



The effect of digitalization in the energy consumption of passenger transport: An analysis of future scenarios for Europe

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ABSTRACT

Digital technologies have the potential to make the transport system more connected, intelligent, efficient, reliable and sustainable. That is, digital technologies could fundamentally transform how people and goods are moved, with significant impacts on transport demand and on the related energy consumption and environmental impacts. This article proposes a scenario analysis for the future of European passenger transport, by evaluating the potential effects of digitalization on mobility demand, energy consumption and CO₂ emissions under different assumptions. The analysis illustrates that the penetration of digital technologies can lead to opposite effects with regard to both energy consumption and emissions. Two opposite scenarios are compared, to evaluate the effects of a “responsible” digitalization, in the direction of a sustainable mobility, against a “selfish” digitalization, where the final users maximize their utility. The likelihood of these two possible pathways is related to multiple drivers, including users’ behavior, economic conditions and transport and environmental policies. Results show the variability range of the potential effects on energy consumption and CO₂ emissions in Europe by 2030 and 2050, by considering digitalization trends including Mobility as a Service, Shared Mobility and Autonomous Vehicles. The variability of key parameters is evaluated in a dedicated sensitivity analysis, where the effects of electric vehicles, electricity generation mixes and vehicles’ efficiency improvements are assessed. The article concludes that in order to fully exploit the advantages of digitalization, proper policies are needed to support an efficient and effective deployment of available technologies through an optimized and shared use of alternative transport options.

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1. Introduction

Fossil fuels consumption is the first cause of climate change. Among different sectors, transport is currently the most reliant on fossil fuels, and specifically on oil (IEA, 2019). Transport thus represents a key bottleneck in the transition towards a low-carbon economy. And decarbonizing transport is challenging, due to the issues related to guarantee the high energy density allowed by fossil fuels by using alternative energy sources.

There is a growing interest in analyzing the potential scenarios of transport decarbonization in different countries, including China (Pan et al., 2018; Wang et al., 2017), Europe (Siskos et al., 2018; Xylia and Silveira, 2017), United States (Zhang et al., 2016) and South

America (Espinosa Valderrama et al., 2019; Rehermann and Pablo-Romero, 2018). Different technologies are considered in the literature for the transition towards a low-carbon future in the transport sector, including electrification (Bellocchi et al., 2019; Crozier et al., 2018), biofuels (Hunsberger et al., 2017) and hydrogen (Ajanovic and Haas, 2018). Multiple factors will have a role in the success of each solution, starting from the costs of the vehicles and the required infrastructure (van der Zwaan et al., 2013), as well as the quality of the service (Mugion et al., 2018). Due to the strengths and weaknesses of each pathway, an optimum scenario may include a combination of technologies to be used in specific applications (Dalla Chiara and Pellicelli, 2016). Financial incentives may be required to reach the best technology mix for the decarbonization of transport (Haasz et al., 2018).

In this process of decarbonization, digital technologies may represent a game-changer, fostering the deployment of innovative mobility solutions and technologies. Mobility as a Service (MaaS)

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(Liimatainen and Mladenović, 2018) and Shared Mobility (Burghard and Dütschke, 2019; Ma et al., 2018), supported by innovative business models (Guyader and Piscicelli, 2019), may represent a paradigm shift to take mobility to another level (Mulley et al., 2018). The strongest impact is expected from the development of Autonomous Vehicles (AVs), which may have disruptive effects on energy consumption and greenhouse gas (GHG) emissions both towards an increase or a decrease, depending on the scenario (Greenwald and Kornhauser, 2019). Setting the right policy frameworks will be crucial to favor a sustainable use and deployment of digital technologies, with the aim of unlocking their potential in optimizing the mobility models and the available transport modes, rather than allowing additional transport demand to rise without control.

This article provides an evaluation of potential energy consumption scenarios for the European Union (EU), to assess to which extent alternative digitalization effects may impact the transport sector. This article focuses on passenger transport, which is likely to be the first transport segment to be affected by digital technologies. The aim of this article is to present some insights on the potential weight of digital technologies in shaping the future energy demand of transport, by evaluating to which extent their development may evolve towards a more sustainable mobility or rather towards an increase of the mobility demand, thus increasing the energy consumption.

While research studies have investigated specific aspects of some digital technologies, including Mobility as a Service (Smith et al., 2018), autonomous vehicles (Liu et al., 2019; Ross and Guhathakurta, 2017) as well as shared mobility (Kawaguchi et al., 2019), there is no study so far on the combined effect on digital technologies in the transport sector. Moreover, the available literature works are generally limited to specific case studies at country level or in cities, presenting results and conclusions that are not always extendable to other contexts.

Therefore, the originality of this research does not lay on the model itself, which is in line with the common approaches used in energy balance analyses, but rather on the effects that digital technologies may have on multiple model parameters. Such parameters include the modal distribution, the use of specific technologies and the average load factors. This is the element of novelty of this article, and thus its added-value vis-à-vis the established literature.

The article is structured as follows. Section 2 presents a literature review on the main contributions related to digitalization in transport. Section 3 presents the methodology, together with the main assumptions at the basis of the scenarios that are presented in this study. Section 4 presents the results of the study, which will be discussed in Section 5, where policy implications are also presented. Finally, section 6 summarizes the main conclusions of this study.

2. Literature review

2.1. Digitalization and transport

2.1.1. The impact of digitalization on passenger road transport energy consumption

Two definitions of digitalization can be found in the literature. In general terms, digitalization refers to the transformation of objects from physical to digital state, enabling communication and interaction between them. More specifically, digitalization refers to the convergence of the real and virtual worlds, that is enabled by information and communication technology (Kagermann, 2015). Scholars distinguish four waves of digitalization: the introduction of computers in the 1990s, the advent of the internet, the advent of

mobile internet, and finally the fourth – currently ongoing – wave, known as the advent of the Internet of Things (IoT) (Davidsson et al., 2016). With this wave, the objects that compose passenger road transport, i.e. vehicles, will be able to share information between them and to be inter-operable. In the case of passenger road transport, only this fourth wave is likely to have a significant impact on energy consumption.

In particular, the effects of IoT on the use of energy in passenger road transport can be either direct, i.e. the use of digitalization directly improves the energy efficiency of the vehicles, or indirect, i.e. digitalization leads to a decrease in the distance travelled by the vehicles all else being equal - e.g. through an increase in the proportion of journeys being done with the public transportation systems or by vehicle-sharing.

2.1.2. Direct effect: autonomous driving and algorithms maximizing energy efficiency of vehicles

The literature highlights two important technological enhancements that are going to significantly reshape the automotive industry and have a direct effect on the energetic consumption of the vehicles: autonomous driving and the use of algorithms to optimize driving behaviors (International Energy Agency, 2017). Of course, those two technologies are linked in the implementation, since autonomous driving allow to optimize driving parameters by replacing the human driving by an algorithmic one. Autonomous driving is probably one of the most spectacular technological enhancement of the road passenger transport to come. When it comes to energy saving, autonomous vehicles (AVs) are expected to decrease the travel times by picking-up the best route and to minimize the fuel consumption by driving more smoothly (Fagnant and Kockelman, 2015), minimize breaking-acceleration phases (Barth and Boriboonsomsin, 2009). Indeed, eco-driving is likely to be one of the key features of algorithmic driving. However, it has to be noted that the adoption of digital technologies in vehicles, especially the Internet of Things (IoT), will depend on the availability of low-cost hardware and components, such as sensors, that will be able to support long-distance wireless data communication (McKinsey & Company, 2015).

Another, and perhaps less intuitive possibility offered by those technology is the use of the platooning, which refers to the practice of multiple vehicles following one another closely. It leads to significant reductions in aerodynamic drag (Wadud et al., 2016). This aspect is expected to bring significant advantages mostly in freight transport, since the coordination of autonomous trucks in highways, but the impact of truck platooning on traffic flow and safety on highways is still unclear (Yang et al., 2019).

Experts generally expect partial autonomous driving to be put in place over the next decade, while the future outlook for fully autonomous vehicles remains highly uncertain. Scholars tend to expect the majority of potential energy-reduction benefits to be realized with partially automated vehicles, and identify some major energy/emission downside risks at full automation (Wadud et al., 2016). The energy outcome of vehicle automation thus remains deeply uncertain, with considered future scenarios ranging from dramatically higher to significantly lower energy consumption. However, as the agents seek to maximize their utility function and therefore follow the best case for business, pessimistic outcomes are unlikely (Greenwald and Kornhauser, 2019).

2.1.3. Indirect effect: digitalization leading to a decrease in the distance travelled by the vehicles - all else being equal

A typical example of the impact of car-sharing through IoT applications is given by the taxi fleet. Autonomous taxis, which communicate with the user smartphones or other devices and would pick and drive clients in an allegorically-optimized manner.

In particular, the impact on energy efficiency is due to two effects: the reduction of the size of the vehicles resulting from trip-specific autonomous taxi deployment, and a higher annual distance per vehicle travelled, which increase the vehicle cost-effectiveness (and therefore the energy used to build it) (Greenblatt and Saxena, 2015). Individual vehicles can also be operated in the car-pooling mode. As a matter of fact, whether automobile vehicles have a positive or negative impact on energy consumption will depend on the extent of car-pooling. When individual vehicles are operated as a fleet, car-pooling will reduce fares and therefore there has a clear economic incentive. Together with the use of sophisticated algorithms, it can reduce significantly deadheading and therefore energy consumption (Greenwald and Kornhauser, 2019). In terms of the vehicles-miles travels (VMT), a network analysis conducted across the USA computed that car-pooling could decrease the VMT by approximately 30%. The authors of the studies even reveal that this positive impact would also exist in rural areas (Magill, 2018).

On the other hand, a strong diffusion of private automated vehicles driven by low costs could lead to a significant additional mobility demand both for current users, since many drivers would prefer to be driven and would be driven more than they would drive (Greenwald and Kornhauser, 2019), and for additional users groups (Chen et al., 2019). Moreover, AVs will also show an uncertain share of trips without passengers, especially if parking lots will be moved from densely populated areas to the outskirts of the cities. This aspect may become an advantage for land use in urban areas, but at the same time become a rebound effect for energy consumption and climate change impacts.

Another particular interest of vehicles using IoT technologies is the possibility to dramatically reduce congestion and traffic jams, which account for a significant part of both the fuel over-consumption and city atmospheric pollution (Davidsson et al., 2016). Similarly, IoT communication between car is likely to lead to a significant improvement of performance during the parking phase, the vehicle become able to find an empty slot and preventing the driver to circle around (Davidsson et al., 2016; Wadud et al., 2016).

When it comes to public transport, one of the most promising application is the optimization of the routes and timetables of public transport, in real time. Indeed, in spite of a rigid system comprised of vehicles picking up users in predefined stations at predefined times, regardless of the affluence and the journey plan of the user, automated and algorithm driven public transport vehicles communicating with each other can work in a more dynamic and efficient way. Again, a potential rebound effect is the increased demand that could be caused by more convenient and cheaper mobility services, although shared, with consequences on the total energy consumption of the sector.

Moreover, IoT is likely to enable information sharing between private vehicles and public transportation systems, therefore encouraging and facilitating the multimodal journeys, that is the use of a public transportation system for part of the journey in spite of using only the private vehicle. In this way, by increasing the attractiveness of public transportation system, IoT technologies application in road passenger transport can significantly reduce the in-direct emission of non-public transport system (Davidsson et al., 2016). In particular, the possibility to do last-mile trips with automated vehicle could increase public transport use, notably in commuting situations (Greenwald and Kornhauser, 2019). A study done through survey calculated that user in major US cities would decrease their bus use by 6%, their light rail use by 3%, but increase by 3% their commuter rail use (Bliss, 2017).

2.1.4. Quantitative assessment

When it comes to quantitative assessments, the majority of studies do not focus on the energy gain due to the digitalization, but

they include in their calculation the increase proportion of electric vehicles. As an example, the use of an electric and autonomous taxi fleet on the US would lead to in decreased US per-mile GHG emissions in 2030 per AT deployed of 87–94% below current conventionally driven vehicles, and 63–82% below projected 2030 hybrid vehicles (Greenblatt and Saxena, 2015).

Regarding the difference in fuel-efficiency between human and algorithmic driving, the impact has been calculated to be up to 10%, without taking into account the reduction of driving distances due to car-sharing and optimized routes (Mersky and Samaras, 2016). Some experts even use the figure of 10–20% (Barth and Boriboonsomsin, 2009). Moreover, when it comes to IoT the network effects resulting from the fact that vehicles do not optimize only their own utility function, in term of efficiency, but the one of the entire network can make the attempt of quantification hazardous in the absence of tangible experience of large-scale experimentation for the moment (Davidsson et al., 2016). Finally, a study which forecast a smaller share of car-pooling find that vehicle automation (alone) could lead either to a 60% decrease in fuel use or to a multiplication by 3 (Stephens et al., 2016).

As long as autonomous vehicles are concerned (Chen et al., 2019), evaluate the potential impacts of automation on fuel consumption in the US, resulting in a significant variability across scenarios, between a 45% reduction and a 30% increase. The researchers highlight that government guidance or regulations on autonomous and shared mobility services are needed to mitigate the risk of induced travel demand due to automation. The importance of regulation in the transport sector to limit environmental impacts is an aspect that has already been confirmed by multiple research works (Greenwald and Kornhauser, 2019; Macmillen and Stead, 2014).

3. Methodology

This section describes the model that is at the basis of this work, together with the main hypotheses that have been chosen for the definition of alternative future scenarios. The first subsection is dedicated to the description of the model itself, with particular attention to the parameters that are used and the mobility demand that is derived from historical trends. The second subsection is focusing on the baseline and digitalization scenarios that are compared, while the last one illustrates the hypotheses used for the sensitivity analysis that is performed on the most influential parameters.

3.1. Description of the model

The analysis that has been carried out in this work has the aim of connecting the demand for transport with its energy consumption and other derived impacts (including fossil primary energy consumption, CO₂ emissions and local pollutants 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 passenger 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 impacts of the transport given its demand. Through the definition of proper parameters, multiple indicators can be calculated, including final and primary energy consumption, CO₂ emissions, share of renewable energy sources, other pollutants emissions, etc. The transport demand is an input to the model, and its future trends have been defined in accordance with historical values and evolution scenarios from different literature sources.

The logic of the model is based on a calculation of the impacts (final and primary energy consumption, GHG emissions) of a

defined mobility demand, which may be disaggregated based on specific categories (i.e. the year, the transport mode and the energy source). For each combination of categories, proper parameters are required, including efficiency and load factor, while other parameters depend only on a subset of categories: primary energy and GHG emission factors are specific for each fuel (and possibly vary over years for some energy carriers), but not on the transport mode. The model uses exogenous data on the transport demand, and the final energy consumption is calculated by multiplying the demand (in passenger-km) by the proper parameters.

For each transport mode and each energy vector (mostly fuels, but also electricity), the final energy consumption $E_{m,v}$ is calculated with equation (1):

$$E_{m,v} = \frac{D_m \cdot f_{m,v} \cdot e_{m,v}}{I_m} \quad (1)$$

Where D_m is the mobility demand for each mode (in passenger-km), $f_{m,v}$ is the share of each energy vector in any specific mode, $e_{m,v}$ is the specific energy consumption of the vehicle (in MJ/vehicle-km) and the denominator I_m is the average load factor of the vehicle (in passengers/vehicle).

While these factors are here used as average values, they show a very large variability that in turn depends on several additional aspects. For instance, the specific consumption of a gasoline car may be considered with an average figure, but huge variations are due to the size of the vehicle, its age, the driving cycle and user behavior (including average speed but also frequency of accelerations/decelerations, stops, etc.), the engine technology and the year of construction, etc. In a similar way, the load factor of the vehicle is affected by the purpose of the trip, its length, the characteristics of the users, and so on. The current application of the model is considering average values, that are already weighted on an EU basis to account for all the parameters that may influence it. This is a necessary approximation to avoid an excessive complexity of the model, which would also require several input data that are not always available with the necessary level of detail.

The calculated final energy consumption can be aggregated either by mode or by energy carrier, depending on the application of the outputs. From the final energy consumption, other impacts can be derived, including the CO₂ emissions and the fossil primary energy, as will be better described in section 3.1.2.

The current version of the model has the goal of providing a general assessment of the energy consumption of the passenger transport in the EU, by considering average values for a number of parameters. The model is not able to calculate any optimization scenario, since it has been built with the aim of evaluating the effect of specific choices and hypotheses. To provide synthetic and aggregate results on such a wide and heterogeneous region, the model is not capable of capturing the significant complexity of the sector: while it can be used to provide a general overview, it lacks the possibility of evaluating local phenomena and impacts, including congestion, urban planning, load profiles of mobility demand, geographical distribution of the traffic flows. Moreover, no economical evaluations are currently integrated into the model, although they will be part of a future implementation.

3.1.1. Model input: passenger transport demand

The historical information for passenger demand used as a basis in this work is available from European statistics (expressed in “passenger km”, or pkm) divided per transport mode (EU-Eurostat, 2017). Fig. 1 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 (which corresponds to a 25% increase over two decades). 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.

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, 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 et al., 2018), where estimated cycling data is available for almost all EU countries, and walking data is available for a limited number of 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 for walking 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, 2017a), where a split by fuel for passenger cars and medium and heavy commercial vehicles (including buses) is provided for each 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). Electric cars are gaining momentum, and updated statistics show a significant increase in last years: 287,000 electric vehicles have been sold in Europe in 2017 (+39% on 2016), being the second market worldwide after China (Energy and 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, 2018a).

3.1.2. Model parameters

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

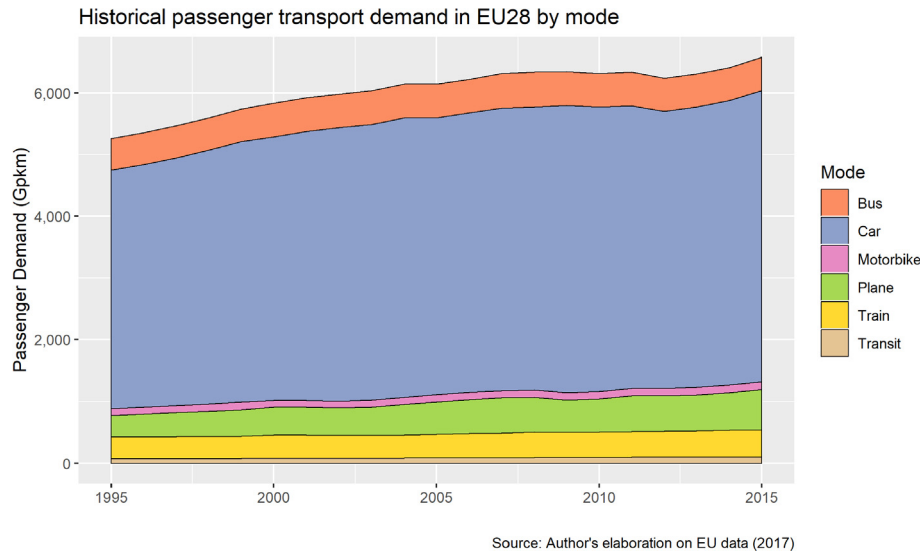


Fig. 1. Passenger transport demand in EU28 by mode. Authors' elaboration from (EU-Eurostat, 2017).

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 for the vehicles, nor the energy required for the building and maintenance of the infrastructure. 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 CO₂ 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-fuelled 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.

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. 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). 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. Occupancy is generally lower on commuting trips, with values that are often lower than 1.1, while in leisure trips the load factor is usually higher. 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 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 et al., 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 CO₂, CH₄ and N₂O, 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 1, 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.

3.2. Future scenarios

Different scenarios have been defined to evaluate the effect of digital technologies: a baseline scenario will be used as a benchmark to compare two opposite pathways in which digitalization may evolve. To separate the effect of digitalization trends, the parameters that are not directly affected by digital trends in transport (e.g. CO₂ emission factors, vehicle efficiency, etc.) will remain the same over the three scenarios.

3.2.1. Baseline scenario

Thanks to the availability of a consistent 20-years historical trend, the baseline scenario has been built by extrapolating 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 Fig. 2, with a total of 7757 billion passenger km in 2030 rising to 9616 in 2050.

These values can be compared with the results from other studies, of which the most detailed are the EU Reference Scenario 2016, published by 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

Table 1
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 (gCO ₂ eq/MJ)	Total EF (gCO ₂ eq/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

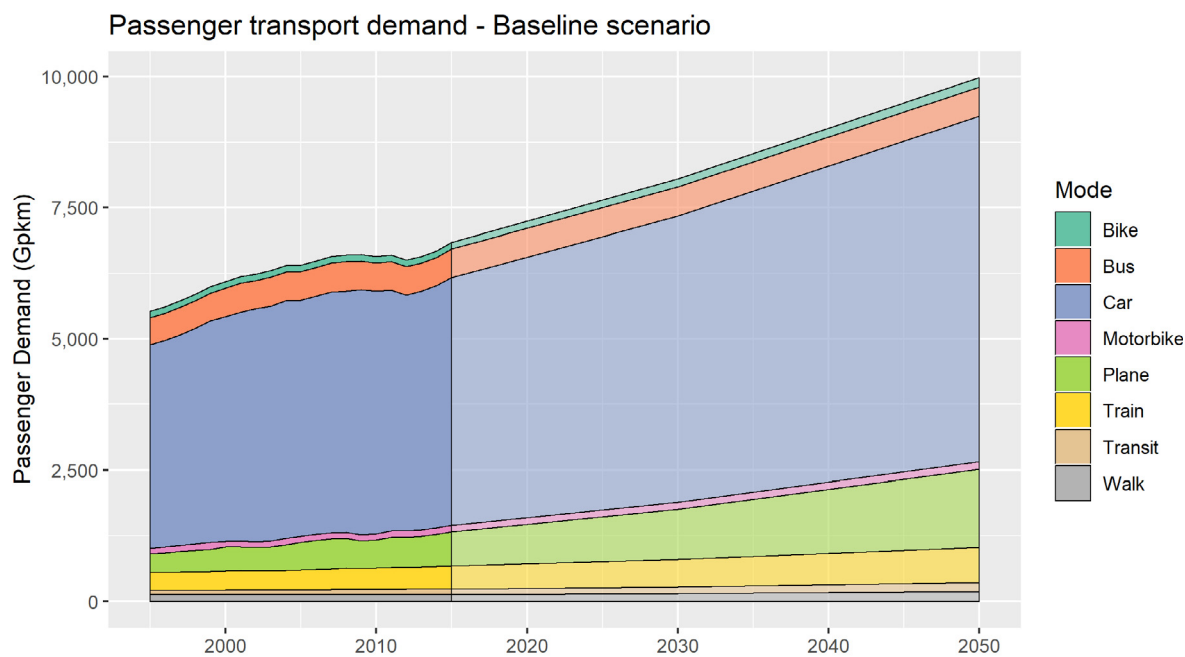


Fig. 2. Passenger transport demand in EU28 – reference scenario. Authors' elaboration from (EU-Eurostat, 2017).

2015-value of 6056 Gpkm in spite of the official value of 6602 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). The aviation demand considered in this study 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.

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 variability 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 up to 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, which can show significant variations across countries

and regions (Liu and Lin, 2018), and some authors provide 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, 2018b). This fleet replacement 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.

Finally, the values of primary energy and emissions factors related to different pathways (reported in Table 1) 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.

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 1 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, published by (European Commission, 2011).

3.2.2. Digitalization scenarios

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 in EU official studies, when considering the final energy consumption of passenger transport (Capros et al., 2016). 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 each digital technology that has been considered.

The potential effects of digital technologies have been grouped in three main areas, that have been referred to as Mobility as a Service, shared mobility and autonomous vehicles. While there may be some overlaps (e.g. in the future AVs may be part of a car-sharing system), this distinction has been chosen to highlight some peculiar trends. Additionally, some effects of digital technologies outside the transport sector have been accounted for. Mobility as a Service is a mobility model that is starting to be applied in different cities, and it is relying on the availability of a live digital platform that is able to provide the users with a real-time comparison of the multiple options that are available for any given trip. The integration of all the available transport solutions in a single platform, together with the data collected from vehicles, will further increase the user experience and at the same time provide additional information for the optimization of the traffic management. Shared mobility options, which may benefit from an integration into a MaaS system, will be strengthened with the availability of operational data allowing more detailed forecast models based on analytics. The potential deployment of autonomous vehicles will totally rely on IoT solutions, since vehicles will need to have access to updated information while at the same time providing operational data to the other objects around them.

The specific effects for each digitalization trend are listed in Table 2. These assumptions have been estimated based on the limited number of studies performed so far on real cases, due to the early maturity of these technologies and their limited penetration in comparison with traditional transport solutions. Thus, the aim of the authors is to define a set of reasonable assumptions that can be the basis for evaluating the effect of digitalization trends on the energy consumption of the transport sector. The focus has been put more on the indirect effects, i.e. on the changes in transport demand, modal shares and average load of the vehicles. However, the direct effects are included into the analysis in the evolution of the specific consumption of vehicles, which is expected to improve significantly thanks to a number of technological improvements. Moreover, this parameter will be also examined with greater detail in the sensitivity analysis.

The assumptions for each digitalization trend have been defined based on their main contribution to the parameters involved in the model. Some assumptions represent the net effect of different phenomena, due to the need of limiting the number of hypotheses to obtain relevant results. The central point for MaaS and Shared 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

Table 2
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).
Shared 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 @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.

different market segments. The hypotheses for the SD scenario are consistent with the ranges defined by (Chen et al., 2019), both for the increased mileage and for the new users that can travel with AVs.

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 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 this study.

3.3. Sensitivity analysis

The results of the simulation are based on multiple assumptions, as discussed in the previous 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 3 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 4.

Table 3
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%

The share of low-carbon electricity generation is directly related to the GHG emission factor of the EU power system, which has an increasing impact with high penetration of EVs. Both these parameters are affected by high uncertainty, but they will be crucial for the decarbonization of the sector. The range of variation for power generation has been defined by considering reasonable hypotheses based on the historical evolution of the system, considering the current push towards decarbonization in the EU, and the related emission factors have been calculated. The potential penetration of EVs is much more difficult to predict, since they are at the very beginning of their development, but the upper bound has still been set to 100% of new cars sales by 2050, due to the current development of both policies and manufacturers' strategies to phase out traditional vehicles.

A final aspect is related to the improvement of vehicles efficiency, in particular private cars. The base assumption has been related to the estimations from (Heywood et al., 2015), as discussed above. However, this parameter may have a crucial impact on the results, and the evolution of car performance is related to multiple factors (including technological progress, manufacturing, users' behaviours and choices, costs, etc.), resulting in a high uncertainty. The range of variation of this parameter has been set between 25% and 60% in comparison with the current performance (considering the new cars sales).

4. Results

4.1. Evolution of the transport demand

The evolution of passenger demand by mode is reported in Fig. 3. 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

Table 4
Parameters variations for the sensitivity analysis.

	Parameter	Year	Low	Base	High
Low-carbon Electricity	Electricity GHG emission factor (kgCO ₂ eq/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%

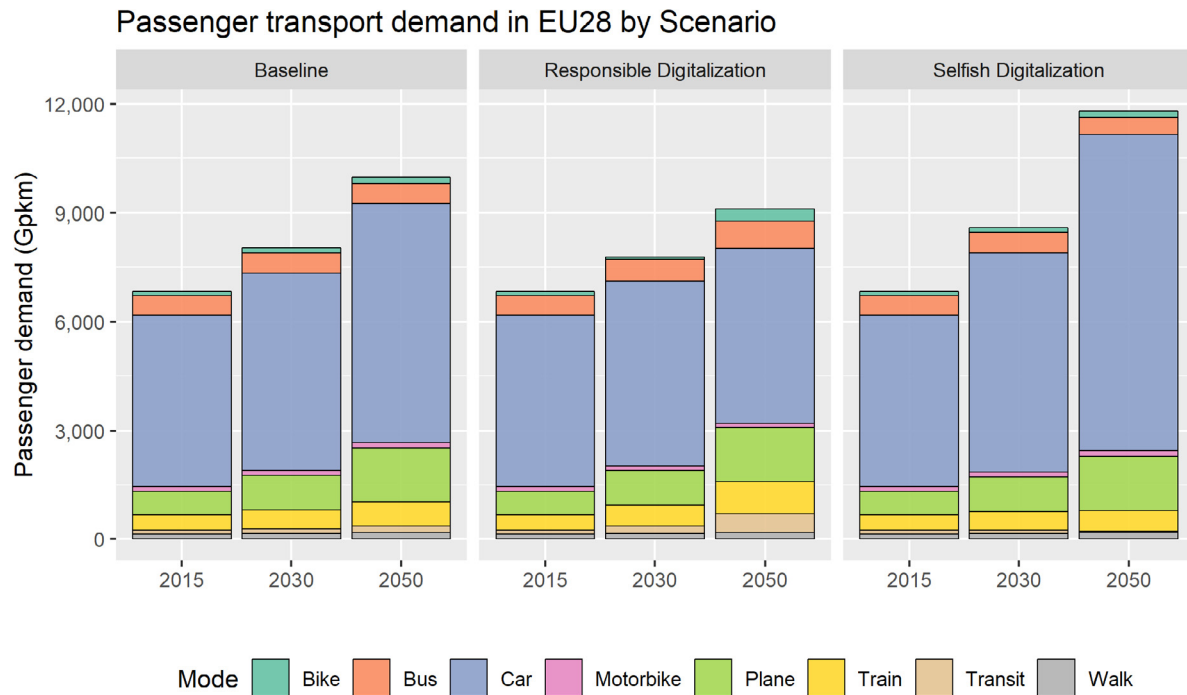


Fig. 3. Comparison of passenger transport demand by mode in different scenarios.

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 (Fan et al., 2017), where the lower population density is generally limiting the benefits that can be reached through shared 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.

4.2. Energy consumption and CO₂ emissions

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 Fig. 3) 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 Fig. 4 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 counterbalance 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.

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

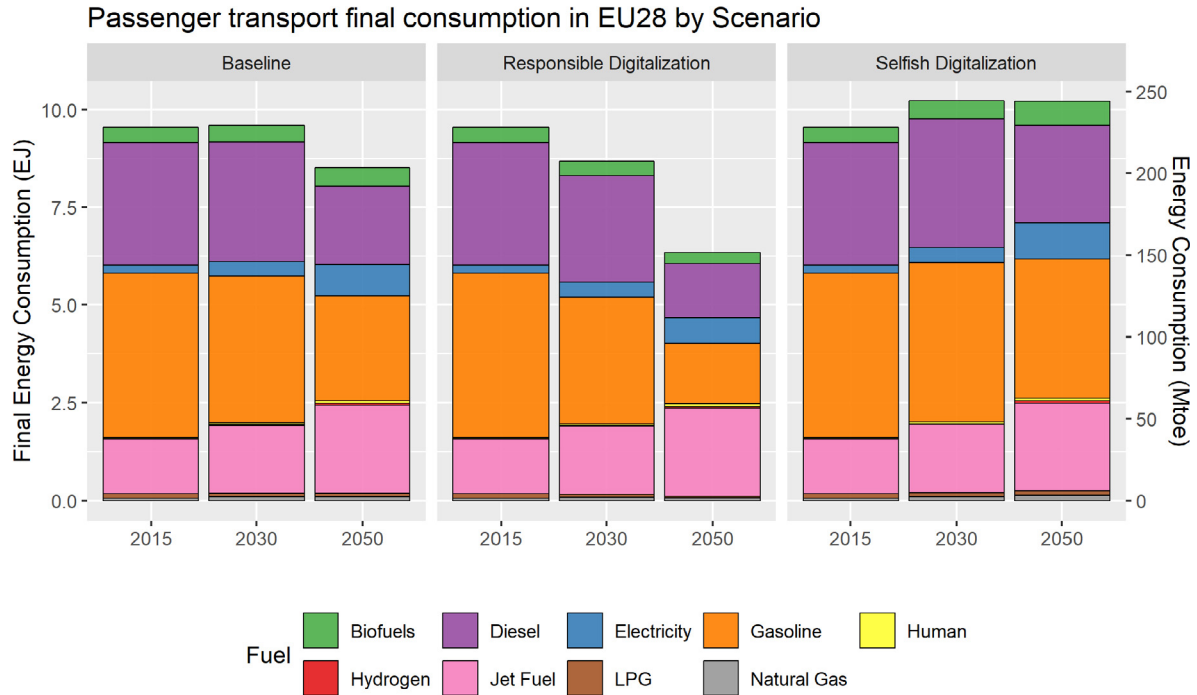


Fig. 4. Comparison of passenger final energy consumption by source in different scenarios.

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 Fig. 5 are in line with those related to final energy consumption, although some differences are related to the specific emissions for each energy source (see Fig. 6). 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.

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

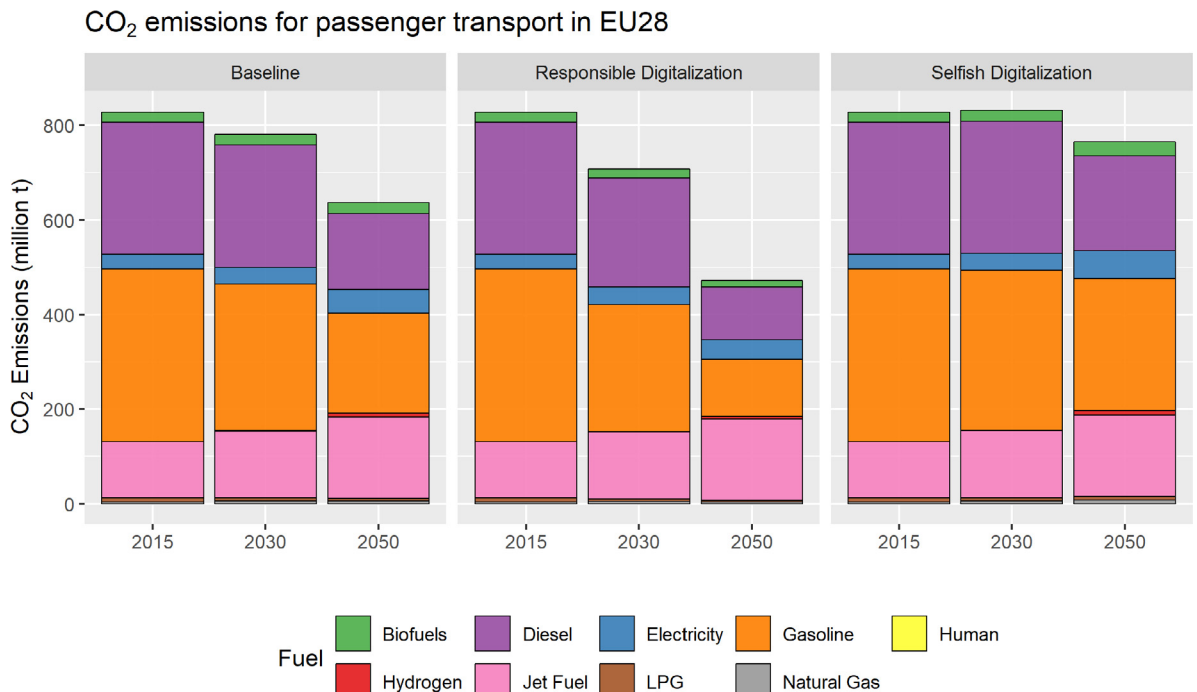


Fig. 5. Comparison of CO₂ emissions by source in different scenarios.

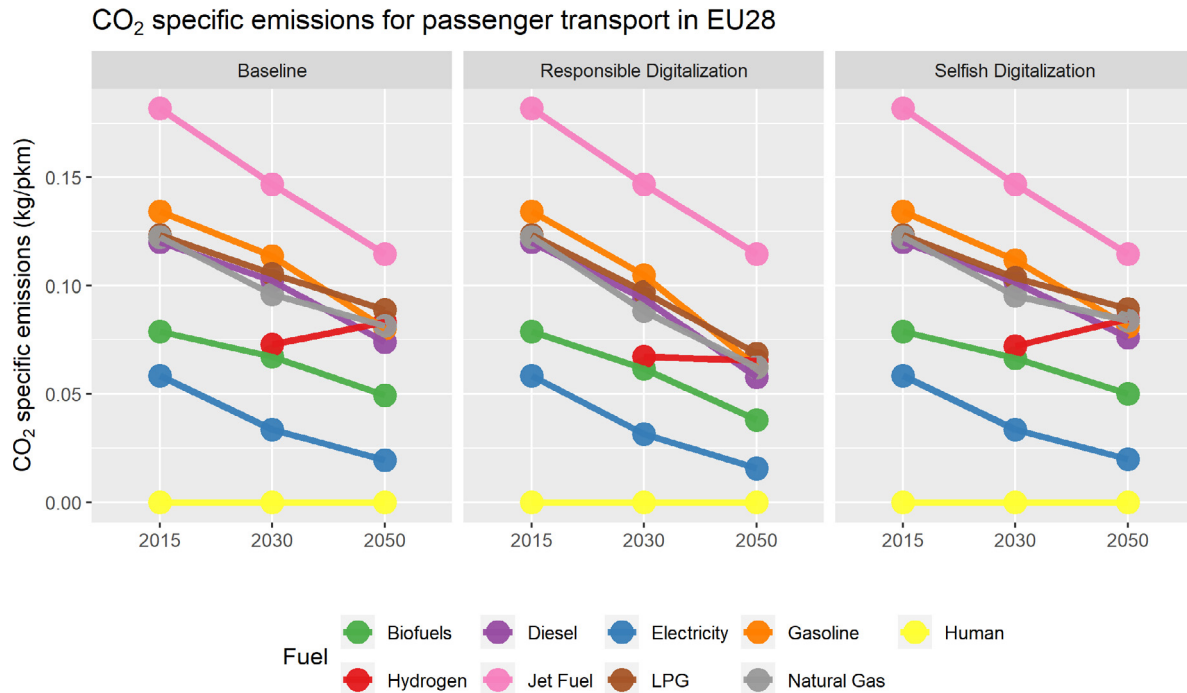


Fig. 6. Specific CO₂ emissions by source in different scenarios.

limited applications, the increase of its specific emissions is related to the hypothesis of transition from steam reforming to electrolysis supplied by grid electricity, 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 technologies that rely on renewable electricity, 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.

4.3. Results of the sensitivity analysis

A compact representation of the results obtained from the sensitivity analysis is reported in Fig. 7. Each colour represent a scenario (i.e. Baseline, SD and RD), while each line has been calculated by applied different values to the parameters chosen for the sensitivity analyses (see Tables 3 and 4). The variability of each scenario is 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 in the focus of this work. At the same time, the effect of each variation of the parameters in the sensitivity analysis has similar effects on the three scenarios, although in some cases it may have a larger impact.

A further comparison of the effect of these parameters can be drawn from Table 5, where the average of total CO₂ 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 3 (and to the parameter values of Table 4), but they can give an indication of the relative importance of these trends.

5. 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 CO₂ emissions of 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.

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 CO₂ 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

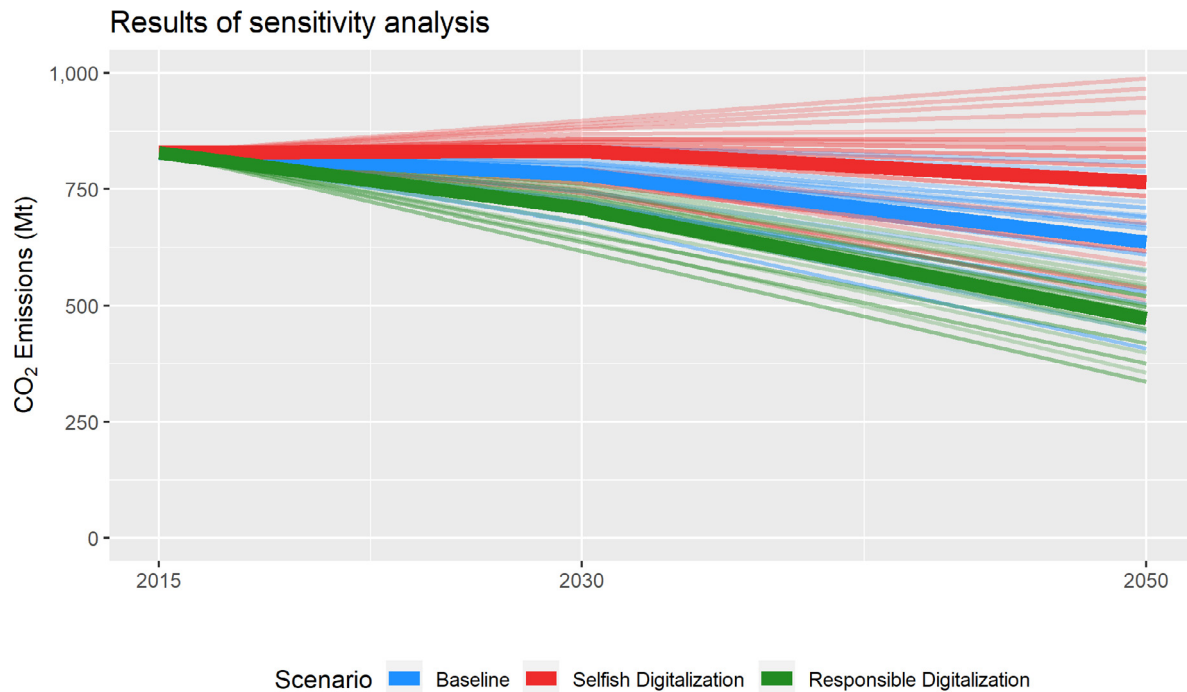


Fig. 7. Results of the sensitivity analysis.

Table 5
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

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 2, 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 numerical results of this work are strictly related to the assumptions and the approximations described above, since several aspects are involved. For this reason, we believe that these outcomes may be a useful basis to develop a discussion of these

topics, but further research is needed to improve the quality of some assumptions, in particular for the technologies that show a lower maturity, leading to a higher uncertainty for their future evolution. However, we believe that the differences across scenarios can provide useful insights to highlight some of the main aspects that are involved in transport planning and environmental policies.

A final remark is related to the fact that other aspects may affect the future of passenger transport, including users' behaviours and the availability of new transport modes, such as the electric scooters that are rising in large cities in the last few years. Multi-modal trips in cities could be the key to an evolution from the current model based on private car. Also, alternative ownership models may definitely impact the number of passenger vehicles circulating in European cities, with additional effects on congestion and land use. Moreover, while much attention is currently focused on electric vehicles, some experts believe that hydrogen has an even stronger potential due to some specific advantages.

5.1. Policy implications

In Europe, to fully exploit the advantages of digitalization also in terms of transport decarbonization, proper policies must be put in place. In particular, to ensure that a "Responsible Digitalization" scenario materializes rather than a "Selfish Digitalization" one, sound policy frameworks are needed to promote the increase in the average occupancy of vehicles and the shift from private cars to public transport, coupled with active transport modes for the first- and last-kilometers.

Digital applications such as smartphone apps can allow information about transportation services from public and private providers to be better combined through a single gateway that creates and manages the trip, for which users can pay via a single account (International Energy Agency, 2017). Such solutions are already being introduced in European cities. For instance, Vienna introduced in 2015 the Smile platform, a smartphone app combining

various means of transportation such as underground, train, bike and e-car sharing. According to a survey carried out by the Vienna University of Technology, the platform fostered a more environmentally friendly mobility behavior. Half of the survey's respondents indeed stated that since using the app they have used public transport more often, while a quarter of them stated to have used private care less frequently (Smart City Wien, 2015). Such new approaches could help overcome a major comparative disadvantage of public transport – the longer door-to-door travel times – which mainly arise from the first and the last mile in the transport chain (Davidsson et al., 2016). On its side, the environmental impact of freight transport could be reduced by promoting a switch from road to rail and maritime, and including the environmental cost of transport in the final purchase price of goods (Blauwens et al., 2006). Another way to promote this switch is to close gaps, remove bottlenecks and eliminate technical barriers that exist between the rail networks of different countries. For instance, in order to develop a Europe-wide infrastructure network, the EU has established the Trans-European Transport Network (TEN-T), a policy which includes the implementation of cross-border railway lines. The implementation of this policy is crucial to promote an effective modal shift in freight transport and thus to also improve air quality. Preliminary estimates indicate that implementing cross-border railway infrastructure and other TEN-T measures could reduce EU GHG emissions by about 7 million tons between 2015 and 2030 (Versini, 2017). But all this is challenging, as reducing demand for transport means changing people's daily habits and taking an integrated policy approach. The policy issue is particularly relevant here, considering that road transport in Europe is governed by a complex series of policy frameworks developed separately at different levels – cities, national and EU. And national and local policies on taxation, infrastructure choices and other matters seem to determine road transport demand. For example, Belgians used 741 kg of oil equivalent of diesel and gasoline in 2016, which was 30 percent more than the EU average, while Germans used 623 kg and French drivers only used 581 kg (Tagliapietra and Zachmann, 2018). At the same time, digital technologies and big data can become a valuable tool supporting the definition of more accurate transport policies (Paffumi et al., 2018).

Cities are responsible for a wide range of transport policies, such as public transport, enabling car-sharing, congestion charges, parking management and cycling and walking zones. EU countries have different transport taxes and charges, and different policies in relation to the development of transport infrastructure and the creation of alternatives to road transport for freight and in urban areas (ACEA, 2017b). On top of this, the EU has developed a wide range of policies aimed at making European transport systems more connected, competitive and sustainable (European Parliament, 2019).

Such a fragmented governance framework risks impeding the unleash of the potential of digitalization to decarbonize transport in Europe, as policy measures implemented at the various levels without coordination can neutralize or even hinder each other. For this reason, more efforts should be done to create a coherent European policy framework for transport, aimed at promoting policy consistency between various levels and at exploiting potential synergies.

For instance, as transport becomes increasingly digitalized, questions about vehicle and software certification, liability, cybersecurity, data privacy, and employment will need to be addressed. To do so, harmonization and standardization of communications and data protocols will play a key role. Policies can also push automated and connected mobility solutions towards lower energy use and emissions, for instance through a gradual introduction of distance- and congestion-based pricing aimed at moderating potential rebound effects stemming from high levels of automation.

Another key policy issue relates to transport taxation. This indeed represents a key policy tool to reshape passenger transport, as different taxes apply throughout the transport system, from the initial purchase of a vehicle, to ownership taxes (e.g. annual registration tax, company car taxation) and usage taxes (e.g. taxes on fuel, tolls, road-space, parking, commuter tax deductions) (Green Fiscal Commission, 2010). These taxes can be used to influence user decisions, and possibly also to influence the automotive industry's strategies. For instance, to promote the deployment of clean and connected vehicles, taxes can be differentiated on the basis of vehicles' carbon emissions, or simply allow for deductions or other special provisions (e.g. subsidies, grants, tax credits, tax exemptions). European countries still have very different transport taxation regimes. For example, only ten countries take into account CO₂ emissions in the composition of their vehicle registration taxes (ACEA, 2017b). Fuel cost savings – which largely arise from the different taxation of gasoline and electricity – can for instance provide electric vehicles with an important cost advantage. Savings are significant in Norway where running an electric vehicle can cost 64 percent less than running a diesel or petrol vehicle. In Germany, by contrast, the difference is only 25 percent (Lévay et al., 2017). Given the importance of taxation in delivering transport decarbonization also via digitalization, a greater coordination at the EU level could be highly beneficial. For this reason, the EU could seek from its Member States a mandate to act in the field, as already being done in the field of digital taxation (European Council, 2017).

6. Conclusions

Digital technologies have a significant potential in shaping the future energy demand of passenger transport. This article presented an analysis of possible scenarios for the EU, with the aim of highlighting the main aspects that are involved in the digitalization of the transport sector. The work was structured on the application of a model based on a wide range of data from different sources to evaluate the impacts of passenger transport in terms of both energy consumption and GHG emissions. The choice of focusing on the European Union allows to obtain useful information on the potential effect of digital trends at a macro scale, but at the cost of being unable to represent the significant variability that arises from a country to another.

Alternative scenarios were considered, by comparing the positive and negative potential of digital technologies with respect to a baseline scenario. The results shown that digitalization may have a significant impact on the energy consumption of the sector, as well as its GHG emissions, by affecting the modal shares, occupancy rates and future transport demand. All the effects are limited by the strong expected increase in vehicles efficiency, which somehow compensate the additional increasing transport demand of some scenarios.

These results confirmed 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 determined effect, but rather the potential of bringing positive or negative consequences on the final energy consumption of the transport sector.

As already discussed, one of the main limitations of this work lies in the necessity of relying on average parameters, given the focus on an international level. Future focuses on specific countries may add interesting information on the potential variability related to context-specific aspects, and at the same time highlighting which aspects are the most important in influencing the adoption of the digital technologies that are being considered. Furthermore, a necessary integration will be the inclusion of freight transport, in

which digital technologies may play a crucial role for the optimization of logistics and operational strategies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRedit authorship contribution statement

Michel Noussan: Conceptualization, Methodology, Software, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Simone Tagliapietra:** Conceptualization, Writing - original draft, Writing - review & editing.

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