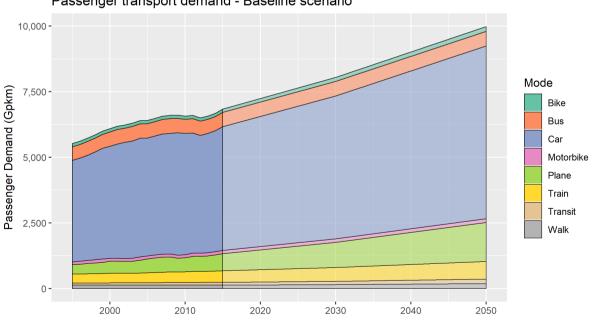
	2010	2030	2050
Population (million)	504.84	529.64	541.11
Urban Share (-)	73.8%	80.8%	85.6%
GDP PPP (billion USD)	14,073	23,223	33,759

However, other drivers have an impact on the transport demand and the choices of the users, as reported in a survey on the quality of transport performed at European level (European Commission, 2014). Convenience and speed appear to be much more important than price when choosing a specific transport mode. Although the results are significantly varying from a country to another, other drivers considered in the survey are available facilities, possible alternatives and security.

Since the price appears to be a minor driver for EU-28 countries in the modal choice, a relation with GDP appears of lower significance with respect to other analyses that have been carried out on a world basis. Thanks to the availability of a consistent 20-years historical trend, the baseline scenario has been built by considering the evolution of the total passenger transport demand, as well as a parallel evolution of the share of each mode, again based on past evolution. The mobility demand for bike and walk has been increased with the same average growing factor, i.e. 1.08% per year (calculated as the average on a 20-years basis). This assumption leads to the evolution that is represented in Figure 6, with a total of 7,757 billion passenger km in 2030 rising to 9,616 in 2050.

These values can be compared with the results from other studies, of which the most detailed are the *EU Reference Scenario 2016* (European Commission, 2016) and the *ICCT Roadmap model baseline results* (ICCT, 2017b), which are provided for a number of world regions, including EU-28. The values estimated by the EU Scenario are very similar to the baseline scenario of this work for 2030 (7.9 Gpkm vs 8.0 Gpkm), while the total demand estimated by 2050 is 9% lower (9.1 Gpkm vs 9.9 Gpkm). Considering the ICCT results, the total passenger demand is very similar in 2030, but ICCT numbers are 15% higher in 2050, whereas it has to be noted that Roadmap model scenario is starting from a 2015-value of 6,056 Gpkm in spite of the official value of 6,602 Gpkm from (EU-Eurostat, 2017). Therefore, the baseline scenario defined in this studio appears in line with other scenarios when considering the total mobility demand.

Looking at the modal shares, the most significant evolution is the rise of the aviation, increasing its share by 0.16% per year, while car is losing weight by 0.09% per year. These trends are to be considered in line with the mobility demand increase discussed above: while car modal share will go down to 68.4% by 2050 from its current 71.5%, the total demand for car transport will eventually increase by almost 40% by 2050 (compared to a global mobility demand increase of roughly 45%). Also the modal shares evolutions are in line with the hypotheses performed by (European Commission, 2016), with similar growth rates for each of the considered modes (e.g. a 67% share of car in 2050). It has to me reminded that the aviation demand is limited to national or intra-EU flights (in accordance with usual statistics), whereas a strong increase is expected in EU-Asia flights in the next decades.

Source for historical data: Author's elaboration on EU data (2017)

Figure 6 – Future transport demand in EU28 by mode in the reference scenario.

Together with the evolution of total mobility demand and modal shares, other parameters influence the impacts of passenger transport, including the fuel shares, the vehicle efficiency and the average load factors. The main hypotheses that have been used in the baseline scenario are discussed below.

The fuel shares evolution shows a significant complexity for the car transport demand, as multiple fuels and technologies are involved, and different external factors affect this trend. The other modes are simpler to model as the fuel variety is much lower. Considering the car fuel shares, two recent trends may affect the market in EU-28: electrification and diesel phase-out. While there are strong synergies between these trends, the current aversion to diesel cars is both reflected in national and local policies aiming at reducing pollution in cities and in the resulting choice of many manufacturing companies to stop diesel car production for Europe in the next years. The same firms are switching to electric cars, thanks to the fast technology evolution of the batteries, which are now produced at lower costs and allow acceptable driving ranges. However, there is still a high uncertainty related to expected penetration of electric vehicles in the markets, especially after 2040. Some studies expect even a 100% market share of EVs by 2035 in Europe, while others are far more cautious. In the baseline scenario of this work a conservative approach has been chosen, by estimating a share of electric vehicles sales of 22% for 2030, up to 45% in 2050. A dedicated sensitivity analysis will assess the effect of different hypotheses on such a significant and uncertain aspect.

The vehicle efficiency is mainly driven by technological improvements, and some authors provide some estimations of the expected increase of efficiency of light-duty vehicles in the future, related to improvements in the propulsion systems, the use of lighter materials and the size reduction, an optimized operation and energy management. The evolution of car efficiency has been evaluated according to (Heywood et al., 2015), which provides specific scaling factors for 2030 and 2050 starting from the current performance of gasoline-powered cars. Expected performance improvements for 2050 reach 49% of savings for traditional gasoline, 56% for turbocharged gasoline, 57% for diesel, 69% for hybrid gasoline cars, 81% for fuel cell EVs and 86% for battery EVs. It has to be reminded that FCEVs and BEVs are already consuming 65% and 77% less final energy than traditional gasoline respectively, and the primary energy required for the generation of electricity is highly country-specific (with an average primary energy factor of 2.21 in the EU28 for 2015). However, these values are showing the evolution of the state-of-the-art technology, while the market sales are generally a minor part of the entire vehicle stock for a given region. In 2016 new passenger cars registrations in EU-28 reached 14.6 million units (ICCT, 2017a), compared to an estimated vehicle fleet of roughly 260 million units (Eurostat, 2018a). This fleet renovation rate of 5.6% has been considered for the calculation of efficiency increase, leading to slightly lower results for 2030 and 2050 compared to the previous data.

For the other transport modes, due to the lack of specific estimations, a generalized decrease of specific fuel consumption of 15% has been set for 2030 and of 30% for 2050, with respect to the current performance of the vehicle fleet.

The last parameter that has an impact on the final energy consumption is the load factor of the vehicles. This is particularly evident for private cars, where the passenger's average occupancy ranges from 1.2 to 1.5 in some European cities. In this model the value of 1.2 has

been considered, in accordance with (OECD-ITF, 2016). An improvement of this parameter would have substantial benefits in decreasing energy consumption and environmental impacts, as well as in lowering the congestions in cities, especially during the peak hours. However, an important aspect related to the increase of this load factor is the origin of the additional passengers: while a decrease of single-passenger private cars would be a clear benefit, the shift of users from public transport to 2- or 3-passenger cars would probably lead to a decrease of the mobility system performance.

The distribution of the final energy consumption by source is at the basis of the calculation of primary energy consumption and total GHG emissions. Emission factors and primary energy factors are available in the literature with a specific focus on Europe (Edwards, Larive, Rickeard, & Weindorf, 2014), and have been used for an evaluation of the impacts of mobility by including the effects of the production, transport, manufacturing and distribution. The GHG emissions include the analysis of CO_2, CH_4 and N_2O, with 100-years conversion coefficients, as other GHGs are not emitted in significant quantities in the processes analysed by the study. The primary energy factors from fossil sources and the emission factors for the main fuels considered in this study are reported in Table 2, and for the latter both Well-to-Tank (WTT) and total emissions are provided. All these values have been calculated with current data on the state of the art, and therefore in this study to account for future technology improvements they have been lowered by 5% for 2030 and by 10% for 2050, since no detailed information for each conversion path is available.

Table 2 – Fossil Primary Energy Factors and GHG Emission Factors for selected fuels. Source: Author's elaboration on (Edwards et al., 2014).

Fuel	Fossil PEF (MJ/MJ$_{fuel}$)	Well-to-Tank EF (g$_{CO2eq}$/MJ)	Total EF (g$_{CO2eq}$/MJ)
Gasoline	1.18	14	87
Diesel	1.21	16	89
LPG	1.11	8	74
Biodiesel	0.45	55	55
Natural gas	1.16	14	70
Hydrogen – from natural gas	2.20	125	125
Hydrogen – from electrolysis, EU mix	2.22	230	230
Electricity – from EU mix, low voltage	1.70	150	150

A final aspect that needs to be cited is the electricity production scenario, whose importance is increasing together with the use of such energy carrier for transport. While in the reference scenario electricity consumption in transport is by far lower than fossil fuels, in a hypothesis of strong penetration of EVs the importance of an efficient and low-carbon electricity generation mix becomes evident. The fossil PEF and GHG EF reported in Table 2 for electricity are related to the EU-mix considered in the study, but from the same source additional values are available for each conversion technology. Thus, it is possible to evaluate these factors also for different electricity mixes, in accordance with the evolution of the power sector in EU. The fossil PEF and GHG EF have been calculated in accordance with the baseline scenario illustrated in the Energy Roadmap 2050 (European Commission, 2011).

Digitalization trends and their parameters

The digitalization trends considered in this study are analysed by means of evaluating their impact on the mobility demand and the mode shares in the future, as well as their influence or other specific parameters such as the average passenger load. Each digitalization driver can lead to very different outcomes, depending on multiple aspects including the policies and regulations. In this study the two extreme scenarios are evaluated for each driver, to propose a quantification of the impacts in the two boundary situations. While the effects will be analysed together, the model allows considering each driver separately if needed. The main aspects concerning the expected impacts of digitalization drivers are illustrated in Figure 7, while they are described in detail in the following sections.
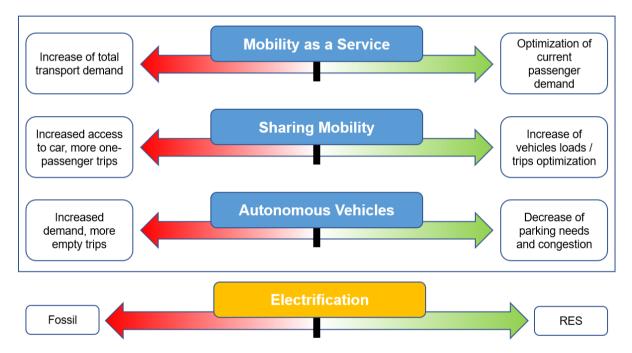

Figure 7 – Main digitalization trends and their possible impact ranges.

A further step to define proper mobility scenarios requires the definition of the share of transport that can be allocated to urban mobility. There is few information of total urban mobility at European level, and therefore some hypotheses are needed. For some modes the choice is rather trivial, as they can be integrally allocated to urban context (walking and cycling, if considered as a transport mode and not a leisure activity) or integrally excluded from urban mobility (plane and ship). On the other hand, for other modes the definition of the urban share is way less trivial. The report from (ITF, 2017a), considering road and rail passenger transport, suggests a 62.7% share of urban vs total transport demand in OECD countries, and 57.0% on a world basis. No specific information is given for Europe, but the OECD basis appears to provide an acceptable approximation. However, only 23% of urban transport demand is estimated to be covered by public transport in OECD countries, although this value is probably slightly higher for European countries. The domination of the car is still evident, and it is probably partially related to the weight of smaller cities that have fewer public transport networks in comparison with the larger cities and EU capitals, for which the weight of the car appears to be generally lower (see Figure 1).

These shares are used in the model to weight the impact of some drivers that are specifically limited to the urban context.

Mobility as a Service (MaaS)

Mobility as a Service has the potential to drastically modify the user experience in planning, buying and organizing the travels, as well as to support a real-time modification of the trip to provide effective alternatives in case of delays, accidents or need of modifying the trip destination. For this reason, the strong potential of MaaS is to increase the flexibility of alternative modes to support the users in avoiding the choice of private car.

The potential positive effects of MaaS can be modelled by considering a modal shift from private car to public transport, which is the main target of this digital technology. At the same time, the exploitation of AI-driven algorithms for the prediction of passenger flows could lead to an optimized allocation of the vehicles, increasing their load and avoiding the need of operating empty buses or trains and tailoring the timetables on the real users' needs. Other modes may be integrated into the platform, including car sharing and bike sharing, as well as taxis and eventually autonomous vehicles. In particular, a rebound effect can be caused by the inclusion of taxis in flat tariffs for MaaS, leading to an increase of car usage from passengers that are currently relying on public transport for economic reasons. A similar pattern could emerge if the AVs lead to a strong decrease of the taxi costs for the owners. These transport modes could then become an interesting alternative to private cars, but at the same time they could be of interest for a group of users that were relying on public transport for economic reasons. Finally, a more efficient and convenient mobility environment could lead to an increase of the mobility demand for users that were discouraged to travel for a number of reasons (e.g. cost, comfort, security, etc.).

Shared Mobility

As discussed in the previous sections, shared mobility includes two different trends, i.e. the sharing of an asset for individual use (e.g. car sharing) or the sharing of a vehicle for the same trip (e.g. carpooling). Given the rise of these mobility modes, the main reason that leads to positive or negative effects for energy consumption is the type of modes that are being substituted by shared vehicles.

Sharing mobility has the aim, again, of providing a flexible alternative to the need of owning a private car. Although car sharing in principle may not lead to a change of the total number of circulating cars if it is chosen by single users, there could still be some advantages. The need of paying for any single trip in comparison to the use of a private car may lead the users to a better evaluation of the real need of using a car instead of alternative transport modes, especially for short trips. Other advantages are a faster renewal of the car fleet, resulting in more efficient and less polluting vehicles, and a larger utilization rate, leading to a lower need of parking spaces in the central part of the cities. On the other hand, car sharing can become an interesting alternative for public transport users, with negative consequences on the efficiency and impacts of the transport sector.

Considering carpooling, the possibility of grouping different users with the very same travel need could be a strong driver towards a better utilization of private cars. A slight decrease of flexibility is generally accepted with the aim of reducing travel costs and in some

cases to decrease the environmental impact. However, also in this case a potential rebound effect comes from the attractiveness of this transport model for users that are currently exploiting public transport, and in particular subway or train. These latter modes have the double advantage of running on electricity (reducing local emissions and in some cases also GHG emissions, depending on the electricity generation mix) and limiting the road traffic by transporting users on alternative paths. While the city congestions will not be specifically modelled in this work, this issue should be taken into account, since it is among the most significant aspects in the current mobility patterns.

Autonomous Vehicles

A third major trend is related to autonomous vehicles, which is the less mature technology today, but it is probably the one that may have the largest impact of future mobility patterns. Even in this case the effects on energy consumption and GHG emissions have a large variability, depending on the paths that AVs will follow for their development and use in the future.

Autonomous vehicles will eventually increase the total transport demand, since even people that today are not able to or do not choose to drive will be able to move with more flexibility. The acceptance of autonomous vehicles, rather than being limited to a matter of price, will need to be based also on psychological aspects, including the sense of freedom for the user and the privacy (Hunecke, 2018). In particular, the automation could lead to an increased attractiveness for taxis, for which privacy and cost are currently a barrier for some users. On the other hand, other social and cultural aspects related to owning and driving a private car will probably hinder a sudden and large diffusion of shared autonomous cars.

Anyway, the penetration of AVs in substitution of private cars could lead to a decrease of parking needs in the cities, but at the price of doubling the mileage of vehicles due to the need of empty trips to reach available parking areas. At the same time, more empty vehicles on their way would cause a rise of congestions, and probably the areas saved by parking would be needed to support this additional traffic. For this reason, specific regulations would probably push for shared AVs, in order to optimize their benefits to lower the current traffic in cities rather than to increase it.

External digitalization trends

While digital technologies have various effects in the mobility sector, other external trends may have a significant impact on mobility demand. These trends, including agile working, e-commerce, virtualization of goods and services, will directly affect the passenger demand by lowering the transport needs or by shifting the current timing with benefits on congestion during current peak times. Some trends are already gradually gaining momentum in current lifestyles, especially in developed countries.

It must be noted that some of these trends, such as e-commerce, could decrease passenger demand but increase freight transport, which is currently not modelled in this work. A future development of this model will be able to tackle this specific issue and give a more complete vision on the impact of these digital trends on the whole transport sector.

Electrification

Electrification is not a proper digital trend, although its full and efficient deployment requires a strict integration with digital technologies, e.g. in optimizing the battery charging profiles to maximize the use of available RES or provides capacity services to the power grid. For this reason, electrification will not be directly included into the analysis, but the average penetration of EVs of the baseline scenario will be kept constant through the other scenarios, although some specific considerations will be performed in the sensitivity analysis at the end of the study.

Scenarios for the case study

The case study considered in this work aims at evaluating the potential effects of digital technologies in EU-28 by considering 2030 and 2050 as time horizons. The baseline scenario, already described above, is based on a moderate effect of digital technologies and considers an evolution of the historical trends. This scenario is comparable with other baseline scenarios defined by different studies. The other two scenarios are purposely pushing towards a strong penetration of digital technologies, eventually too optimistic, to assess their potential effect in two opposite directions: a "responsible" digitalization and a "selfish" digitalization. The idea is to analyse the use of digital technologies to optimize the collective benefits in the former scenario and the individual benefits in the latter. As a result, the real possible outcomes are expected to fall between these two boundaries, depending on the paths that will be followed by the development of digital technologies.

Baseline scenario

The baseline scenario is used as a comparison by providing a reference trend that is compliant with the main evolutions estimated by current literature studies. A moderate effect of digital technologies is foreseen, with car remaining the main mode for road transport with a slight decrease of its modal share. EU cities show an increase of public transport and active modes, and aviation mobility demand is showing a significant increase, although not comparable with the expected rise of extra-EU flights (this model is currently limited to national and intra-EU flights, in accordance with economies). Some hypotheses of the baseline scenario will remain the same in the two digitalization scenarios, namely the evolution of the fuel shares for each mode, as well as the fuel efficiency trends. Conversely, modal shares, modal demand and vehicle loads may vary in the other scenarios.

Responsible digitalization

This first digitalization scenario has been defined to estimate the potential evolution towards a mobility path aiming at optimizing the entire transport system. Digital technologies are coordinated to decrease the private car usage, by maximizing an efficient use of private transport as well as of sharing mobility options (car sharing, bike sharing, etc.). Future technologies, including autonomous vehicles, are evaluated by considering their potential positive contribution towards lowering the energy consumption and the GHG emissions. In this scenario all the potential positive effects are considering, to define a lower boundary for the calculation of the energy and environmental impacts. The specific effects for each digitalization trend are listed in Table 3.

Selfish digitalization

On the other hand, digital technologies can lead also to the maximization of the advantages for each single user. For this reason, another boundary scenario has been defined to depict the evolution of digitalization towards a rather "selfish" path. The underpinning idea is the fact that an increase of transport efficiency can lower the costs of private cars and car sharing services, leading to a rebound effect that has the result of increasing the modal share of the car with respect to its already high current value. In this perspective, autonomous vehicles will have a disruptive effect in providing the opportunity of using a private car for groups of citizens that are currently not allowed to drive (e.g. senior and young people, injured or invalids, etc.) or for drivers that can use the car to perform other activities during their travels. Again, the objective of this scenario is to propose an upper boundary for the evaluation of the impacts of digitalization when there is no aim to optimize the collective welfare but rather an interest of increasing the quality of life of each single citizen. The main effects that have been considered in this study are described in Table 3.

Synthesis and comparison

The main assumptions of the two scenarios mentioned above are reported in Table 3, where for each digitalization trend the effects of the two scenarios are described in detail for 2030 and 2050 horizons.

Table 3 – Main hypotheses underpinning the two digitalization scenarios.

	Responsible Digitalization (RD)	Selfish Digitalization (SD)
Mobility as a Service	Modal shift from private car share to public transport in cities (5% @2030, 15% @2050). Optimized use of urban public transport thanks to AI-driven mobility platforms (+5% load factor @2030, +10% @2050).	Increase of urban demand (+5% @2030, +10% @2050). Shift from urban public transport to single-passenger taxis by 2030 and AVs by 2050 (+5% @2030, +10% @2050).
Sharing mobility	Development of private carpooling, thus increasing average passenger/car (1.3 @2030, 1.5 @2050). Car sharing substitutes private car in cities (reaching 10% @2030, 20% @2050). Bike sharing for last mile in cities decreases other modes (1% @2030, 5% @2050).	Car sharing substitutes PT in cities (5% @2030, 15% @2050). Extra-urban carpooling shifts from train and bus to private cars with 3.5 passengers/car (10% @2030, 25% @2050).
Autonomous vehicles	AVs penetration in private cars that increases mileage by 50% (5% @2030, 20% @2050). Car sharing by AVs with optimized operation leads to 3 passenger/car (25% of car sharing @2030, 80% @2050).	AVs penetration in private cars that increases mileage by 50% (5% @2030, 20% @2050). AVs increases the private car demand for additional citizens (+5% @2030, +15% @2050).
Extra-sector digitalization	Decrease of urban demand due to agile working and e-commerce (2% @2030, 10% @2050).	No significant change in passenger transport.

As already described in the previous sections, the same digitalization trend could lead to opposite effects on energy and environmental impacts (see Figure 7). The central point for MaaS and Sharing mobility is similar: these digital technologies can help in reducing the modal share of the private car by shifting users to public transport or to a shared use of third-party cars, but an alternative deployment of the very same technologies could lead instead to an increase of demand for shared car by previous users of other modes. These two macro-trends are well defined by the hypotheses used in the two digitalization scenarios, where some potential consequences of these two extreme paths are represented. However, other intermediate scenarios are possible, since those aspects can also coexist. Considering autonomous vehicles, the key point become the use of this technology to enhance the flexibility and convenience of private cars, and consequently increase its demand, or to support a strong development of enhanced carpooling services aiming at combining the flexibility given by AVs with the potential of transport demand forecasts to allocate vehicles where and when they are truly needed. These two opposite possibilities will depend on multiple technology developments (including artificial intelligence, communication infrastructure, vehicle performance, etc.) as well as on issues related to safety, society and policy. Again, they will be probably developed together, as they could be of interest for different market segments.

Finally, additional aspects related to digitalization trends outside the transport sector could have a potential impact on the passenger demand. In this study, only a positive impact on passenger demand is added to the scenarios, by considering the effect of agile and smart working, together with the virtualization of some sectors (e.g. books, movies, social interactions, etc.) and the rise of e-commerce. On the other end, a strong e-commerce penetration will have significant impacts on the freight transport demand, which is however not assessed in the present version of this model. Future activities will include the modelling of freight transport, thus leading to a better picture of additional impacts of some digitalization trends.

3 – Results

This section presents the results of the study by analysing the evolution of passenger demand, energy consumption and greenhouse gases emissions. Some sensitivity analyses are presented at the end of the section. A broader discussion on the results is presented in section 4.

Passenger demand

The evolution of passenger demand by mode is reported in Figure 8. The total demand is increasing in the three scenarios, although with different magnitude across them: RD scenario is showing a lower increase (+33%) in comparison with SD scenario (+72%), while baseline scenario lays in the middle with an increase of 46%. However, a larger difference is evident when considering the transport modes, the car being the most significant driver for the evolution of total transport demand. While in SD scenario a further increase of the already dominant modal share of the car is evident, the RD scenario in 2050 reports a decrease of the

car share with a parallel increase of transit, bus, train and bike (mainly from bike sharing services). It is worth highlighting that these differences would appear in an even major scale if considering only urban mobility, as digitalization is expected to mainly affect mobility in cities rather than in rural areas, where the lower population density is generally limiting the benefits that can be reached through sharing mobility or MaaS solutions. Finally, the aviation demand shows the same evolution across the scenarios, as it is not affected by the trends analysed in this work.
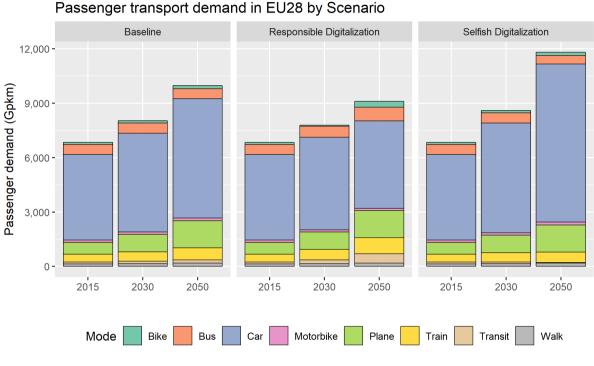

Figure 8 – Comparison of passenger transport demand by mode in different scenarios.

Final energy consumption

The results show the stabilization of the overall final energy consumption from 2015 to 2030, with a subsequent decrease by 2050 in both baseline and RD scenarios, while in the SD scenario the consumption remains rather constant. It has to be noted that the decrease of energy consumption despite the increasing of transport demand (see Figure 8) is due both to the increase of vehicle efficiency and the shift towards EVs, that have a higher efficiency when considering Tank-To-Wheel energy consumption (i.e. final energy). The results are slightly different when analysing primary energy consumption, i.e. considering both the Well-To-Tank and the Tank-To-Wheel energy consumption of a given vehicle. Since the evaluation of fuel shares and vehicles efficiency may be subject to significant uncertainties, two dedicated sensitivity analysis are performed to assess the entity of potential variability of the results.

A deeper look on the plot of Figure 9 shows the lower energy consumption of the RD scenario, which results from the combined effects of the shift towards more efficient modes (i.e. power transport) or a more effective use of car through the increase of average

passengers per trip. These improvements lead to a strong decrease of diesel and gasoline energy consumption, but at the same time also electricity consumption has a slight decrease due to the same reason. The increase of electricity consumption that can be noticed in the three scenarios has both common and diversified causes. The increase of EVs share is significant, and so is the shift towards electricity-based power transport. However, while these phenomena are balanced in the Baseline scenario, the former has more importance in the SD scenario, while the latter in the RD scenario.

The final energy consumption for aviation (i.e. the area related to jet fuel) is showing the same increase in the three scenarios, as the expected efficiency improvements are not enough to counter-balance the significant rise of the demand. Although some studies point out the potentiality of shifting towards biofuels for aviation, this aspect has not been included into the analysis in its present version, although it may be of interest for future improvements.
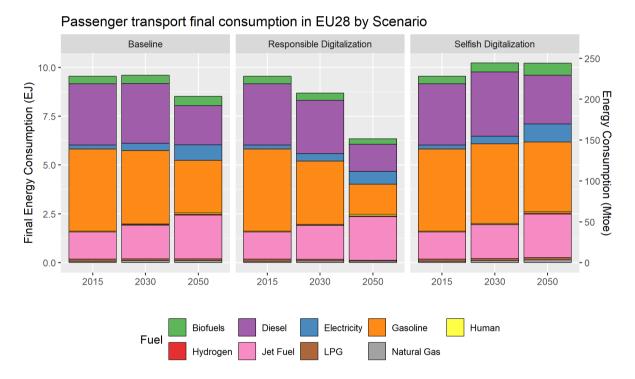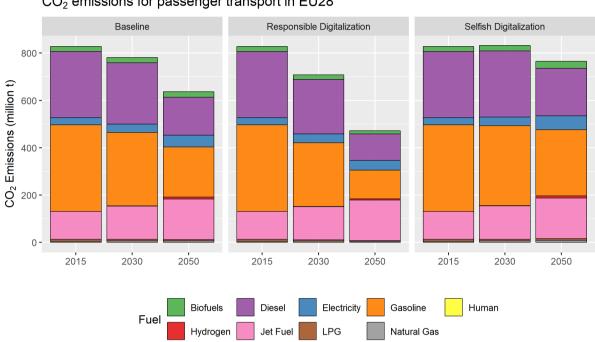

Figure 9 – Comparison of passenger final energy consumption by source in different scenarios.

Greenhouse gases emissions

The GHG emissions considered in this study are on a Well-to-Wheel basis, i.e. including also the production, transmission, conversion and distribution of the energy sources of the vehicles but without accounting for the impacts of the infrastructure and vehicles themselves. For this reason, the values obtained may not be directly comparable with other statistics in the field.
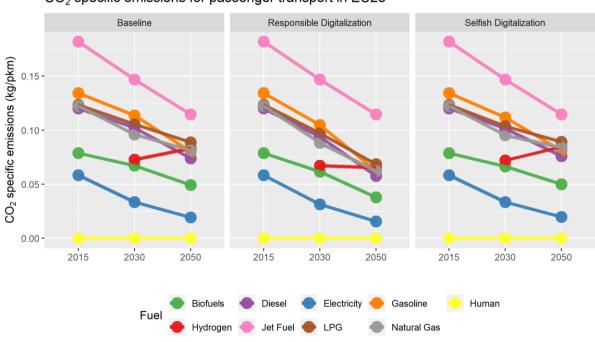
The GHG emission trends reported in Figure 10 are in line with those related to final energy consumption, although some differences are related to the specific emissions for each energy source (see Figure 11). From a value of around 828 million tonnes of GHG emissions

in 2015, the baseline scenario decreases to 637 Mt in 2050, in between the 766 Mt of the SD scenario and the 472 Mt of the RD scenario.

Figure 10 – Comparison of CO₂ emissions by source in different scenarios.

Figure 11 – Specific CO₂ emissions by source in different scenarios.

All the sources but hydrogen show a generalized decrease of their specific emissions, due to various technology improvements both in the vehicles' operation performance and in the supply chain of each fuel. The different slopes are related to the distribution of the energy sources throughout the transport modes. Electricity changes its GHG emission factor also because of a different generation mix, as already explained above. Considering hydrogen, which has not been included in 2015 technologies due to its very limited applications, the increase of its specific emissions is related to the hypothesis of transition from steam reforming to electrolysis, as the latter shows higher specific consumption and emissions than the former (Edwards et al., 2014). This hypothesis is based on the general trend toward less carbon-intensive technologies, in line with the EU targets. Some scaling coefficients have been considered to account for expected improvements in the technologies. However, the market dominance of a technological solution over the other will be crucial in determining the impacts of the hydrogen-fuelled cars, and the drivers will be both technical and economical.

Sensitivity analysis

The results of the simulation are based on multiple assumptions, as discussed in the Methodology section. However, some of those assumptions have a strong uncertainty, as they depend on several variables from economic, technological, social and policy fields. For this reason, some of these assumptions are further evaluated through a dedicated sensitivity analysis, which is focused on the following parameters:

1. Share of low-carbon sources in electricity generation mixes, leading to different GHG emission factors for electricity;

2. Electric vehicles penetration, considering the market share of vehicle sales;

3. Vehicle efficiency improvements, in comparison with current efficiency.

These parameters have been modified by considering two additional variations with respect to the reference value, i.e. a lower and a higher case. Table 4 summarizes the hypotheses used for the sensitivity analysis, where the "Base" column is related to the current values used in the simulation model. The effect of these hypotheses on the model parameters is represented in Table 5.
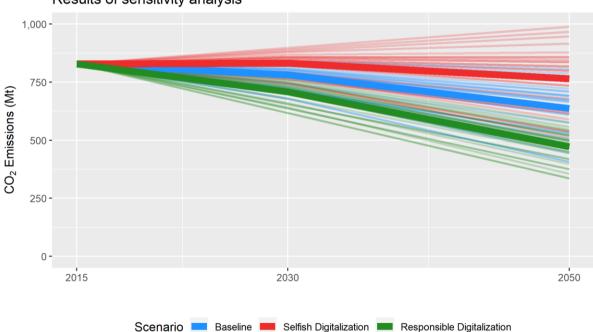
Table 4 – Hypotheses for the sensitivity analysis.

	Hypothesis	Year	Low	Base	High
Low-carbon Electricity	Share of low-carbon electricity generation	2030	47%	56%	70%
		2050	55%	70%	87%
EVs penetration	EVs Market share (new cars)	2030	10%	23%	80%
		2050	25%	45%	100%
Vehicle efficiency	Improvement vs 2015 (new cars)	2030	15%	28%	32%
		2050	25%	47%	60%

Table 5 – Parameters variations for the sensitivity analysis.

	Parameter	Year	Low	Base	High
Low-carbon Electricity	Electricity GHG emission factor (kg$_{CO2eq}$/MJ)	2030	0.120	0.095	0.070
		2050	0.100	0.063	0.030
EVs penetration	EVs in total fleet	2030	4%	9%	29%
		2050	15%	28%	72%
Vehicle efficiency	Average car efficiency in total fleet (improvement vs 2015)	2030	5%	10%	11%
		2050	17%	30%	36%

A compact representation of the results obtained from the sensitivity analysis is reported in Figure 12. The variations arising from the hypotheses are significant, which means that the variations of such parameters, especially when combined, could reach an effect even larger than the results obtained from the digital trends that have been considered in this work. However, the effect of each variation of the parameters in the sensitivity analysis has similar effects on the three scenarios, although in some cases they may have a larger impact.

Figure 12 – Results of the sensitivity analysis.

A further comparison of the effect of these parameters can be drawn from Table 6, where the average of total CO_2 emissions in 2050 is reported for each value ("Low", "Base", "High") of the three parameters. The reference value, i.e. the average of the three scenarios with all the parameters set to "Base", is equal to 625 Mt of CO_{2eq} in 2050. In comparison to this

reference value, the EVs penetration is the parameter that leads to the highest increase (+12%) as well as the largest decrease (-25%). These results are tightly related with the hypotheses of variation reported in Table 4 (and to the parameter values of Table 5), but they can give an indication of the relative importance of these trends.

Table 6 – Effect of the parameter variations for the sensitivity analysis by 2050.

	Average CO_2 emissions from all scenarios by 2050 (Mt)		
	Low	Base	High
Low-carbon electricity	639	602	569
EVs penetration	699	644	466
Vehicle efficiency	660	588	562

A possible future development of this sensitivity analysis can evaluate these parameters with a continuous variation, rather than analysing the discrete values proposed hereby. However, these results already show the range of variability of the CO_2 emissions under these assumptions.

4 – Discussion

The results of the two digitalization scenarios presented in this study show the potential that digital technologies and trends can have on the energy consumption and CO_2 emissions of the passenger mobility. Some potential effects have been included in this study, although the multiple interactions between different aspects (technology, economy, social and cultural behaviours, policies, etc.) may lead to additional effects linked to digitalization.

Analysis of the results

The two scenarios have been defined with the aim of providing an interpretation of two very distinct pathways of digitalization: (1) a shared evolution towards the optimization of the mobility system by exploiting the potential of the support from digital technologies, against (2) a scenario where the benefits from digitalization are exploited to provide additional individual services to the citizens without aiming at an increase of the mobility system efficiency.

The positive effects obtained through the "Responsible Digitalization" scenario are mainly due to the increase of the average occupancy of vehicles, and to a shift from private cars to public transport coupled with active transport modes for the last miles. The RD scenario leads to a decrease of final energy consumption in comparison to the baseline scenario of 9.5% in 2030 and of 25.4% in 2050. Considering the current values, the expected decrease of energy consumption reaches 9% in 2030 and 34% in 2050, thanks to the combination of three main trends: (1) the decrease of the passenger demand thanks to external digital technologies (agile working, digitalization of services), (2) a more efficient mobility system

thanks to the increase of public transport and load factors of vehicles, and (3) the increase of the average vehicle efficiency due to technology improvements. Similar decreases are obtained for CO_2 emissions and primary energy consumption in the comparison with the baseline. Considering GH emissions, in the RD scenario the current estimated value of 830 million tonnes of CO_{2eq} is reduced to 710 Mt in 2030 and 470 Mt in 2050.

A different figure emerges from the "Selfish Digitalization" scenario, where digital technologies are exploited to maximize the individual benefits through a decrease of the cost of private cars and taxis, also supported by a strong AVs deployment. These assumptions lead to an increase of the demand for mobility by car (for users that are currently not allowed to drive) as well as a shift from other modes, especially public transport. The effect is an increase of final energy consumption in comparison to the baseline scenario, up to 6.5% in 2030 and 20.1% in 2050. On the other hand, thanks to the technology improvements mentioned above, the total final energy consumption remains stable to around 2015 levels, with a slight increase of 7% for both 2030 and 2050. The total GHG emissions will remain comparable to current levels in 2030 (832 Mt), and decrease to 766 Mt in 2050 (8% decrease from 2015 level).

These two scenarios represent the potential effect of the trends that are reported in Table 3, with the aim of evaluating the specific contribution of digital technologies with respect to the baseline evolution of energy consumption and GHG emissions. These trends could have different magnitude, leading also to a mix of the two scenarios described above. The potential combinations are countless, and these two pathways are intended as an input for further discussions on these subjects. Moreover, other external parameters may impact significantly these outcomes, as resulting from the sensitivity analysis presented in this work.

The three parameters that have been varied to evaluate the impact on digitalization scenarios are: (1) the share of low-carbon technologies in the electricity generation, (2) the share of electric cars in the total market and (3) the improvement of vehicle performance compared to current levels (i.e. the energy consumption required to transport a passenger for 1 km). The variations of these parameters can have a strong impact on the results of the model, and in some cases, if combined, they may have a larger impact than the digitalization hypotheses themselves (see Figure 12).

These results confirm the complexity of the mobility-energy nexus, by showing the effects of the main aspects that are related to digital technologies. Digitalization itself, like other technology improvements that have arisen and will arise, has not a fixed effect, but rather the potential of bringing positive or negative consequences on the final energy consumption of the transport sector.

Current limitations of the model and future improvements

The aim of this simulation model is to show some potential impacts of digitalization on the energy consumption of passenger transport. For this reason, at the current stage some approximations have been performed, but future activities include the expansion of the model in multiple directions, of which the main could be the following:

- **Area**: the analysis performed for Europe can be extended to other parts of the world, where there are significantly different social, economic, cultural conditions that have an impact on the mobility development in those countries;

- **Freight**: the inclusion of freight transport will allow considering further digitalization trends, both in the direction of e-commerce and virtualization of goods, but also in the digital technologies for logistics and the revolution that will affect distribution chains worldwide;

- **Urban and extra-urban**: this work has been performed on the total passenger transport, but digital technologies have differentiated impacts depending on the travel length/duration. For this reason, a more detailed analysis can be performed by dividing the transport into urban and long-haul trips;

- **Multilevel**: the flexibility of this model could potentially be exploited to perform cases studies at different scales. The application to single cities or local regions could be an interesting test to evaluate the potentiality of this approach;

- **Environmental Impacts:** the model may include in its impacts also an assessment of the local pollutant emissions, by considering proper emission factors related to PM, NO_X and other compounds. However, in comparison with GHG emissions, there is a stronger effect of some drivers that lead to a large variability of the average emissions (e.g. the age of the vehicle, the driving style, the idle times, etc.) which may lead to a significant inaccuracy of these calculations. A dedicated study is needed to evaluate the possibility of including this aspect;

- **Economy**: the model may integrate an economic assessment of the expected costs of each of the solutions of the calculations. The level of detail of the economic investigation will be tightly linked to the choice of including additional aspects related to the supply chain of the mobility sector (such as infrastructure, maintenance, etc.).

These aspects represent the most important directions in which this simplified model could be improved in the future, based on the available resources and the research needs that will arise. Moreover, a continuous tuning of the model can be performed by increasing the quality and reliability of input data, depending on the available statistics from different sources and the need of their analysis and comparison.

Policy indications

Policies will have an important role in supporting and driving the potential role of digitalization in the transport sector. The development of timely and tailored regulations will be crucial to support a "responsible" digitalization, to aim at sustainable mobility models that can support the decrease of GHG emissions and the reduction of air pollution in urban environments. Policies should firstly focus on access to services and opportunities for citizens, while at the same time reducing the unnecessary mobility demand if alternative solutions are available (e.g. smart working). However, passenger transport will remain a central sector for economic development, and digital technologies have the potential to support both an increase

of the quality of the service and to decrease the energy consumption needed to perform it. Three main directions in which policies could play a fundamental role are related to the main digitalization trends considered in this study: (1) the support to public transport systems, (2) the fostering of an optimized use of cars by increasing the average passenger load, and (3) tailored regulations to support the development of autonomous vehicles to solve existing problems rather than add new issues.

The public transport system is currently the more energy-efficient and sustainable solution for passenger transport, especially in urban areas with high population densities. Current urban polices are dealing with problems related to congestions and local pollutants, which are the most important impacts for the citizens. The public transport system could be strengthened by the development of integrated Mobility as a Service platforms, that can provide to passengers an enhanced travel experience and become a tool for mobility planners to improve the current organization and management of the system. However, transparent rules are needed for the development of such platforms, as multiple players are interested to participate in these new business models and proper regulations are needed to avoid monopolies and dominant positions. Policy makers should guarantee competition, but at the same time avoid unnecessary redundancies that would lead to an over-supply of mobility services leading to increased impacts.

This aspect is also strictly related to the sharing mobility business models that are currently evolving worldwide, for which each city is choosing different approaches. Sharing mobility services (i.e. car sharing, bike sharing, scooter sharing, etc.) should be part of the urban transport management system, since their proper integration with public transport can optimize their potential benefits. Moreover, there are already existing examples suggesting that the use of data from sharing mobility systems can become a valuable support for urban and mobility planning. However, to fully unlock the opportunities of data usage, attention must be paid on some related issues, including privacy concerns and data ownership, which may be related to specific National regulations.

While a more efficient transport system will require a decrease of the modal share of cars, parallel actions are required to increase the effectiveness of private car usage. The most critical aspect is the average passenger load of cars, which ranges from 1.2 to 1.5, as already discussed in this work. Strong policies supporting car-pooling, especially for commuters, could lead to a strong decrease of energy consumption as well as congestions. In this direction, digital technologies could provide additional tools to match mobility demand and supply, but incentives are needed to support people towards this choice.

These aspects are strictly related to the car ownership, which in turn depends on the alternative solutions that are available for people. In the current context multiple people, especially outside of the largest cities, rely on private car as the only possibility for fulfilling all their demand needs. This choice, which is also based on cultural and behavioural aspects, may change in future generations, and is strongly related to the available alternatives for matching the mobility demand of the users. Potential alternatives can be based on public transport and sharing mobility services on demand, but a strong push from policies is needed to change the current trend. Moreover, there is a need of coordination at different policy levels, since different actions are required at municipality, regional and national levels.

The future of private car ownership and use is also tightly related to the eventual development of autonomous vehicles. This potentially disruptive technology could dramatically change the transport models on which users are currently relying, and the crucial point will probably be related to the ownership of AVs. Private-owned AVs would potentially result in an increase of use, mileage and passenger demand, with the claimed advantages of reducing parking needs in city centres, but at the same time with the risk of increasing the number of moving vehicles. On the opposite, third-party- or public-owned AVs could optimize their use by matching the mobility supply and demand thanks to optimized algorithms to group people based on their travel needs. Although these evolutions will probably coexist if AVs will be effectively implemented, policies will be crucial to drive their usage towards the aim of optimizing the transport effectiveness and minimizing the impacts. Again, policy makers will be requested to define regulations to anticipate market trends rather than following them, in a rapidly changing technological context. This challenge will probably require an international effort of coordination to avoid solutions limited to single countries, which could lead to strong barriers to potential technology improvements.

Digitalization is increasing the pace at which technology solutions can be introduced into the market, and this is currently happening also in other sectors. Regulations and policies should be in charge of setting the frameworks for an optimal development of human activities in accordance with the targets of environmental, energy and economic sustainability. As emerging from the results of this work, a holistic approach is required to account for all the different aspects involved in mobility planning and management, to avoid potential take-back effects on the very same policy targets.

5 – Conclusions

This working paper provides a general analysis of the potential effects of digitalization trends in the passenger transport in the EU-28. The results show the potential directions that can be driven by digital technologies improvements, based on alternative pathways related to several aspects both within the transport sector and from other sectors. Digitalization includes multiple trends, each of which could have opposite results depending on the outcome of its development.

Two alternative scenarios have been considered, to evaluate the two opposite directions that digitalization could support: a case of responsible digitalization against a selfish digitalization. The former case includes the optimized use of digital technologies towards a more sustainable and efficient mobility system, while the latter represents the effects of increased mobility demand driven by further opportunities created by technology improvements. Real outcomes may lay in the middle of these two boundary cases, which have been chosen to provide to the readers an indication of the potential combined effect of the digitalization trends that have been considered.

Considering the numerical results of this study, the digitalization trends leads to a variability range in comparison with the baseline scenario between +25% and -20% of the final energy consumption in 2050. Similar ranges are emerging for GHG emissions and primary energy consumption. Compared to current results, thanks to the significant improvement of the efficiency of vehicles, the total energy consumption is expected to decrease, or at least remain roughly constant in the worst case. An additional sensitivity analysis has been

performed to evaluate the impact of the variation of external parameters (such as the performance improvements related to technology upgrade, the penetration of electric vehicles and the energy sources mix in electricity generation). The results of this sensitivity analysis highlight the importance of these additional parameters, suggesting that the impacts of digitalization trends will be also strictly related to other aspects from different sectors.

The main conclusions that can be driven by this work can be linked to three main aspects of interest: (1) the dynamic equilibrium between the demand increase and the efficiency improvement, (2) the key drivers in the energy transition and (3) the potential extension of these results to other geographical and cultural environments. These aspects are briefly described below.

Will the increase of travel demand outweigh efficiency improvements?

This dichotomy represents the two main drivers that are responsible of the energy consumption of the transport sector, but the very same question will probably affect other sectors too and it will affect not only the digitalization trends but more generally the expected technological improvements. There is no easy answer to this question, as each single technology could potentially contribute both to increase the quality of a service and consequently trigger additional demand and to improve the efficiency of this service and thus contribute to decrease its energy consumption.

The results of this analysis, based on the hypotheses described in the paper, suggest that the expected technological improvements should outweigh the expected increase in mobility demand, when considering EU-28 countries. However, as it is emerging from the sensitivity analysis, multiple parameters are involved in this result, and thus a significant uncertainty is affecting the possible alternative evolutions of the transport sector. Moreover, due to the complexity of these drivers, in other world regions these results could be significantly different.

A major driver will be related to the total cost of each mobility solution, and thus to the extent to which policy choices will push for energy efficiency and environmental targets. Expected transport system efficiency improvements could be driven both by technological breakthroughs in the vehicle powertrains and by an optimized management of alternative travel solutions for the users. In these contexts, policies and regulations will play a crucial role in supporting sustainable mobility solutions.

Which are the key drivers in the digital transition?

Different digital trends have been considered in this study, including Mobility as a Service, Sharing Mobility and Autonomous Vehicles, as well as the indirect effect of external digitalization trends (e.g. smart working, virtualization of services, e-commerce). While each aspect shows peculiar features, a common characteristic is the possibility of contributing to two opposite directions: a "responsible" digitalization path against a "selfish" digitalization path.

This range of variability is driven by several aspects, involving different stakeholders and multiple areas. The strong weight of policies and economic context has already been highlighted, as well as the importance of the available technological solutions. But cultural and social user behaviours will have a major impact in the choice of available transport solutions, and not all these choices will be easily addressed by tailored policies or economic incentives.

An important aspect that is strictly related to digitalization is the electrification of the transport sector, which is currently strongly supported at multiple levels both from governments and from automotive firms. The aim of this process is the potential decarbonization of the transport sector as well as the decrease of local pollution in cities, which is becoming a major issue in some contexts. On the other hand, electric cars are not providing any advantage for reducing the congestion in cities, which is another key issue, especially during peak hours. For this reason, electrification alone cannot solve the issues that are currently affecting the transport sector, but digitalization can become an effective support if properly addressed by regulations and policies.

A final note should be spent for the potential role of Autonomous Vehicles, as this potentially disruptive technology could have a very strong impact in the entire transport sector in the medium-to long term. AVs should be addressed in time by policy makers, as technology is evolving at a very rapid pace, but multiple side aspects need to be addressed, including the interaction with non-autonomous users of the same tracks, legal responsibilities in case of accidents, regulations and business models for the required infrastructures, as well as urban planning and space organization in cities in a potential scenario in which no more parking areas are needed in the city centres.

How will digitalization deal with access to transport in developing countries?

A final aspect that is worth of interest is beyond the scope of this work, but it has been included as food for thought in the debate on digitalization in transport. As it is happening in other sectors, to which extent developing countries could be able to exploit the experience of Europe and the USA in the evolution of their transport models? No clear indications can be obtained by the results of this study, but some aspects can still be highlighted.

The current situation of many African and Asian countries is seeing a very strong diffusion of mobile services, even faster than the access to other services (such as electricity access). Such a high rate of penetration of mobile services could strongly support several sharing mobility options, such as the possibility of shared ownership of vehicles instead of the traditional single-owner model that has characterized the car marked in the last century in industrialized countries. Pay-as-you-go services are emerging in multiple sectors, and this business model may be of interest also for transport in some countries.

On the other hand, many African and Asian cities are expected to grow at a very strong pace in the next few decades, and mobility will be one of the key aspects to be addressed in the pathways towards smart cities. Public transport systems will be among the first services needed to support an increased access to opportunities for inhabitants, to reduce the existing inequality and pave the way for a sustainable economic development.

Acknowledgements

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