Maximizing the value for money of road projects through digitalization

WORKING PAPER

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Abstract:

Roads are a central element of transportation systems, enabling economic and social development, fostering territorial cohesion, and facilitating the movement of people and cargo. Governments have devoted significant financial resources to developing and improving their road networks, and are still facing increasing pressure to ensure proper maintenance and payments to those concessionaires that developed roads under PPP arrangements. As in other sectors, digitalization is paving a way towards significant changes in the way we build, operate, and finance infrastructure. These changes will have a profound impact on the entire lifecycle of an infrastructure, from the design and/or construction stage, to its operation and transfer. This paper provides an overall overview of the main technological developments which are, or could impact road infrastructure in the short, medium, and long-term. For each technological development identified in our research, we analyse the potential impact on CAPEX, OPEX, and revenues as well as their level of maturity and expected lifetime for mass adoption, and also the main bottlenecks or barriers to implementation. The findings show that digitalization and technological development in the road sector can significantly impact the economic performance of roads, thus enhancing the value of money for the society. The findings also show that there might be some excess capacity of road systems once autonomous vehicles achieve higher market penetration. However, there are still some relevant legal, regulatory, institutional, and technological and economic barriers that are slowing down the digitalization process.

Keywords: Road projects; Smart infrastructure; Smart Mobility; Regulation; Public Private Partnerships and Concessions

1. INTRODUCTION

Road networks have always played a fundamental role in ensuring the free movements of people and goods, connecting regions and facilitating economic trade. Roads are an enabler of economic activities, reducing the costs of movement, facilitating the access to markets, and fostering the movement of labour, thus allowing a more efficient allocation of resources (Hoyle and Smith, 1992). Furthermore, a better road system, particularly based on highways, provides several positive externalities, such as reductions in travel time and accidents (Sarmento, Renneboog & Matos, 2017). Fundamentally, roads are an economic enabler, which lead to several spillover effects on increasing productivity (Delgado and Álvarez, 2007). Governments look at road networks as a critical layer beneath economic and social development (Linneker and Spence, 1996), and, as such, the development of road projects has been among the main investment priorities worldwide, and, particularly in the European Union (EU) (see Roumboutsos, 2015).

In the European Union, roads are the backbone of the transportation system, and one of its more valuable assets (Crist et al., 2013). The EU road network accounts for 5.5 million kilometres and is responsible for 75% of freight transport and nearly 90% of passenger transport **(**Karlaftis & Kepaptsoglou, 2012**)**. As such, over the last decades, governments have invested significant financial resources to upgrade and develop the road networks.

Unlike airports, or ports, were several physical changes can occur over a 30 to 50 year period, such as expansion or the switch between types of business profile (in the case of ports bulk vs. container, or, in the case of airports, domestic vs. international passengers), roads are, from a physical perspective, a relatively rigid infrastructure. During the life cycle of a road, it is possible to add an extra lane. However, besides such incremental capacity increases, a road is not expected to change significantly over its life cycle, neither is it able to reconfigure itself to alternative uses.

Nevertheless, this apparent rigidity of roads does not mean that roads are a stagnant infrastructure market, it is quite the opposite. Starting with the overall strategic approach and assessment of road projects, several ongoing trends affect the way roads are managed, operated, used, financed and regulated. Furhermore, there are growing environmental concerns and the sectors of energy, transport, and environment are no longer separate boxes, but interconnecting subjects, often tacked together when considered in public policy (Geerings and Stead, 2003). For this, the factor that roads, or road transport, are among the largest energy consumption activities is important, as is the need for governments to meet the Paris Climate Agreement objectives, and thus it will be necessary to introduce significant changes in the way road transport is organised, both for passengers and cargo alike (Clémençon, 2016). However, the environmental concern over road projects is not just a political concern, but it also affects investors and the way that investors evaluate their participation in infrastructure projects (Flammer, 2013).

In terms of financing, roads have also become a dynamic market in which to invest (Cruz & Sarmento, 2017a). Traditional government-based financing is gradually being replaced by private-financing, under public-private partnerships arrangements (Cruz et al., 2015; Miranda Sarmento & Renneboog, 2016), deepening the involvement of the private sector in these public infrastructures. The private sector is no longer simply a service provider, but rather an active player in financing, building, and managing roads (Hodge and Greve, 2017). This creates a more complex web of responsibilities. Traditional functions, such as managing congestion, can now be performed by private entities, which, by nature, are not focused on maximising social welfare, but rather on maximising returns on equity. This emerging market, which in many EU countries is a mature market, is allowing conservative investors, such as pension funds, to invest in this market (Bitsch et al., 2010). The growing involvement of the private sector is an enormous challenge in terms of regulation, forcing governments to abandon a traditional regulatory model which is based essentially on verifying compliance with engineering and technical standards, with a more active and mobility-based form of regulation (Sumkoski, 2016; Wahyuningtyas, 2016). How we use the roads, at what cost, with what environmental impacts, are, or at least should be, central questions for regulators.

The management of roads is moving from a service-based perspective, towards a consumer-based perspective, offering solutions to improve and optimise travels, and provide additional services, such as electric charging points, and integrated mobility solutions (Kamargianni et al., 2016).

Together with these various trends affecting the road sector, there is a broad change which, possibly, will have a higher disruption potential – digitalization. Digitalization has been the enabler to integrate and diversify traditional mobility functions, allowing to shift the focus from infrastructure to users. The entire road networks involve several distinct types of roads: motorways (which are generally referred to as the "principal network", or "level 1 road system"), regional roads, and municipal roads.

Public infrastructure, and in particular, capital-intensive infrastructure (such as roads, bridges, or railways), have been slowly incorporating technological advancements to improve its economic, social, and environmental performance (Mckinsey, 2016; Finger & Razaghi, 2016; Cruz and Sarmento, 2017b). Despite the relevance of efficiency gains associated with the construction and operation of road projects, it is clear that major advancements will rely on the "digitalization" path.

The way that these advancements are being incorporated into the management and operation of roads differs across geographies. Some are public-private partnerships, where both the public and private sector collaborate in a pilot project to test concepts and validate the technology (e.g. the Washington State Road Usage Charge project), while others are simply B2B transactions where the clients (typically public or private road operators) buy out technological systems essentially to cut costs (e.g. revenue collection, maintenance, etc.).

As the wave of digitalization grows in the road sector, the contracting model for road projects is also increasingly moving towards public-private partnerships (PPPs) models, typically concessions. But these contractual models are based on a "simple" business model: based on *a priori* forecast; there is a business case that ensures a proper level of return on the investment. The project can be financed exclusively by tolls or user charges, or by government payments, or even by a mix of both.

The impact of digitalization may have a profound impact on the traditional business model of PPPs. Not only will it be possible to significantly decrease costs, particularly, in revenue collection and road management, but also, from a revenue perspective, to have additional revenue sources (e.g. electric charging on the infrastructure), plus to be able to have dynamic congestion pricing, thus increasing revenue per car.

However, there is growing a risk factor, which arises from: i) an increasing level of technology which may raise additional technological and security risks, and; ii) an increasing difficulty in forecasting for the long-time. Although the inaccuracy of forecasting has been extensively addressed in the literature (Nicolaisen and Driscoll, 2014), the fact is that forecasting in the past was much easier, with traffic essentially being a function of GDP growth. This will not be the case anymore.

For infrastructure-related innovation, the risk factor involved seems to be relatively low, but the same is not true for services-related innovation, particularly those involving the redistribution of traffic, car-sharing, or any other change in demand. Interestingly, some road concessionaires are already anticipating changes by offering solutions which, at first sight, may reduce demand.

This paper aims to present and discuss the technological advancements in the road sector, identifying the potential impact of the growing dissemination of such technologies, and, particularly, how this can affect the existing management and regulatory models. Based on this, we can formulate the following research questions using theoretical and case studies approach: What will be the impact of newly-contracted PPPs?; Are there any changes that can be made?; Do existing contractual models fit the new reality? This paper focuses on the principal system, but for simplicity, we will refer to the motorway system simply as a road system or a road infrastructure. Together with a conceptual overview of this topic, we present a practical analyse of the Portuguese case, with a case study example of Brisa, which is a traditional infrastructure manager which has evolved its business model towards that of a mobility solution provider with services such as car-sharing, smart parking, traffic management, and digital payments for public transport etc. (Brisa, 2017).

The paper is organised as follows: after this introduction, Section 2 presents the main network developments and breaks down the road into its main components; Section 3 discusses in detail "infrastructure-related digitalization", while Section 4 focuses on service-related digitalization; Section 5 is dedicated to the impacts of each technology; and, finally, Section 6 presents the main conclusion.

2. OVERVIEW OF ROAD PROJECTS

2.1. Network development

European countries have distinct levels of road development and road usage. Table 1 and Figure 1 present an overview of the extension of the existing road network for EU countries, both for motorways as for secondary roads.

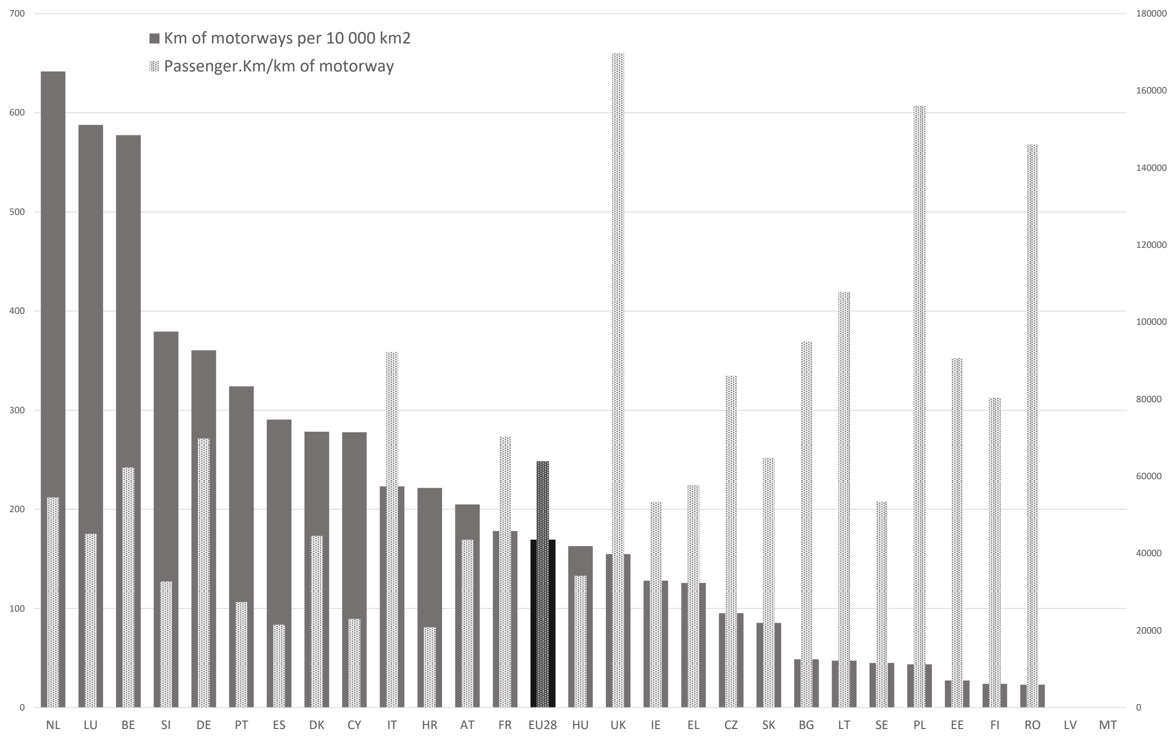
Table 1 – Network extension and demand in the road network (2016)
This table is organised by the column of "km of motorways per 10,000 km2" by descending order.
(Source: European Union Road Federation, 2016)

	Km of motorways per 10,000 km2	Passengers.km (billions pkm)	Km of motorways	Km Other roads	Km of motorways per million habitants
NL	641.7	145.4	2,666	12,969	156.6
LU	587.7	6.85	152	2880	261.1
BE	577.5	109.84	1,763	1,6341	153.3
SI	379.3	25.16	769	6,738	372.3
DE	360.3	899.3	1,2879	230,517	155.7
PT	324.0	81.86	2,988	14,284	289.5
ES	290.5	316.53	14,701	165,595	315.7
DK	278.3	53.22	1,195	74,109	208.5
CY	277.8	5.92	257	4,767	219.6
IT	223.2	620.36	6,726	180,175	110.9
HR	221.5	26.14	1,254	17,644	300.6
AT	204.9	74.83	1,719	14,080	196.5
FR	178.0	805.5	11,465	399,214	171.3
EU28	**169.3**	**4,672.26**	**73,245**	**1,906,200**	**144.2**
HU	162.8	51.82	1515	31,242	154.3
UK	154.8	637.67	3,756	175,760	57.2
IE	128.1	48.04	900	17,044	188.5
EL	125.7	95.81	1,659	41,822	154.3
CZ	95.2	64.65	751	55,716	71.1
SK	85.4	27.15	419	18,016	77.1
BG	48.7	51.36	541	7,551	75.8
LT	47.3	33.32	309	21,242	107.5
SE	44.9	107.6	2,013	98,508	203.2
PL	43.6	213.1	1,365	173,384	35.9
EE	27.3	11.24	124	16,469	94.2
FI	23.9	65.11	810	26,897	147.4
RO	23.0	80.36	550	52,614	28.1
LV	0	11.73		6,987	0
MT	0	2.29		2,361	0

Name of countries: AT – Austria, BE – Belgium, DE – Germany, DK – Denmark, EL – Greece; ES – Spain, FI – Finland, FR – France, IE – Ireland, IT – Italy, LU – Luxembourg, NL – The Netherlands, PT – Portugal, SE – Sweden, UK – United Kingdom, BG – Bulgaria, CY – Cyprus, CZ – Czeck Republic, EE – Estonia, HR – Croatia, HU – Hungary, LT – Lithuania, LV – Latvia, MT – Malta, PL – Poland, RO – Romania, SI – Slovenia, SK – Slovakia; Data for LV and MT is not available.
N.A. Not available

Figure 1– Level of usage and road density in the EU motorway system

This figure presents the passenger.km by car / extension of the motorway system in km and the motorway extension divided by the country area.



The UK is the country that has the highest level of usage of motorways. The level of usage is calculated by dividing the total passenger. Km by car, per the total extension of the motorway system in kilometres. This ratio ignores cargo, given that we were not able to find comparable cargo figures.

For the other countries such as Cyprus, Spain, Croatia, or Portugal, are among those that have the lowest levels of usage. In the case of Spain and Portugal, the results are particularly intriguing, given that these countries have been investing massively in the road sector over the last 25 to 30 years (Cruz & Marques, 2011, 2013) and these countries are among those that have a higher density of motorways per km^2. In fact, Figure 1 shows that countries with a higher network density, generally exhibit lower levels of road usage. What might emerge as an obvious conclusion, in reality shows that the development of road networks is not necessarily the answer to growing demand. If governments had increased the road network to address growing patronage, this would not necessarily represent having lower levels of usage. This data shows that road network development has been a political priority in some countries, even if the levels of demand did not justify such a network density.

2.2. Road system components

Before engaging in the discussion of digitalization, let us break down road infrastructure into its several components and basic systems and subsystems. Figure 1 illustrates the main system components and functional activities. With regards to system components, we have structured the several systems into two large groups: soft assets – which corresponds to movable assets, typically with shorter lifespans, and; hard assets – immovable assets, with longer lifespans which represent the large majority of

CAPEX. Within the hard assets, we further divided them into two classifications: superstructure systems and substructure systems. The latter corresponds to all physical and immovable assets that provide the underlying basis of the infrastructure (e.g. tunnels, bridges, landfills, barriers, or embankments, just to mention some examples), while the former corresponds to an additional layer above the substructure, including systems such as toll booths, electronic toll gantries, lighting systems, or CCTV systems. The functional activities are all the typical functions that a road manager needs to provide. Some are activities related with ensuring proper functioning of the infrastructure (e.g. road side cutting, drainage cleaning, pavement maintenance, etc.) while others are related with the direct operation of the service (e.g. toll collection, information, accidents and incidents assistance and monitoring, etc.).

Additionally, Figure 2 contains a summary list of all the function activities that have to be performed on the assets and/or to ensure that the assets function properly, and which are needed to effectively operate the infrastructure.

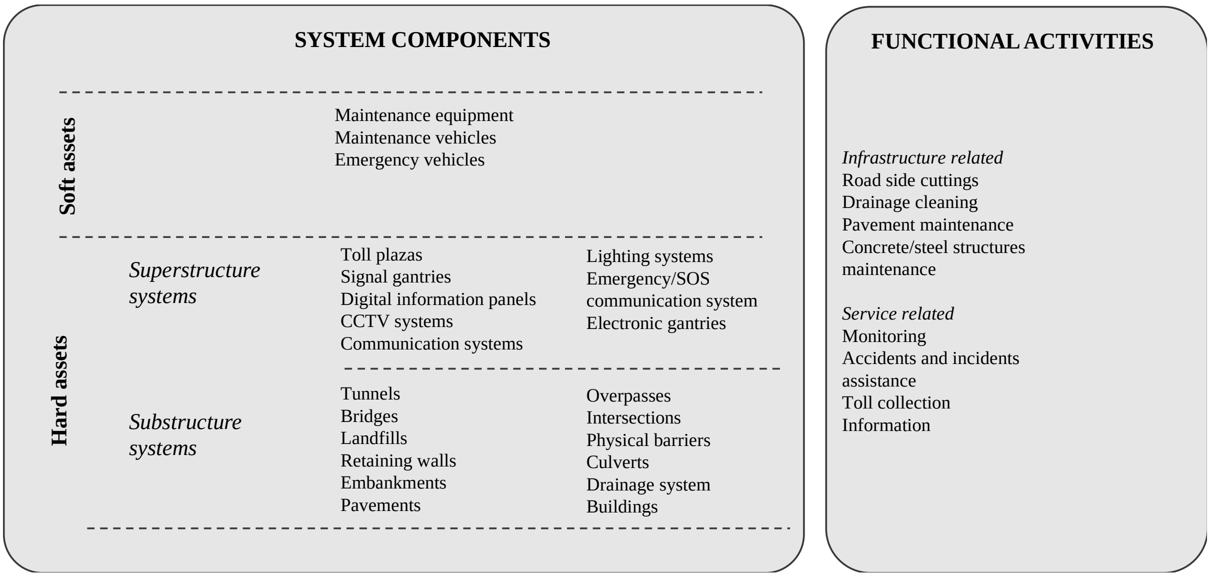


Figure 2 – System components and functional activities

2.2. Infrastructure and service-related innovations

These improvements can be divided into two types: first, “infrastructure-related”, meaning the technological innovations are embedded in the infrastructure to support its maintenance and operation (e.g. remote sensing, electronic tolling, etc.); and second, “service-related”, which are designed to improve how the users utilise the infrastructure/service (e.g. dynamic tools, real-time information, real-time incident detectors, etc.).

While the objective of infrastructure-related innovations is essentially to increase efficiency in the management and upgrading of infrastructure, the objective of service-related innovations is to improve the rationality of the use of the infrastructure and these can have larger benefits, particularly, social, and environmental externalities. Traditionally the private sector has been more concerned with infrastructure-related innovation, as this can decrease the OPEX, while the public sector has focused on service-related innovations, whih make it is possible to achieve the optimal social Pareto regarding congestion and social and environmental externalities.

Table 2 summarises some of the main examples of digitalization at the level of infrastructure and mobility services.

Table 2 – Examples of digitalization at the level of infrastructure and service

Infrastructure-related	Service-related
Electric charging/corridor	Traffic management
BIM and collaborative design	Automatic accident detection
IoT and intelligent monitoring	Autonomous vehicles
Smart asset management	Electronic tolling

3. INFRASTRUCTURE-RELATED DIGITALIZATION

3.1. Building information modelling (BIM) and collaborative design

Road projects are firstly a construction project. Typically, the investment associated with the construction accounts for approximately 50% to 70% of the overall life-cycle costs of a road project over a 40-year period (Sarmento, 2010). The remaining concern typical maintenance costs (e.g. replacement of pavement, cleaning of hydraulic passages, etc.) as well as those operating costs related with accident assistance, toll collection, signalling, and communications, among others. With the majority of investment being in construction, road projects incorporate the typical problems of the construction sector. The construction sector is frequently identified as being one of the sectors where the growth of productivity over the last 50 years has been low when compared with other manufacturing and industrial-based industries (Sveikauskas et al., 2016).

Therefore, the study of digitalization in the road sector also involves a broader analysis of construction digitalization, given that the advancements achieved in the latter will have an impact on the former. It is not our objective to go over all the advancements in the field of construction, however we will focus on those advancements that make a direct impact on the construction and maintenance of roads. Cost overruns typically involve an increase in investment of 20-30% (Miranda Sarmento and Renneboog, 2017) and one of the main reasons for this overrun is the lack of communication between the several stages of design, planning, and execution, along with the interface risk between them.

Unlike other incremental developments in project design, such as automated computer design, BIM **(**building information modelling) technology has disruptive potential. It is not simply a contribution to the digitalization of information, but it also involves a redesign of project management and patterns of collaborative design. Instead of a project development based on a sequential supply chain, where several teams develop their own technical work (e.g. geologists, geotechnical engineers, road engineers, structural engineers, hydraulic engineers, telecom and signaling expeerts, etc.), BIM allows for an easier and more integrated participation of all stakeholders involved in the design and management of infrastructure assets, namely, roads.

The overall improvement in collaborative work and the use of BIM systems is estimated to bring about an increase in productivity and the mitigation of project errors with an expected decrease in costs by 15-20% (Blanco and Chen, 2014).

The advantages regarding having a common basis allows for improving the design management, scheduling and assignment of teams, quality control, performance management, and documental management.

Other drivers affect the performance of the construction activities. A rise in transparency and improvement of the contractual agreements are also current trends which will, in the long run, contribute to improving the productivity of the sector. Although technology and digitalization are also playing a role in these trends, an example being that it is easier to create and implement key performance indicators if more data is available through digitalization, for this paper we have not considered these contributions. We have only addressed those drivers of change that are a direct result of improvements arising from digitalization.

3.2. The Internet of things and intelligent monitoring

As mentioned above, a pre-requisite for smart asset management is the ability to collect and process real-time data. The innovations in the field of the internet of things have had profound implications at the level of asset management. The traditional maintenance paradigm was based on the principles of preventive and corrective maintenance. Most, if not all, of the existing road projects have an associated maintenance plan which stipulates the several levels of maintenance to be performed each year for the several subsystems of roads.

Lidar detection and ranging will improve the ability to analyse (in 3-D) terrains and simulate terrain, which will bring about significant advantages when planning and designing new roads.

Intelligent monitoring will allow an effective and efficient crew tracking, and thus improve the ability to carry out a performance analysis (Raza et al., 2017). In road projects this is particularly relevant, as these linear infrastructures often have more than one distant active construction site.

However the benefits of intelligent monitoring are not limited to optimisation in construction. During the operation phase, the use of digital sensors, remote sensing systems, and GIS-based systems, permit the real-time monitoring of the several types of road system (e.g., pavement, tunnels, bridges, etc.).

In fact, the ability to have on-time data regarding asset conditions is bringing about a structural change in the way maintenance is performed.

3.3. Asset management

Traditionally, maintenance has adopted a typical approach of *a priori* planning. The infrastructure manager would design a maintenance plan for the identification of maintenance actions to be performed in a given year. This is what is usually known as "preventive maintenance". Irrespective of the condition of the asset under maintenance, the manager would carry out the planned action according to the calendar. In this case, the owner would verify the compliance of the maintenance plan, verifying whether all the planned actions had been executed according to the plan (Stenstrom et al, 2016). Together with "preventive maintenance", the infrastructure manager could also carry out "corrective maintenance" actions, if, and when such unplanned intervention was necessary because a component had manifested wear and tear earlier than expected. Digitalization is leading to the emergance of a new trend in infrastructure maintenance: asset condition-based maintenance (Verbert et al., 2017).

Asset condition-based maintenance makes use of real-time data and sophisticated algorithms (e.g. artificial intelligence) and/or GIS-based tools (Sandrone and Babiouse, 2017) to predict the evolution of the condition of an asset and to plan the necessary interventions accordingly (Daneshkah et al., 2017). The combination of data collectors (sensors) and data processing techniques (algorithms) allows managers to preventively detect potential deficiencies and act to avoid them. The potential savings of using this type of technology are various: First, it enables managers to maintain the infrastructure at a nearly constant predetermined level of quality; second, it allows for the optimisation of maintenance actions towards a quasi-optimal level of lifecycle costs, and; third it provides more data that can be useful for the future planning of infrastructures.

3.4. Electronic Tolling

In Europe a large number of road charging schemes are in operation. These are distinct from the charge concept (real tolls vs. shadow tolls vs. availability payments), the type of vehicles and respective toll-oriented classification, the calculation method for tolls (based on type of vehicle, time of day, level of congestion, etc.), or even tolls based on the extension and location of tolled roads. As a result, the EU exhibits a diverse and heterogeneous set of toll regimes. However there is a common trend towards moving from traditional toll booth payment methods towards electronic payment. The EU is concerned with the heterogeneity of the road charging schemes, as these can be a barrier towards the complete interoperability of road infrastructure, thus obliging international users to use multiple on-board units (OBU) in different countries.

Several technologies are emerging (Steer Davies Gleave, 2015), such as: i) Automatic Number Plate Recognition (ANPR), which is also referred to as 'Video Tolling'; ii) Dedicated Short-Range Communications (DSRC) technology; iii) Radio Frequency Identification (RFID); iv) Global Navigation Satellite Systems (GNSS) technology; v) Tachograph-based technology, and; vi) Mobile communications (GSM and smartphones) tolling systems. These technologies have the potential to significantly impact CAPEX and OPEX.

Traditional manual tolling usually involves an investment of around 1 to 4 million Euros per lane, with an annual operating cost of 370.000 Euros to 840.000 Euros per lane. Additionally, for payments with a credit card, 1 to 4% of annual card revenue is received as an extra. When using self-service machines, the investments are similar, however the operating expenses are lower, in the range of 160.000 to 630.000 Euros per lane, per year (Steer Davies Gleave, 2015).

For GNSS-based tolling, the CAPEX is around 200.000 to 450.000 Euros per lane with the OPEX being a fixed cost related with customer relationship services, which can add up to 3 to 6 Million Euros per lane, per year.

However the benefits of electronic tolling systems are not limited to a reduction in OPEX and CAPEX. Several other opportunities are unlocked by the digitalization of payments. The main one being the possibility to implement dynamic toll regimes that can enforce a pricing model based on marginal costs to mitigate congestion. Traditional pricing policies have regarded tolls as a financing mechanisms. As congestion grows, the role of tolls as a mechanism for regulating demand becomes central. The application of dynamic tolling regimes enables the calculation and collection of variable tolls based on real-time traffic flows, i.e., congestion levels, depends on the digitalization of payments.

3.5. Electric charging/corridors

With the advent of electric vehicles (EV), roads will have to adapt to the requirements of these vehicles. Several approaches are under development. More minimalistic approaches involve the construction of EV charging points, which could replace and/or complement existing fuel stations. However there are other disruptive solutions under development, one of them being the construction of electrified corridors, using either the pavement or an overhead gantry. Recently, in Sweden a 2-kilometre stretch of pavement was unveiled that uses electric rails to transfer energy and charge an EV, using a mechanical arm (Taljgard et al., 2017). The potential of this technology is enormous, as it provides the ability to charge while in circulation, thus eliminating one of the main bottlenecks of EV (long charging periods and a relatively low autonomy when compared with traditional fuel engine vehicles). However the dimension of the potential comes at a high cost, as it is estimated that the cost per kilometer of building such a solution would be more than US 1.2 million. However these first projects are experiments, and one should expect a significant reduction in costs once this systems came into mass production.

4. SERVICE-RELATED DIGITALIZATION

4.1. Traffic management

Congestion is probably one of the biggest negative effects of road usage. It increases travel time, increases greenhouse emissions, and has an overall negative effect on the economy.

Tackling congestion is a complex task, which involves taking action in several areas, such as regulation, policy making, user-incentives, road pricing, marginal taxation, etc. However technology can play, and is playing, an important role in decreasing the effects of congestion. One of the most visible action is related to the smart management of traffic flows in urban roads. The intelligent management of traffic signals has become a common solution, which equates to the active monitoring system of traffic patterns that optimise the real-time management of flows at intersections. These solutions are based on advanced algorithms, which are permanently adjusting the signals at intersections in order to decrease congestion levels (Li et al., 2017)

4.2. Automatic accident detection

Road accidents are among the main causes of public injury worldwide. They are also a concern for road managers, as it is their responsibility to ensure that, firstly, the road provides safety conditions that prevent accidents and, secondly, in case of a road accident, the infrastructure manager is responsible for providing the support in solving the incident and avoiding additional problems. In fact, many highway concessions contracts have performance incentives to stimulate the reduction of road accidents, injuries, and fatalities (see more in Rangel et al., 2012).

Technology provides a fundamental tool in helping tackle this problem. Several different technologies have been used. In some cases, accident detection is carried out by the vehicle and/or the driver, through in-vehicle sensors and/or based on information collected from the driver’s mobile phone, or through the accelerometer and gyroscope (Fernandes et al., 2016). However, from the road manager’s perspective, this type of solution is less interesting, because it depends on the initiative of automakers and/or the overall use of mobile apps by drivers, which allows automatic detection.

However, other solutions are currently being developed and applied which depend solely on the road manager. This type of technology relies on data collected by closed-circuit television (CCTV) cameras. The analytical processing of the videos, using incident-detection algorithms, allows for an automatic identification of the incident, reducing the need to deploy emergency teams, whilst, on the other hand, enabling the same traffic operation centre to be able to monitor, in real time, several different roads, and overall extensions in the range of thousands of kilometers.

4.3. Autonomous vehicles

There are several levels of autonomous driving, which are usually defined on a 0-5 scale, where 0 is business as usual - “driver does it all”, and 5 is fully-autonomous vehicles, where no particular action is required by the driver (Stocker and Shaheen, 2017).

Given that the objective of this paper is to explore the impacts of technology and digitalization on road infrastructure, we will consider the ultimate level, or in other words, full autonomy.

Autonomous driving is probably the largest disruption in the automobile industry since the creation of the combustion engines. The potential impact of such technologies are several, ranging from vehicle and road safety to congestion mitigation (Fagnant and Kockelman, 2015). From an infrastructure perspective, autonomous driving will enable a much more efficient management of capacity, based on the low probability of accidents, potentially lower lead times, and the elimination of the randomness associated with a human driving the vehicle (Olia et al., 2017).

Schranck et al. (2012) estimate that for a 10% market penetration of AV, congestion on motorways will drop by 15%. For a 50% market penetration, Atiyeh (2012) estimates a reduction in congestion of 39% and an enhancement of capacity of 20% of existing road capacity.

However there are still numerous challenges to be overcome before the mass adoption of these technologies. High costs, complex legal and security issues, insurance regulation, and the overall regulatory framework, are all still significant barriers (National Highway Traffic Safety Administration, 2013)

The market penetration of such technologies will take time to ramp-up. Bansal and Kockerman (2017) estimate a 24.8% level 4 AV penetration by 2045, assuming an annual 5% price drop in technology, while maintaining the existing levels of willingness to pay for consumers. However, if ones assume a 10% annual rate of decline in prices and a 10% increase in willingness to pay, whilst penetration climbs to 87.2% by 2045. Fagnant and Kockelman (2015) consider that these values can go up to an increase in 80% of capacity, considering 90% penetration rates.

4.5 “Network tolling” vs. “road tolling”

Frequently, road projects have been developed under PPP schemes, which, from a business perspective, work on a stand-alone basis. Although roads form a network, the reality is that, in many countries, this network is composed of separate special-purpose vehicles (one for each concession), and each one of these has its associated toll revenue, debt, and operating costs. This organisation has led to a toll regime that has the main function of funding the project. As discussed by Hensher (2017), this traditional approach erodes the value for money of road projects, as it does not allow one to define toll levels that explore network effects and also manage congestion, e.g., increase the level of toll for a certain stretch of road with higher or lower levels of congestion.

The design of dynamic tolling mechanisms, which can be adjusted on a real-time basis to fully explore the benefits of network effects, is dependent on the ability to actively monitor traffic regimes and on being able to collect tolls electronically. Both these technologies are at the point of commercial use. However, this does not mean that legal, regulatory, and also financial barriers that need to be overcome do not exist, such as, for example, the fact that each concession is a specific SPV. However, these barriers can also be dealt with, bearing in mind that if these concessions are set on an availability basis, this means that the public sector owns the toll revenues. In these cases, it can be possible to implement such schemes.

5. ANALYSIS OF THE IMPACTS IN ROAD PROJECTS

Having presented and discussed the main technological trends and the advent of digitalization in the road sector, this section presents a critical analysis in terms what is the expected impact of such technology on road infrastructure. We have structured the analysis according to the following variables:

i. Road system applicable: identification of the road component that will most likely be affected by the trend;
ii. Level of maturity: identification of the level of development of such technology; this variable was structure according to a scale – low (there are only pilot cases and the technology is not ready for the roll-out and mass application); medium (the technology is still not being widely adopted, but the existing level of knowledge allows for a quick application), and; high (the technology is well developed and permits an immediate application);
iii. Level of technological complexity: identifies whether the level of complexity of the technological development, privacy issues, and regulatory challenges is low, medium, or high;
iv. Barriers to entry: summarises the main technical, economic, regulatory, and legal barriers to mass adoption;
v. Expected mass adoption timeline: establishes a provisional time horizon for when expecting a wide use of this technology, being structured into 3-time horizons: low (0 to 4 years), medium (4 to 8 years), and long-term (+ 8 years);

vi. Potential to impact CAPEX and OPEX on road infrastructure: analyses whether that specific technology will have the ability to significantly decrease CAPEX or OPEX;

vii. Potential to impact revenues and/or road capacity: identifies whether the technology has the potential to increases revenues and/or increase the capacity of the road system.

Table 3 summarises the results of this analysis.

Table 3 – Analysis of potential impacts and level of development

Technology	Road system applicable	Level of maturity	Level of technological complexity	Main barriers to entry	Expected mass adoption timeline	Potential to impact existing road infrastructure	Potential to impact revenues and/or road capacity
BIM/collaborative construction planning	Hard assets/substructure systems	Medium	Low	Institutional and regulatory	Medium term	High	
IoT / intelligent monitoring	Hard Assets /super and substructure systems	Medium	High	Economic and technological	Long-term	Very high	
Asset management	Hard Assets /super and substructure systems	High	Medium		Medium term	Very high	
Electric charging	Hard Assets /superstructure systems	Low	Medium	Technological, regulatory and economic	Long-term	Medium	
Electronic tolling	Hard Assets /superstructure systems	High	Medium	Institutional	Short term	Very high	Very high
Traffic management/congestion pricing	Users	High	Medium	Technical and institutional	Medium term	Very high	High
Automatic accident detection	Users	High	Low	Economic	Short term	Low	Low
Autonomous vehicles	Users	Low	High	Economic, regulatory and legal	Long-term	Low	Very high

Based on the expected impacts of each technology, we have estimated what would be the potential impact on CAPEX, OPEX, revenues, and capacity if these technologies are incorporated in a road project.

Table 4 – Analysis of potential impacts and level of development

Technology	Potential impact	Source
BIM/collaborative construction planning	Reduction of 27-38% in Capex	Mckinsey (2017)
IoT / intelligent monitoring		
Asset management		

Electric charging	Not available	--------------------
Electronic tolling	Reduction of 50% on toll collection costs (Opex)	Steer Davies Gleave (2015)
Traffic management/congestion pricing	Up to 20% on revenues	Li et al (2017)
Automatic accident detection	Reduction of 25% on assistance costs (Opex)	Fernandes et al. (2016)
Autonomous vehicles	Up to 20% capacity increases	Schranck et al. (2012)

The results summarised in Table 4 show that there is a strong potential to impact the economics of roads. Bearing in mind that the average cost of motorways can easily be in the range of hundreds of thousands of Euros, a reduction of 30% in CAPEX can have a profound impact on the economic assessment of road projects. The same principle can be applied to OPEX, or even to the ability to increase revenues. These impacts (CAPEX and OPEX reduction, as well as an increase in revenues) could mean that it will be easier, from an economic perspective, to develop road projects. However, the advent of autonomous vehicles and the expected impact regarding capacity increases could represent a major step backwards in road network development. If capacity increases, then we will need less roads. This is particularly relevant in countries where the existing levels of road usage are low when compared with road density. The same might happen if dynamic congestion pricing is implemented. This tolling mechanism will enforce the payment of a higher toll during congestion periods, increasing the generalised cost of travel, thus forcing users towards public transport.

6. THE PORTUGUESE CASE

Besides having a large network of highways and roads, Portugal has also been a leading country with regards to innovating services related with roads. In this section we present the case of how Brisa, the main operator of highways in Portugal, has created some digital solutions to reduce operational costs, improve service quality, and increase revenues. Brisa has 30 years of experience in managing highways, twenty of which have adopted its solutions, from tolls to roadside. Brisa created a specific company for its innovation lab, called A-to-Be. As mobility keeps evolving and pushing boundaries, it goes beyond vehicles and infrastructures, and the question nowadays is more and more about people and mobility experiences. A-to-Be has been developing, along with their clients, solutions from tolling to parking, and from traffic management to monitoring, connecting them all to mobility networks. As the company website explains: "*It's about transforming the ride. Making it easier, safer, more sustainable and fulfilling. And when people get to the end of it, it's not a b, it's a beyond*".

The company is structured into two main areas, divided by sub-areas: 1) Mobility payments (for smart city players, road operators, public transport, smart parking, and commuting services), and; 2) Mobility operations (traffic management and revenue assurance). Table 5 presents the company's solutions, organised by the technologies described above.

The MaaS (Mobility-as-a-Service) Provider is the operator of operators, an entity that combines the needs of cities, citizens, and mobile operators. A-to-Be MoveBeyond™ is the technological platform used for the MaaS provider. In the field of Traffic Management/ Congestion Pricing technologies, "Smart city players" presents two solutions (A-to-Be® Congestion Pricing™ and A-to-Be® Access Control™). "Smart city players" addresses Urban Mobility, answering the growing demands of citizens through infrastructure optimisation and implementing transportation policies. The company's focus is on being able to deliver a solution that enables the optimisation of existing infrastructures and operations, whilst maintaining control and direction over mobility policies under the city's jurisdiction, recognising that citizens have become more and more demanding. Electronic tolling technology is provided by the "road operators solutions" (A-to-Be® ManualTolling™; A-to-Be® ElectronicTolling™, and; A-to-Be® RUC™), ranging from the roadside to central systems, independent of the toll system. Electronic tolling technology offers solutions at several levels, namely: Road-side radio-frequency based solutions; Road-user charging; Open Road configurations for AET; Classic toll booths with channelled lanes; Self-service and remote cashier manual tolling, and; a Back Office system.

With regards to mobility operators, the A-to-Be company provides solutions that are especially geared for road operators, concessionaires, and authorities. It implements central coordination centres, emergency response units, and infrastructure operations theatres. By connecting solutions from other portfolio lines and by enhancing and assuring better results and efficiency, such as with the Audit platform that allows independent auditing of roadside equipment performance and accuracy. The company's goal is to know what is happening in the road network in real time with an integrated solution. A-to-Be® VideoWall™ is used for IoT/intelligent monitoring, and with regards to Asset Management, the solutions used improve revenue collection and confidence about the implemented systems, at both road and central level. A-to-Be® Revenue Assurance solutions (A-to-Be® Audit™; A-to-Be® Monitoring™) provide an overview as to whether the critical revenues systems are working properly, and if they are minimising toll leakage and fraud, thus reducing the underperformance of systems.

Table 5 – Analysis of potential impacts and level of development

This table presents the Brisa (A-to-Be) solutions for each technology described above. Source: the Authors, based on A-to-Be information

Technology	Brisa (A-to-Be)	Short description	Benefits
IoT / intelligent monitoring	A-to-Be® VideoWall™	Control and act on complex operational theatres.	▪ Improve maintenance periods over 8 years. ▪ Ability to replace defective LCD without service disruption.

			▪ Provide the operator with the choice of using open-architecture and supplier-neutral for video codecs. ▪ Resilience in failure, with easy recovery to prior condition.
Asset management	A-to-Be® Audit™	Performance measuring for road operators that need to verify road-side equipment and systems.	▪ Maximize revenues collection. ▪ Optimize human intervention in enforcement process. ▪ Uphold service level agreements. ▪ Monitor and enforce KPIs for suppliers and subcontractors.
	A-to-Be® Monitoring™	Improves companies' planning and the execution of preventive and corrective maintenance.	▪ Preventive and predictive maintenance. ▪ Implementing business rules. ▪ Monitoring equipment and applications ▪ Integrate stock management.
Electronic tolling	A-to-Be® ManualTolling™	Integration with current legacy systems and smooth technological evolution, for cashier or remote-user operation in self-service environments.	▪ Operational costs with manual tolling lanes decrease by using remote cashiers, without compromising customer service. ▪ Capacity to commute the operating mode of lanes between manual, all-electronic, and remote cashier. ▪ The assignment of lanes per remote cashier is dynamic and flexible, being easily defined by the back-office. ▪ A fully auditable and traceable solution which allows the operator to see the performance of cashiers.
	A-to-Be® ElectronicTolling™	Paying without stopping.	▪ Reduce carbon-emission operation. ▪ Lower operational and transaction costs. ▪ Coexistence of video and radio-frequency account users. ▪ Multiple equipment vendors plug´n´play.
	A-to-Be® RUC™	Tolling, dematerialised. Satellite-based and mobile solutions	▪ Satellite-based and mobile (smartphone) solutions. ▪ Road-side enforcement.
Traffic management/ congestion pricing	A-to-Be® Congestion Pricing™	Claiming streets for cities that aspire to create better experiences for citizens, walkers, and bike riders	▪ Reduced traffic flow ▪ Reduced urban furniture implementation. ▪ Integrate mobility plans for accessing inner city streets. ▪ Improved urban air quality.
	A-to-Be® Access Control™	Mobility is about getting to places. Managing who accesses, which is now easier.	▪ Improved security for accessing gated perimeters. ▪ Unique identification systems for vehicles. ▪ Seamless user experience with other mobility services (tolling, public transport, parking) and ▪ Commuting services (fueling, drive-through).

The case of Brisa, or its subsidiary A-to-B, is particularly relevant, as it represents, at the corporate level, a trend that is affecting the mobility and transportation sectors globally: moving from an infrastructure-based perspective towards a service/user-based perspective. Brisa was a typical road infrastructure manager that has now moved towards the development of integrated mobility solutions, using technology and digitalization as an enabler for global mobility solutions. The evolution of the role of existing infrastructure managers will be an interesting phenomenon to observe. However, at this point, it seems inevitable that infrastructure manager will have to choose between going "digital" or "user-focused", or perishing.

7. CONCLUSIONS

There are enormous challenges ahead regarding digitalization in the road sector. The fact that roads hold the largest share of passengers and cargo movement, associated with road transport being simultaneously the largest contributor to CO_2 emissions, are all putting pressure on governments to enact public policies that accelerate digitalization in the road sector.

However, there are also strong economic arguments for infrastructure managers starting to incorporate technology, big data, and IoT in road infrastructures. Digitalization has the potential to significantly reduce CAPEX and OPEX, and also to increase revenues and capacity. Bearing in mind that many countries invest significant amounts of the public budget to costs associated with the road systems, this represents an additional leverage to encourage governments to facilitate and enable digitalization.

However, there are relevant barriers to the mass adoption of digitalization. The first is the regulatory framework. The regulatory regime is still too rigid and does not provide the flexibility for changing the way we currently operate and manage roads. The existing regulatory models are still based on contractual regulation (concession-based models) and are used in contracts where maintenance plans, investments plans, and toll regimes are prescriptive and cannot be easily changeable. In most cases, the adoption of technological novelties will involve a significant re-negotiation of existing contracts, and a complete re-design of the economic and financial balance of projects.

Secondly, there are legal barriers to the implementation and adoption of solutions such as electric corridors, or allowing autonomous driving on motorways, or on urban roads. These legal barriers can also affect the implementation of congestion pricing, bearing in mind that contracts exist with concessionaire that establish the toll regimes, and any change will lead to a renegotiation of the contract. This also raises some economic barriers. For example, changing the toll regimes will impact the financial and economic equilibrium of the SPV. The solution might be to change towards availability regimes.

Additionally, there technological barriers still exist, particularly when it comes to autonomous vehicles. The existing experiences with autonomous vehicles are still pilot cases, which aim to improve technology. The existing legal and regulatory frameworks in most countries do not allow for the free use of autonomous vehicles, the reason for this being that technology is perceived as not yet being ready for full-scale use. The introduction of this technology will most likely start gradually - first in motorways, and then in the urban context, where the interactions with pedestrians and other vehicles, are much higher, as is the potential for accidents.

Another relevant barrier is the risk associated with the obsolescence of technology. In a period where technological advancements are taking place at an extraordinary pace, there is a permanent uncertainty about whether the existing technologies will endure and still be used in the future. The implementation of technology involves a significant investment, which might be postponed in the expectation that future developments may be in different technologies, or even that the cost of technology can decrease in the medium term.

Finally, it is important to mention that the potential of digitalization will be greater for greenfield road projects. Those existing systems that have not been designed in a "technology-friendly" context have more limited potential, or at least in the case of infrastructure-based innovations. With regards to service-related innovations, there is still significant room for improvement.

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