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The business opportunity of Internet of Things to tackle air pollution through traffic management in Europe

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ABSTRACT

Title: The business opportunity of Internet of Things to tackle air pollution through traffic management in Europe**.**

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With 7 million people dying and $3 billion loss to the global economy each year, air pollution is among the most dangerous threats to human life, to the economy and to the environment. Research has shown that traffic is among the biggest sources of air pollution and that city dwellers are the most affected group. To deal with the problem, governments have started to resort to the use of technologies as *Internet of Things* (IoT), given their potential to lead to outstanding results. However, research on the use of IoT to address air pollution is scarce. This dissertation aims at studying the *status quo* of IoT, how it is being implemented to tackle air quality issues in cities and the business opportunity coming from its deployment.

Based on ten semi-structured interviews with experts in the fields of IoT, air quality, traffic management and smart cities and a review of the literature available on these fields, this work provides an analysis of a road pricing scheme powered by IoT-sensors, able to considerably reduce key air pollutants.

To study its economic impact and prove its effects on key stakeholders, a cost-benefit analysis has been performed. The analysis showed the profitability of the project on the mid-term and positive effects on the society as a whole.

On this basis, the research provides governments with the guidelines for a profitable and effective policy implementation harnessing IoT potential to target bad air quality.

Keywords: Internet of Things, Traffic Management, Road Pricing, Environment, Air Pollution, Smart City

SUMÁRIO

Titulo: Oportunidades de negócio de “Internet of Things” para enfrentar a poluição atmosférica através da gestão do tráfego automóvel na Europa.

Autor: Alberto Provedel

Com 7 milhões de fatalidades e $3 bilhões de perdas na economia mundial cada ano, a poluição atmosférica está entre as maiores ameaças para a vida humana, economia e o meio ambiente.

A literatura tem mostrado que o tráfego está entre as maiores fontes de poluição atmosférica, e que a população residente em centros urbanos está entre os grupos mais afetados. Para enfrentar o problema os governos começaram a recorrer ao uso de tecnologias como *Internet of Things* (IoT), dado o seu potencial para obter resultados excecionais. Contudo, a investigação para o uso da IoT em relação à poluição atmosférica é escassa. Este estudo pretende refletir sobre o *status quo* da IoT, como esta tecnologia está a ser implementada para lidar com problemas relacionados com a poluição atmosférica nas cidades, e as oportunidades de negócio provenientes do seu desenvolvimento.

Baseado em dez entrevistas semiestruturadas com expertos nas áreas de IoT, qualidade do ar, gestão de tráfego, “Smart cities”, e uma revisão da literatura existente nestas áreas, este trabalho fornece uma análise de um esquema de tarifação rodoviária, proporcionado por sensores-IoT, que permitem uma redução considerável de poluentes atmosféricos em cidades.

Para estudar o seu impacto económico e provar o seu impacto nas partes interessadas, foi realizada uma análise custo-benefício. Esta análise mostrou a rentabilidade do projeto a médio-prazo e os seus efeitos positivos na sociedade.

A investigação oferece aos governos diretrizes para implementação de políticas rentáveis e eficazes, aproveitando o potencial de IoT para mitigar a má qualidade do ar.

Palavras chave: “Internet of Things”, Gestão de tráfego, tarifação rodoviária, meio ambiente, poluição atmosférica, Smart City

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Acronym	Explanation
AAQ	Ambient Air Quality
AQP	Air Quality Plans
CAGR	Compound Annual Growth Rate
CCTV	Closed Circuit Television
CO	Carbon Monoxide
EC	European Commission
ECA	European Court of Auditors
EEA	European Environment Agency
EPA	United States Environmental Protection Agency
EP	European Parliament
EU	European Union
GHG	Greenhouse Gases
HFC	Hydrofluorocarbons
ICT	Information and Communications Technology
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IOT	Internet of Things
KPI	Key Performance Indicators
LTE	Long Term Evolution
MLN	Million
N.A.	Not Available
NO	Nitrogen Oxide
O3	Ozone
OER	Operating Expense Ratio
PFC	Perfluorinated Compounds
PM	Particulate Matter
SO	Sulfur Oxide
VOC	Volatile Organic Compound
WHO	World Health Organization
WLAN	Wireless Local Area Network
µg	Microgram

CHAPTER 1: INTRODUCTION

1.1 Background and Problem Statement

Air pollution is one of the world's biggest health and environmental problems, causing the death of about 7 million (mln.) people worldwide each year and costing the global economy $3 trillion per year (WHO, 2018). In Europe, during the last decades, emissions of several air pollutants have decreased substantially, providing with an overall improvement in air quality across the region. (EEA, 2017). However, concentrations are still too high and air quality issues persist. Problems are especially evident in cities, where widespread exceedances are seen and the amount of people affected by bad air quality is higher, mainly due to urbanization. In this context, road and non-road transport are one of the major contributors to air pollution (EEA, 2019c).

Governments and city halls have only recently begun to tackle air quality issues in urban areas by implementing new policies, often powered by new technologies, with the goal of finding cost-efficient solutions to improve citizens' quality of life, while converting urban areas into smart cities ("Clean Air Startegy", 2019). Among the alternatives available in the Information and Communication Technology (ICT) sector, Internet of Things (IoT) is considered one of the technologies with the widest range of application, able to provide cheap and productive solutions to tackle issues such as air quality (Medagliani et al., 2014).

However, the lack of prioritization of air quality issues in many European governments' agendas caused insufficient research on the topic during the last decade, which lead to the creation of gaps in the technology employability when it came to provide cities with valid, applicable and financially sustainable options. (McKinsey&Company, 2018)

1.2 Research and Scope

This research aspires to contribute to the application of IoT in traffic management policies aiming at tackling air quality issues within the context of European smart cities. This contribution will be carried out by studying a road pricing policy applicability in European cities, following the examples of London, Milan and Stockholm, with a focus on its effects on key stakeholders and its economic impact. This study wants to provide city councils with an overview of a road pricing policy targeting air pollution and the economic and non-economic impact this might have. Additionally, it intends to raise awareness on the current issues of air quality for the society, emphasizing the potential effects of modern solutions on key stakeholders.

This project aims at providing answers and solutions to the following research questions:

1. What is the state of art of IoT systems in European cities?
2. How can IoT technologies be implemented to reduce air pollution in cities?
3. Is there a business opportunity coming from the implementation of IoT technologies to tackle air quality-related issues?

The scope of this work is restricted to the areas of traffic management in cities within Europe. The analyses performed focused on the exploration of the business opportunity and the employability of IoT and not on its technological deployment.

1.3 Research Methods

In order to address the research questions, a qualitative, exploratory approach was selected, due to the novelty of the topics. Data was gathered through primary and secondary sources.

Secondary data was deployed to provide a rich overview on the literature available on the research topics, namely European smart cities, air quality, traffic management and IoT, with the aim of creating a theoretical foundation for primary investigation (Chapter 2). Furthermore, secondary sources were used to select the most appropriate research methodology, support the results' analysis and achieve concrete conclusions (Chapter 3 and Chapter 4).

Primary data was gathered through the conduction of 10 semi-structured interviews with leading experts from the fields of IoT, traffic management in smart cities and air pollution. The diverse profile of the participants allowed the acquisition of a wide variety of perspectives on the research topics and the use of data triangulation techniques, useful to enhance the study credibility (Thurmond, 2001). Outcomes from interviews have been used to draw conclusions to the study. Finally, gathered data have been processed and analyzed through thematic analysis.

1.4 Dissertation Outline

This thesis starts from a literature review (Chapter 2), where the status quo of the problems is described (urbanization, air pollution), together with the state of art of potential solutions to these (traffic management, smart cities, IoT). The project continues with the methodology section (Chapter 3), where data collection and data analysis are explained. In the following chapter (Chapter 4) acquired data are analyzed and developed in order to provide tangible results. The thesis ends with the study conclusions and limitations (Chapter 5).

CHAPTER 2: LITERATURE REVIEW

The aim of this section is to present a review of the existing literature on the current problems related to the urbanization phenomenon and the issue of air pollution affecting urban dwellers, and on the state of art of the potential solutions identified: smart cities and IoT.

2.1 Urbanization

Towns and cities have a long history: people have always acknowledged the benefits of these settlements, which include exchange of ideas, reduced transport costs, sharing of resources, in addition to the availability of several amenities. For most of human history, most people across the world lived in smaller communities but, during the past decades, the number of people moving to urban areas increased exponentially (Bandarin, & VanOers, 2011). This phenomenon took the name of *Urbanization* and has exploded mainly due to the natural increase of population and the rural-to-urban migration (Harris, 2015).

As of today, world population amounts to 7.7 billion people. In 2017, 55% of world's inhabitants lived in urban settings and the remaining 45% in rural areas (Ritchie, 2018). These shares vary considerably between countries and continents: across most high-income countries, such as Western Europe, the Americas, Australia and Japan, the number of city dwellers amounts to more than 80%, while the percentage decreases substantially in low and middle income economies, reaching the nadir at 12.7% in Burundi, Africa (Ritchie, 2018).

In Europe, the European Union (EU) applied a universal definition of urban areas across all countries (Dijksra & Poelman, 2014); according to this classification, settlements can be divided into:

- Urban centers: these must have more than 50000 inhabitants, a population density of 1500 people/km^2 or density of build-up area greater than 50%;
- Urban clusters: these must have at least 5000 inhabitants, a population density of 300 people/km^2;
- Rural areas: zones with fewer than 5000 inhabitants.

According to EU definitions, by 1950 already half of European citizens were living in urban areas. In 2018 this share reached 76% of EU population and is expected to grow up to 83% by 2050 (Pesaresi, Melchiorri, Siragusa & Kemper, 2016).

Higher urban agglomerations have strong impact on socio-economic, technological and environmental factors. Urbanization has a positive direct relation with income growth, labor productivity as well with technological adoption and competitiveness level, quality of infrastructure and workforce (BBVA, 2016). However, the phenomenon also has a negative impact on equality (Gini coefficient), waste management, air quality and overall efficiency (i.e. in public transport and health sector) (Brandmüller, 2016).

2.2 Air Emissions

Clear air is essential to human life. While a person can survive up to 2 days without water and 2 weeks without eating, it can handle just a few minutes without air. An average adult consumes 2 kg of water, 1 kg of food and 20 kg of air daily. If the latter is polluted, it has direct negative effect on human health (Zhongchao, 2014). As of today, each year one in eight of total global deaths (about 7 million people) happens as a result of air pollution exposure. Therefore, during the last decades, air pollution has become the single largest environment and health challenge to society and governments worldwide have started to enhance policies to contain its negative effects (WHO, 2014).

2.2.1 Air Pollution and Greenhouse Gases (GHGs)

Air emissions can be classified under two clusters: air pollution and greenhouse gas (Eurostat, 2013). Air pollution occurs when unwanted materials are added to the air, resulting in effects on the environment and health. Air pollutants comprise primary and secondary air pollutants: primary air pollutants are emitted directly from sources and include compositions such as Particulate Matter (PM), which incorporates solid and liquid particles suspended in the air such as sea salt, pollens and human carcinogens like benzoapyrene and black carbon, Nitric Dioxide (NO2), a toxic gas of reddish-brown color belonging to the family of the Nitrogen Oxides (NOx), and Sulfur Dioxide (SO2), a toxic and colorless gas with a sharp odor, which belongs to the Sulphur Oxides (SOx) (Zhongchao, 2014).

Secondary air pollutants, instead, are produced as chemical reactions among two or more primary air pollutants or between an air pollutant and a normal atmospheric constituent. Examples of secondary air pollutants are ground-level Ozone (O3), formed from a chain of chemical reaction between NOx, CO and VOC, and smog (EPA, 2018).

The second type of air emissions are greenhouse gases. These include Carbon Dioxide (CO2), Hydrofluorocarbons (HFCs) and Perfluorinated Compounds (PFCs). Most of them are produced by natural sources and have been present in the atmosphere for a long time. Only recently extra GHGs are considered contributors to global climate change and extreme weather (Zhongchao, 2014).

The main difference between greenhouse gases and air pollutants is that, while GHGs are not toxic, unless at extremely high concentrations, air pollutants directly affect human health (Zhongchao, 2014): O3, PM10 and SO2 mainly affect respiratory and cardiovascular diseases, PM2.5, a subclassification of PM, can cause stroke and lung diseases, including lung cancer, and NO2 contributes to liver and blood diseases, in addition to respiratory difficulties (Liu et al., 2019).

In 2014 the European Court of Auditors (ECA) reported that PMs caused about 400000 premature deaths of EU citizens, NO2 75000 and O3 13600. The organization also warns that air pollution affects people daily and that, while pollution peaks are its most visible effect, long-term exposure to lower doses poses a greater threat to human health (ECA, 2018).

2.2.2 Regulations on Air Pollution: European Union and World Health Organization

In order to impose limits to the presence of harmful pollutants in the atmosphere and to its effects on citizens, several organizations have set general guidelines to fulfill United Nations Environmental Assembly resolution *UNEP/QA.3/Res.8* from December 2017, whose goal is to prevent and reduce air pollution, in order to improve air quality globally (EC, 2020).

Fincluding limit values, to improve air quality by controlling emissions of harmful substances into the atmosphere. Member states are required to collect information on air quality through a network of monitoring stations containing devices that analyze and measure the levels of several air pollutants and to report the outcomes to the European Commission (EC) and to the European Environment Agency (EEA) each year. The EC assesses these data against the standards of the Ambient Air Quality (AAQ) Directive. Where concentrations exceed the limits, Member States must produce Air Quality Plans (AQP) to tackle the problem. The EC assesses these plans and takes legal action where it considers that Member States fail to comply with the directive (EC, 2019).

Another international organization that is contributing to air pollution reduction is the World Health Organization (WHO) Its guidelines, however, differ from what ruled by the EU: the international health entity settled stricter limits to emissions, implying that EU’s concentrations need to be reinforced to reach values that limit the negative effects on humans (WHO, 2020).

As shown in Table 1, the main discordances between EU Air Quality Directive and WHO guidelines appear in the different limitations applied by the two entities, as for PMs and O3, in the different time limits in which guidelines apply and in the exceptions made by the EU, which currently allows countries to exceed established limitations during some days per year.

Table 1. Air pollutants limitations: comparison between EU and WHO guidelines, own representation based on EEA (2013).

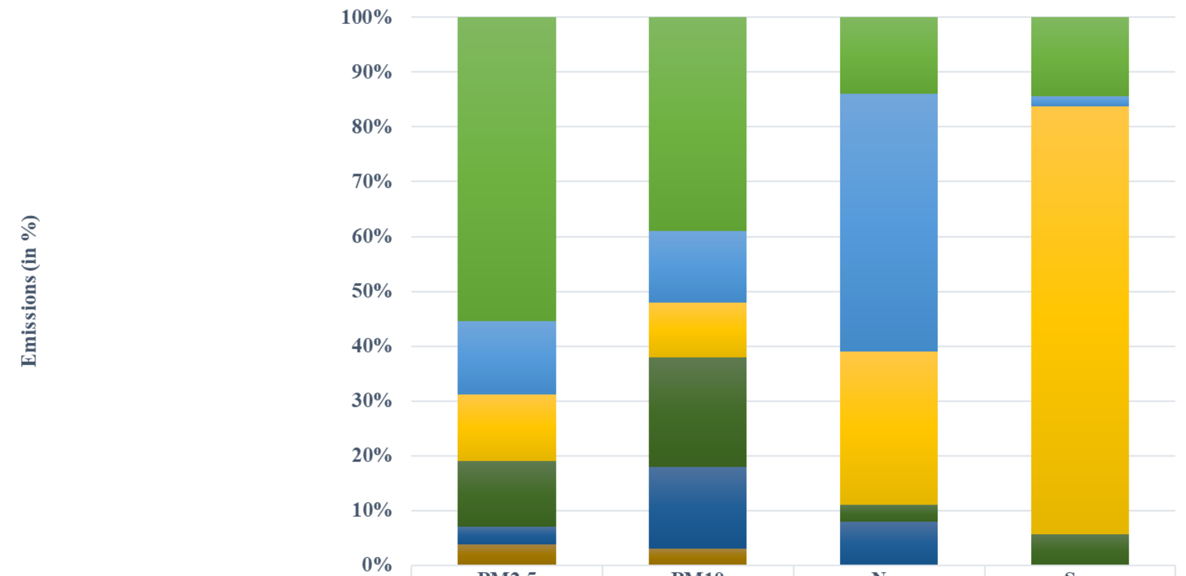
	EU limit value (in µg/m3)	**EU time reference**	**EU exposure estimate (%)**	**WHO limit value (in µg/m3)**	**WHO time reference**	**WHO exposure estimate (%)**
PM2.5	20	Year	20-31	10	Year	91-96
PM10	50	Day	22-33	20	Year	85-88
O3	120	8-hour	14-18	100	8-hour	97-98
NO2	40	Year	5-13	40	Year	5-13
SO2	125	Day	<1	20	Day	46-54
CO	10	8-hour	<1	10	8-hour	<2

Discordances in guidelines translate also into different population exposure estimates to air pollution: according to the EU, 33% of the population living in the EU-27 area experiences air pollution concentrations harmful to health. The forecast triples for WHO estimates, where up to 98% of European citizens are negatively affected by air pollutants (EEA, 2016).

2.2.3 Sources of Air Pollution

To address the problem with effective measures, governments should first identify how different sectors and processes contribute to the emissions of the main air pollutants (World Bank, 2014).

The main sources of dangerous gas emissions are waste, agriculture, industrial processes and product use, commercial/institutional and household, road and non-road transport, energy production, distribution and use in industry. These sectors together contribute to 99% of the negative emissions present in the environment (EEA, 2019).



	PM2.5	PM10	Nox	Sox
Commercial, Institutional, Households	55%	39%	14%	14%
Road and non-road transport	13%	13%	47%	2%
Energy production, distribution and use in industry	12%	10%	28%	78%
Insutrial processes and product use	12%	20%	3%	6%
Agriculture	3%	15%	8%	0%
Waste	4%	3%	0%	0%

Fig. 1. Emissions of main air pollutants by sector group in Europe, own representation based on EEA (2019).

As shown in Figure 1, in Europe the main sources of air pollutants are road and non-road transport, which produces 45% of NOx emissions and 13% of total PM2.5 and PM10 releases, commercial/institutional and households, responsible for 14% of the total NOx production, 56% of PM2.5 and 39% of PM10, and finally energy production, distribution and use in industry, emitting 31% of total NOx gases and 19% and 26% of total PM2.5 and PM10 emissions respectively (EEA, 2019c).

2.2.4 Air Pollution in European Cities

The analysis on air pollution provides a clear picture of the current situation from a country perspective, but if the focus is narrowed down to urban areas, elucidations are needed.

Air pollution tends to affect city dwellers approximately 2.3 times more than inhabitants of towns, suburbs or rural areas (Koceva et al., 2016). This because, due to the high density of people living in urban areas, air pollutants are released on a larger scale and because in a city-like environment dispersion is more difficult, if compared to the countryside (ECA, 2018).

Among all sources of air pollution in cities, road transport is the principal emitter of nitrogen oxides emissions (Institution of Civil Engineers, 1990, pp. 47). Given the congestion in many of Europe's cities it is not surprising that the highest concentrations of these emissions are recorded next to roads in major agglomerations (Eurostat, 2016).

Cities now more than ever have a role to play in relation to delivering sustainable economic growth and alleviating the problems associated with climate change. There is a wide range of policies that can be implemented to increase resource efficiency and lower pollution levels, as the promotion of recycling schemes for a range of waste streams, higher energy performance for buildings, cleaner transport or schemes that are designed to eliminate traffic and congestion (Eurostat, 2016).

Some European cities have started to implement policies, in order to tackle the increasing issue of air pollution. These include cars ban or limitations (i.e. Milan), providing citizens with free or more efficient public transport (i.e. Paris) and improving the number of cycle lanes (i.e. Oslo). Measures normally come as part of more extensive city halls plans to transform cities into smarter and greener cities (C. Harris, Cereceda, & Armstron, 2019).

2.3 Smart Cities

Cities consume between 60% and 80% of energy worldwide and are responsible for large shares of air emissions (UN, 2019). The metabolism of cities, most of the times, consists of the input of goods and output of waste, generating negative externalities which might affect social and economic sectors. However, there is a huge potential to make cities widely efficient, as resource use per person in urban areas is lower than in sparsely populated areas (EEA, 2019c).

The approach through which cities nowadays started to tackle urban issues and to implement efficient policies is using harnessing technologies, which help to create what some call "smart cities" (Albino, Berardi, & Dangelico, 2015, p. 4).

The term "smart city" was first used in the 90s, when the focus was on the use of ICT for modern infrastructures, and one of the first definitions available was created by the California Institute of Smart Communities, in the United States (Albino et al., 2015, p.4). Since then, the concept evolved and today it is described as "the application of information and communications technology with their effects on human capital/education, social and relational capital, and environmental issues" (Lombardi, Giordano, Farouh, & Yousef, 2012).

The main technologies being used nowadays in the context of smart cities are big data, blockchain, sensors, 5G connectivity, geospatial technology, robotics, artificial intelligence and internet of things. Some of the benefits coming from the use of technologies in cities regards topics such as public safety, improved public transport, more effective data-driven decision making, reduced environmental footprint, efficient public utilities and better citizen-government engagement (McKinsey, 2018).

To assess the level of smartness of a city, Lombardi et al. (2012) have also identified a list of indicators and the related aspects of urban life, which can be found in Appendix 1. Among these, one can name several socio-economic factors to which ICT can be applied, but also the presence of environmental aspects, which nowadays are considered by most as essential part of any smart city plan.

The importance of fostering environmental aspects or "green growth" in cities is all the more apparent in light of the rapid growth of cities and the concept of green growth has attracted much interest from governments at all levels, not only to respond to environmental challenges but also to stimulate growth (OECD, 2013, pp. 1–3). The birth of the "green" factor is dated back in the 2000s, when the international political agenda started to bring climate change issues into international political agendas. Since then, energy, resources efficiency and especially environmental performance became central elements in the quantification and definition of city sustainability (Vita et al., 2019, p. 4).

A green economy means new growth and job opportunities: EU governments could benefit from increase resource productivity by 30% by 2030 and boost Gross Domestic Product (GDP) by nearly 1% and creating 2 million additional jobs, while businesses could take advantage of eco-innovation, waste prevention and the reuse of raw materials to save up to €600 billion. Altogether, such measures could help turning the EU and Member States into resource-efficient, greener and competitive low-carbon economies (EC, 2020a).

2.4 Internet of Things

IoT is one of the key components of the ICT infrastructure of smart sustainable cities thanks to its great potential to advance environmental sustainability (Bibri, 2018). Connecting physical devices to the internet is not a brand-new idea: in 1999 Kevin Ashton coined the term 'Internet of Things', known as pervasive computing ubicomp and ambient intelligence (Ashton, 2009). However, given that in the 90s database storage was too expensive, only from the 00s new opportunities for IoT have opened up, mainly favor of the rapid decrease in cost and the broader availability of other technologies essential to IoT proper use, such as sensors, wireless, mobile networks and platform technologies (IOT Council, 2020). IoT was initially proposed to refer to uniquely identifiable interoperable connected objects with radio-frequency identification technology (Xu, He, & Li, 2014, p. 2236). Later, researchers started to relate the term with more technologies such as sensors, actuators, GPS devices and mobile devices.

Today, a commonly accepted definition for IoT is a "dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual 'Things' have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network" (Noura, Atiquzzaman, & Gaedke, 2018). Such *smart* objects come in a wide range of sizes and capacities, including simple objects with embedded sensors, household appliances, industrial robots and cars (EP, 2015)

2.4.1 IoT Architecture and Technical Requirements

In the context of smart cities, IoT offers diverse applications. However, the broad potential use of IoT devices demands the following technical requirements (Mehmood et al., 2017):

- Short- and wide-range communication protocols to transport data between devices and back-end servers, i.e. Wi-Fi, Bluetooth, Long Term Evolution (LTE);
- Cutting-edge services and platforms for smart city applications brought by servers' providers;
- Capillary IoT networks offering short- and long-range services to ensure a fully autonomous environment, i.e. Wireless Local Area Networks (WLAN);
- Activities of standard bodies, as Internet Engineering Task Force (IETF) and Institute of Electrical and Electronics Engineers (IEEE), which ensure the development of standards to support smart city applications on a large scale, for instance by reducing the bandwidth for applications better network coverage and by supporting low-power consumption devices;
- Availability of IoT solutions which are low cost, low energy consumption, high quality service, able to cover wide areas, interoperable and connectible, high security and privacy.

Once the requirements are set, IoT-powered system work on a 4-stages procedure:

- **Stage 1: Networked things (sensors and actuators)**
  A sensor is a device that detects and responds to some type of input from the physical environment and that can convert the information obtained in the outer world into data for analysis. Sensing technology allows objects to collect information about their surroundings, record it and then forward it. Actuators, instead, are devices able to convert electrical signals into mechanical motion or physical variables (Minerva, Biru, & Rotondi, 2015).

Any IoT device should have a unique identification and localization. To achieve this, radiofrequency identification and bar codes can be used. Radiofrequency is often preferred because direct vision between transmitter and receiver is not required, as in the case of bar codes.

Finally, technologies such as Wi-Fi, Bluetooth and Infrared can be adopted to automatically identify and track the location of objects in real time (Wickramasinghe, 2018);

- **Stage 2: Sensor data aggregation systems and analog-to-digital data conversion**

  Sensors and actuators are then connected to the web to become accessible. Data acquisition systems connect to the sensor network to aggregate the enormous amount of data.

  Data aggregation is the process in which data is gathered and analyzed to express them in a meaningful and summarized form. Received output is squeezed into the optimal size for further analysis through Wi-Fi/WLAN (Medagliani et al., 2014, pp pp.287-313);

- **Stage 3: Edge Information Technology (IT) systems (analytics, pre-processing)**

  Edge IT systems perform enhanced analytics and pre-processing through technologies as machine learning and visualization technologies. At this stage, further processing may happen before data is sent to the data center. IT systems are used to process and generate meaningful results while passing them to the next stage (Wickramasinghe, 2018)**;**

- **Stage 4: Analysis, management, storage of data**

  The main processes in the fourth and last stage happen in data center or cloud. These enable storage, in-depth processing and a follow-up revision for feedback time. These powerful platforms can pinpoint exactly what information is useful and what can be ignored. Obtained information can be used to stimulate actions, but also to detect patterns, make recommendations and forecast possible problems before they occur (Wickramasinghe, 2018). The big value of IoT lies exactly in its association with big data analytics, a vast quantity of data captured by the interconnection of all devices, and in their ability to communicate in real time, which prompts quick actions, especially if compared to traditional systems (EP, 2015).

As such, IoT and related big data applications can play a key role in catalyzing and improving the process of environmentally sustainable development. However, studies and policy makers often apply IoT and related big data applications in relation with economic growth and quality of life within smart cities, ignoring the potential it also has in improving environmental sustainability (Bibri, 2018).

2.4.2. Market of IoT Technologies

The number of connected devices worldwide is projected to increase from around 18 billion in 2015 to 50 billion by 2020 (Statista, 2020). McKinsey forecasts the range of the IoT potential impacts on the global economy by 2025 in the range between $3.9 and $11.1 trillion, as countries all over the world started to invest more and more on this technology. In 2014 total IoT market worldwide amounted to $655.8 billion (McKinsey, 2018). This already impressive amount tripled in just a few years: as of 2020, the estimate total expenditure for IoT related technologies is around $1.7 trillion, which compounds an annual growth rate of 16.9% (IDC, 2019).

The EU acknowledges the importance of research and testing on the IoT to support the development and the take-up of this technology. For the period 2014-2021 under Horizon 2020, a European research and innovation program, the Union will invest almost €500 million in IoT-related research, innovation and deployment; this sum should be added to country specific investments on IoT-related projects (EC, 2019a).

2.4.3 IoT for Air Quality Control

Conventionally, air quality monitoring is performed by large, expensive scientific instruments permanently installed and professionally maintained, at a relatively small number of fixed locations typically in cities and along major transportation routes. Government agencies manage and often publish the data collected from country, regional or citywide environmental monitoring networks. These data are verified and aggregated, often resulting in at least a 24-hour lag before publication, offering no opportunity to use this data in real-time to avoid or reduce risks from poor air quality conditions (World Bank, 2016).

However, a new generation of cheaper and faster devices is starting to spread. Through new IoT and related technologies, modern cutting-edge air quality monitoring sense the environment more often than traditional stations, up to several times a minute, share acquired data in a quicker way, through continuous connection, with the use of more cost-efficient and precise devices (Lyon, 2020).

The global market for air pollution control equipment is expected to increase from over $14 billion in 2016 to over $20 billion in 2021, with a Compound Annual Growth Rate (CAGR) of 7.8% (Biswas, 2017).

The benefits coming from the implementation of smart air quality monitoring systems in cities are numerous: it can prevent governments from high health costs, help city halls in improving urban planning and accessing the green bond markets, and provide regulators with reliable devices which allow them to ensure regulatory compliance through independent monitoring and to reduce the societal impact of poor air quality. However, the implementation of these new technologies could also present some cons, mainly related to cybersecurity (AQ-Mesh, 2016).

2.4.4 IoT for Traffic Management

Traffic congestion is a major issue that happens across urban cities around the globe. The dramatic increase of registered vehicles, mainly caused by urbanization, requires more efficient ways to manage traffic, in order to improve public transport services, decrease air pollution and save time for drivers (EPA, 2020).

Several countries are overcoming this traffic bottleneck by fetching information from closed circuit television feeds and transmitting vehicle-related data to city traffic management centers to help create improvements (SILEO, 2018). Better organized traffic systems mean a better flow of vehicles on the road, and it means no idling cars, buses and trucks in traffic jams (CORDIS, EU Research, 2019)

IoT can help city halls in improving traffic management systems in several ways: the technology can be used to make video analysis, create wireless sensors networks and adaptive traffic control systems, among other functions (Soni & Saraswat, 2017).

The global traffic management market size is expected to grow from $30.6 billion in 2019 to $57.9 billion by 2024, at a CAGR of 13.6% during the forecast period (MarketsAndMarkets, 2020). Europe accounts for the highest market share in terms of revenue from traffic management, benefitting from strong technical expertise, with a higher number of traffic control vendors in the region and bigger IT budgets. The European Commission (EC) allocated a total of $6339 mln. for the smart, green and integrated transport challenge for the period 2014–2020 (EC, 2020b).

The main benefits of introducing IoT systems in transportation are improved mobility and traveler experience, enhanced safety and security, lower energy usage and congestions and better operational performance (MarketsAndMarkets, 2020). The main challenges lay on security and extended network infrastructure issues (HERE Mobility, 2020).

CHAPTER 3: METHODOLOGY

3.1 Research Approach

This research aims at studying the business opportunity for public bodies to implement IoT systems in traffic management policies for the purpose of air pollution reduction and its effect on different stakeholders. Several studies are available on the topics of focus but comprehensive research on the linkages between them is still lacking and insights from city halls and governments are not always available. For this reason, a qualitative, exploratory approach is considered the most appropriate.

Qualitative research allows to define the “how”: it is suitable for complex problems not fully defined and studied yet and for situations in which linkages between different sectors need to be explained (Creswell, 2003, pp. 1–3). Within the context of qualitative research, whenever no comprehensive theory or hypothesis are available in forehead, the suggested approach is the exploratory (S. Kumar & Singh, 2001). The exploratory approach is a form of social inquiry that adopts a flexible and data-driven research design, to use relatively unstructured data, to emphasize the essential role of subjectivity in the research process, to study a small number of naturally occurring cases in detail and to use verbal rather than statistical forms of analysis (Hammersley, 2013).

The research is based on two methods: the collection and analysis of primary and secondary data. Primary research consists in information gathered directly from a subject, either as a group session or individually. This type of research is suggested to explore a problem which requires in-depth understanding of the topic. Primary research methods include the use of surveys, interviews and focus groups. Secondary research consists of collecting information from published research. It includes sources such as reports, books, newspapers etc. Secondary data will be used to articulate some concepts, supporting findings obtained through primary data (Kite, 2020).

Furthermore, in order to provide a comprehensive picture, data triangulation was applied whenever possible. This approach refers to the practice of using multiple sources of data in order to enhance the credibility of a research study (Thurmond, 2001, p. 255). Among the sources, the focus is firstly on the different perspective of all stakeholders on the implementation of IoT in smart cities. Secondly, databases, case studies, reports and articles, will provide additional information, which will allow for a cross-check with previously acquired data. Lastly, gathered data have been processed using the thematic approach.

3.2 Primary Data

For the purpose of this research, the type of primary sources chosen have been interviews with experts in fields of IoT, traffic management and air pollution. Interviews have been necessary to understand the status quo and the different stakeholders' perspectives on the research topics: experts could provide more pragmatic perspectives, raise novel angles of debate not identified and provide with complementary information with respect to secondary data available.

3.3. Secondary Data

Secondary data used in the research includes books, researches from major journals, reports and articles. Gathered information has been used to provide a theoretical background on the field of air pollution, traffic management and IoT, allowing the creation of a cohesive and consistent literature review able to clarify previously started research questions.

Furthermore, secondary data has also been used to add concrete data to the information acquired through the interviews with experts, enabling the use of tangible cases to justify and further develop experts' statements.

3.4 Data Collection

Data collection is the process of acquiring and analyzing information on specific variables, which allows to answer relevant questions and determine outcomes (Jamshed, 2014, p. 87). Data have been collected through 10 interviews conducted between 18th March and 21st April 2020 with traffic management experts, city-hall advisors, IoT experts and consultants. Interviews lasted between 45 and 90 minutes and have been conducted remotely, though the use of web video services. The complete description of the participants is available in Appendix 2.

Conducted interviews were organized using the semi-structured method. This includes both predetermined and unplanned questions, which provide with an opportunity to clarify specific points and spontaneously explore other relevant topics. Moreover, the semi-structured type ensures reduction in biases, whist allowing for objective comparison of candidates and of final outputs (Adams & Lawrence, 2018).

Unique scripts have been created for each stakeholder, in order to leverage the different expertise of each interviewee. However, a common set of questions regarding needs, solutions, opportunities and challenges of IoT application in traffic management to solve air pollution related issues have been used. Questions are available in Appendix 3.

3.5 Data Analysis

In order to analyze gathered data, a thematic content approach has been used. Thematic analysis, besides being one of the most common forms of analysis within qualitative research, aims to find common patterns across a data set by identifying, analyzing and interpreting its content (Braun & Clarke, 2006, p. 95). This approach can be used to analyze most types of qualitative data, including interviews and secondary sources, and is suggested whenever a set of different approaches is available, as in this research (Saldana, 2012).

Attempts to define a sample size have been accomplished focusing on the concept of saturation, the situation in which codes and themes are evident in acquired data. These attempts suggest that code saturation can be achieved with a minimum of 6 interviews (Guest, Bunce, & Johnson, 2006, p. 72). In this study the minimum threshold is fulfilled by conducting a total of 10 interviews.

The main findings from the interviews can be found in Appendix 4.

CHAPTER 4: FINDINGS

In this chapter the focus is on describing the main findings from the interviews with experts on the research topics. Outcomes are successively narrowed-down to one case, on which a full employability and cost-benefit analysis is performed. Furthermore, additional externalities caused by its implementation are highlighted. Primary data has been complemented using secondary sources, in order to provide a rounded overview of the results.

4.1 Importance of Air Quality and Measures Being Implemented

Air pollution is now more than ever an urgent need, due to the numerous studies available confirming the direct correlation between pollutants and damages on people's health in terms of morbidity and mortality, but also with the economy as a whole, in terms of productivity, absenteeism at work, environmental costs (i.e. damage to local natural-related economies as wood production), in addition to the evident decrease in health costs (Manisalidis, Stavropoulou, Stavropoulos, & Bezirtzoglou, 2020). Throughout the last decades European countries have begun to implement policies to fight air pollution, directly and indirectly: most of EU-27 governments decided to address the problem by investing in solutions within the transport sector: as presented in Figure 2, 46 % of the measures concerning PM10 reduction target road transport, 20% address the commercial and residential combustion sector and 17% the industry. For NO2, more than 60 % of the measures reported mainly target the road transport sector. Industry (13 %) and the commercial and residential combustion sector (11 %) are respectively the second and third most targeted sectors (EEA, 2018).

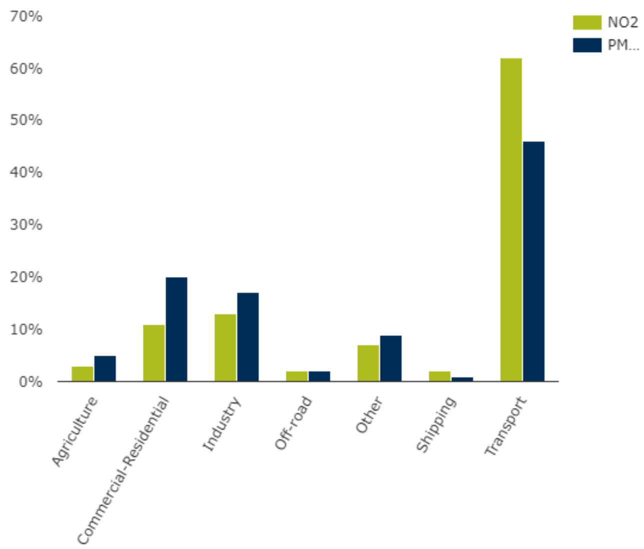


Fig. 2. Sectors addressed by the reported measures for PM10 and NO2, from EEA (2018).

Through the implementation of these measures, most Member States tried to addressed traffic sources, especially for NO2 (Figure 3). Concretely, most common measures include:

- Public procurement (purchase of low-emissions vehicles by authorities);
- Shift in transport mode (expansion of bicycle and pedestrian infrastructures);
- Land use planning (transport facilities improvement);
- General improvements in public transport.

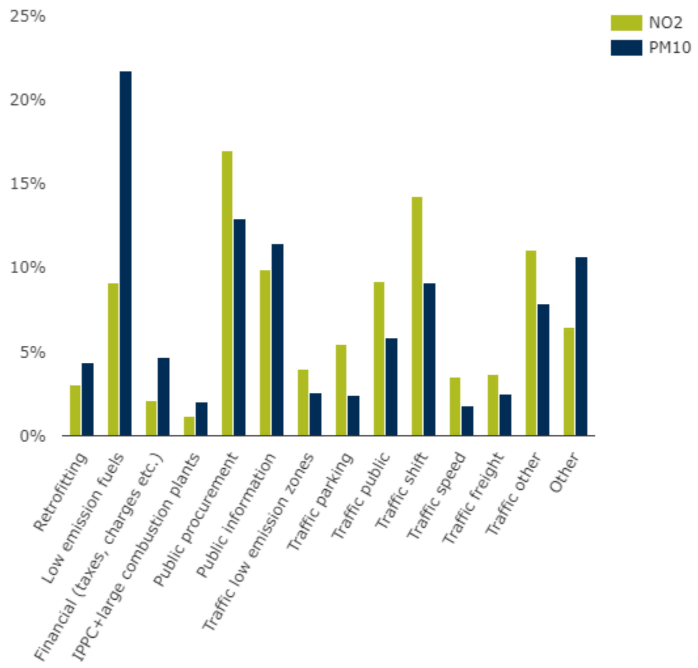


Fig. 3. Classification of measures designed to reduce PM10 and NO2, from EEA (2018).

Traffic low emission zones, traffic speed and traffic freight are among the least targeted policies within the traffic sector. Other measures being undertaken, 25% of them for PM10 and 10% for NO2, target combustion related sources. These include low-emission fuels and public information, aiming at raising awareness among the population about measures individuals can take to reduce air pollution (EEA, 2018).

Over the last decades, a mix of cross-sectional measures implemented in different sectors within the EU have shown positive results: between 2000 and 2018 PM2.5 concentration has decreased 39.9%, PM10 presence fell 36.2% and NO2 has seen a drop of 76.3% (EEA, 2018).

In this framework, road traffic moved from contributing in 42.2% of total NO2 emissions to 36.5%, from 16.1% to 10% in PM2.5 and from 10% to 8% in PM10 (Krzyżanowski, Kuna-Dibbert, Schneider, & WHO). Besides being positive results, which in some countries allowed air pollutants concentrations to land below European threshold, for several other countries it has not been enough to achieve their targets, translating in rebukes from the Union and sometimes in highly expensive fines (EEA, 2019c).

4.2 Air Pollution KPIs for Member States

Air quality has been in EU's agenda for a long time. Over the last decades, the Union has settled not only air quality common threshold every Member State must respect, but also taken actions is case this was not fulfilled or excessively delayed (ECA, 2018).

As previously presented in Table 1, EU's and WHO's thresholds differ in some air pollutants limits, being WHO stricter in terms of concentrations and tolerance days. The AAQ Directive, one of the backbones of air quality within the EU, mentions that Member States should develop and introduce air quality plans where exceedances are reported. By doing do, the Union wants to focus only on results, letting each country decide the most appropriate means of action (EEA, 2019d).

According to some of the experts interviewed, most public bodies responsible for air quality share the same target: "the goal to achieve in terms of air pollution is similar all over Europe" states expert Expert10 and corresponds to "decrease air pollution concentrations, letting them fall below European limits, in order to avoid trials with the EU and the eventual issue of expensive fines." However, as of today, not all countries have been able to implement successful plans to achieve these goals. (EEA, 2019a).

In the last report on air quality in Europe, made in 2017, the results on key pollutants, namely PM2.5, PM10 and NO2, showed several cases of exceedances in air pollutants concentrations among the Union, with Poland, Bulgaria and Italy being the countries with most reporting locations exceeding the limits and Estonia and Finland among the ones with no exceedance recorded (EEA, 2019a). The report highlighted the heterogeneity of the exceedances, as some countries are outperforming others in air pollution detection and reduction, and stated that not every country is prioritizing air quality issues on its agenda. A worrying signal comes from the lack of official and detailed plans to reduce national emissions from countries that are not respecting common rules (Arbinolo, 2019). Additionally, another big issue concerns long term goals (additional reductions in air pollution): "often times, once European goals are achieved, there is little to no political will to make further improvements", states Expert5 since legal pressure disappears.

4.3 IoT Applications to Tackle Air Pollution Through Traffic Management

IoT is considered a valuable solution to address air pollution in cities: such systems would allow to collect pollutants data, to control air pollution levels and to take preventive and corrective actions when needed (Toma, Alexandru, Popa, & Zamfiroiu, 2019). Its considerable value, however, does not only consist in its wide employability, but also in the low cost of the technology, the ease of implementation, guaranteed by its non-invasive essence, and the huge impact its adoption could entail (Arano, Sun, Ordieres-Mere, & Gong, 2019).

Investments on IoT systems are increasing every year, with the biggest global share (23%) being allocated to smart city project; 45% of which is deployed in Europe. This makes IoT within the context of smart city a real opportunity for companies operating in the sector, always willing to find new solutions to implement to improve citizens' life (Columbus, 2018).

For what concerns air quality management, as of today low-power wide area networks have enabled the development of portable and cheap sensors. These sensors are included in bigger projects and often used attached to streetlights, public benches and even people to measure and report air quality with great precision (A. Kumar, 2019b). Some of the most evident benefits lying on IoT-powered solutions to solve air pollution issues that highlighted by experts relate to the low cost and potential high benefits, high amount of data to be gathered and analyzed, broader areas to be controlled, smart city integration, possibility to raise awareness on environmental issues and communication of accurate air quality information (McKinsey&Company, 2018).

For what concerns traffic management, city halls and governments are turning to connected devices to gather data and insights about the status of numerous factors important to efficiently serving the needs of citizens. The rise of low-price sensors enables more effective ways to monitor and actively manage traffic using real-time data (McKinsey&Company, 2018). Detection algorithms are applied to video streams and the huge number of sensors and by doing so data is collected. Gathered data is then sent to the city traffic management board where everything is checked and traffic adjustments are made accordingly (Guerrero-Ibáñez, Zeadally, & Contreras-Castillo, 2018). In other cases, cities pre-settle different levels of emergency, which automatically enable bigger or smaller changes in traffic lights timing and smart signals displays. Expert2 explained specifically how such system works in the city of Rotterdam, where city smart traffic systems are used to limit cars access in some areas of the city, modify drivers' routes and improve the "road experience" for environmentally friendly movements (i.e. bikes, pedestrians).

The most recurrent benefits of IoT systems for traffic management are better overall performance with positive effects on congestion decrease and traffic safety, dynamic traffic information, reduce energy use, economic benefits on both short and long term and increased safety (Thakur, Malekian, & Bogatinoska, 2017).

The potential solutions for IoT to tackle air pollution issues through traffic management in cities are many: IoT devices are being incorporated in most of the components of a smart infrastructure technologies, from traffic lights to smart signals and from video-recording cameras to parking lots for vehicles (Garcia, Jiménez, Taha, & Lloret, 2018, p. 23).

4.4 IoT: Status Quo and Potential Limitations

According to interviewed experts, IoT implementation in most European cities in every sector is a matter of time and security limitations, not of technological barriers nor budget. Its applicability in a wide range of sectors (e.g. environmental monitoring, healthcare, inventory and product management) clearly shows the possibility of this technology to interoperate not only in different fields but also with different systems, proving technological barriers for its implementation are scarce and can be easily overcame (di Martino, Li, Yang, Esposito, & Di Martino, 2017). As of today, technological advance for most technical requirements of IoT, such as communication protocols, device management, alongside services and platforms for smart city applications, achieved a very high-quality level and an unprecedented refinement. This can be easily justifiable by the availability of hardware, software and processes that scale to billions of connected devices and trillions of messages, edge-processing systems which can respond in few milliseconds and large-scale processing that combines loads greater than 100000 events per second (Cognizant, 2019).

From a budget perspective, most of the interviewed experts agreed that IoT solutions are the best in terms of cost and benefits, as there are few cheaper solutions available in the market which can have the same potential impact in traffic control and in air pollution reduction. For what concern the cost of sensors for IoT usage, between 2004 and 2018 it has seen an average drop from $1.30 to $0.44, following a price fall trend and with a proportionated decrease in operational costs too (Microsoft, 2020). Even though the implementation cost should consider not only the cheap devices available in the market, but also software for data analysis and traffic management, certifications, data security and additional systems to which IoT might connect, which might have a big impact on the initial investment to be made, the potential economic and health benefits is expected to overcome initial expenses, especially on the long term (McKinsey&Company, 2015). However, some of the interviewed experts highlighted the need to implement IoT systems as part of a broader plan for a smart city, in order to decrease projects' costs, allocating implementation expenses to a bigger variety of projects and to achieve exponentially bigger results, through the creation of a net of interconnected projects within a city environment. According to Expert7 "Every city must have a vision overall to become smart, clear goals and a strategy to have a conglomerate system to deploy IoT devices. Only afterwards a city could really benefit from IoT implementation and … maximize its results". A conglomerated system of devices would also serve to mitigate the environmental impact of IoT devices: Expert1 underlined the importance of taking into consideration "the trade-off between air-pollution decrease and the environmental impact of the components of measuring devices" as these, could have an indirect negative impact on the problem as well.

For what concerns timing for future implementation of this technology, according to Expert4 "Public and private sectors have brand different approaches to the problem", with the first being willing to develop and invest in new technologies and the latter more keen on policies that can guarantee big results on the short term. However, the expert also added that this might change very soon, as central governments and city halls started to understand the huge economic return new technologies as IoT can have through programs such as the "Mayors deal", which allows mayors from different countries to share best practices implemented in their cities.

Lastly, security might be the biggest concern in adopting IoT, on one side due to the fast development this technology has seen throughout the last decade and on the other due to the lack of appropriate regulatory changes (Feamster, 2017). Most of the concerns include weak authentication, unencrypted messaged between devices and poor handling of security. These security issues are also present among servers, workstations and smartphones. The additional issue with IoT devices comes from its operational limitations and from the computational power available to them, which sometimes make it complex to take counteractive security measures autonomously (Bastos, Shackleton, & El-Moussa, 2018, p. 7).

Furthermore, security issues coming from increased digitalization include also privacy-related concerns, with the most evident aspects being potential for unexpected uses of consumer data mainly by corporations seeking financial advantage and governments craving for more control (TomDispatch, 2014; Hajdarbegovic & Toptal, 2015). However, Expert7 stated that "data security issued can be easily solved when … considered from the implementation stage of the project. The biggest problem comes from the cost and the weak impact of tackling privacy issues once a project has been implemented". This statement is also supported by EU researchers, which claim that a widespread solution to tackle privacy-related issues has been identified when the concerns are addressed at the design stage of any IoT technology (EC, 2017). Furthermore, from a legal perspective, national governments and the EU have tackled privacy issues, aiming at implementing only IoT-powered technologies which fulfill all regulatory approaches concerning fundamental rights in terms of data protection, privacy and information security, providing additional protection to final consumers (EC, 2017).

4.5 Road Pricing

Among the huge variety of solutions available, this study focuses on the implementation of road pricing or road user charges in city centers. The reason why this system has been chosen is mainly due to its "high potential impact and the low cost of implementation", as advised by interviewed experts. Specifically, this study tests the possibility to link road pricing directly to pollution concentration levels, being an urgent issue many cities are trying to solve. Interviewed experts underlined the huge environmental impact such policy could have, with average low implementation and operational costs.

The following analysis of an air pollutants concentration driven road pricing policy is tested through a dynamic pricing scheme, with the aim of controlling and decreasing air pollution in cities, while generating positive revenues, to invest in parallel activities such as public transport. This will be highlighted through a cost-benefit analysis. Results will be useful to understand the impact on air quality and on governments budgets.

4.5.1 An IoT-Powered and Air Quality Driven Solution in Road Pricing

Road pricing consists in direct charges applied on drivers to the use of roads in specific areas of a city. Pricing can be static or dynamic and the latter can be linked to several factors, such as details of the vehicle and congestion levels. Fees can be distance or time-based and can be applied in specific areas or within the whole city (Small & Gómez-Ibáñez, 1998, p. 229). Users can pay the charge in many ways, with apposite automatic devices owned by vehicles owners, phone-credit (sms, calls) or through registration, which allows a deferred payment (Gibson, 2015).

The primary aim of road pricing implementation is to decrease traffic congestion, especially during peak hour and coming from private vehicles use. By implementing this system, cities can benefit from a decrease in direct and indirect negative externalities such as lower collisions, emissions, noise and street danger (Johnson, Leicester, & Stoye, 2012). The charges are used for revenue generation and most of the times cities re-invest it in other policies such as infrastructure financing and public transportation management. In Europe, cities which are leading the way with the efficient implementation of such systems are London, Stockholm and Milan (Croci, 2016, p. 259). Further analyses will be based on studies on the road pricing measures implemented in these metropoles.

4.6 A Dynamic Road Pricing Scheme to Decrease Air Pollution in Cities

In this chapter the focus is on a model, which links PM10 and NO2 concentrations to road pricing, being these key pollutants strictly related to road pollution, as explained in chapter 2.1, and the only ones with availability of data. The calculi are performed firstly by linking air pollution concentrations to number of polluting vehicles and afterwards by building a pricing scheme, following elasticity of demand's formula, which joins variation of polluting vehicles and variation in road fees. The goal of this section is to understand how to decrease air pollution by applying a higher road pricing, leveraging consumers' responsiveness to price changes.

Successful road pricing implemented in Milan, London and Stockholm, showed that an average decrease in polluting vehicles of approximately 35% has been translated into a reduction of 13% to 15% of NO2 and PM10, respectively. Assuming a linear correlation between these variables, the total amount of polluting vehicles in a city (100%) contributes to 42.9% of the full amount of PM10 concentrations and to 37.1% of total NO2. Therefore, these percentages will be the maximum target achievable in terms of air pollution reduction, which could be obtained with a complete ban of polluting vehicles. Figure 4. shows the direct correlation between the variance in percentages between polluting vehicles and key pollutants concentrations.

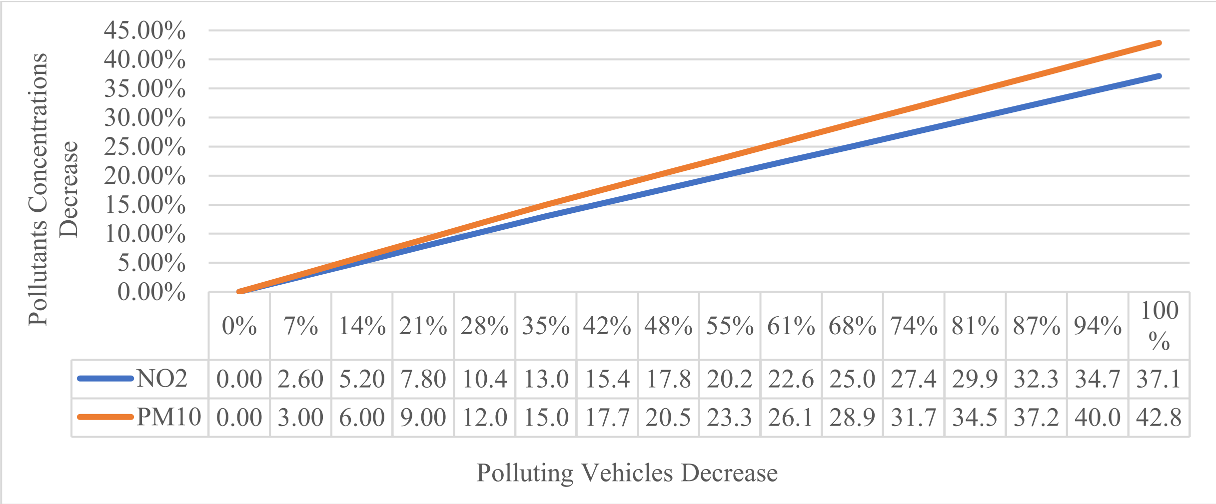


Fig. 4. Correlation between polluting vehicles decrease and air pollution decrease (in %), own representation based on Croci (2016), p. 259

Studying the correlation between the variables and the slope of each line, the following equations can be derived:

$$\mathrm{qPV\%} = 0.37\mathrm{NO2\%} \tag{1}$$

$$\mathrm{qPV\%} = 0.43\mathrm{PM10\%} \tag{2}$$

Equations (1) and (2) prove that for a decrease of 1% in number of polluting vehicles, there is a correspondent decrease of 0.37% and 0.43% in NO2 and PM10 concentrations respectively; these will be useful in the next steps to create a direct correlation between air pollution and price.

Once the relationship between polluting vehicles and air pollutants concentrations has been found, the pricing model based on price elasticity of demand can be created. Price elasticity of demand is "a measure of the responsiveness of consumers to a change in a product's cost" (McEachern, 2008). The equation for any calculation of demand elasticity is the percentage of change in the quantity that is in demand divided by the percentage change in the economic variable, which is represented in (3), where ε is price elasticity, $\Delta Quantity$ stands for positive or negative variation in quantity as a consequence of $\Delta Price$, positive or negative variation in price (McEachern, 2008).

$$\varepsilon = \frac{\Delta\, Quantity}{\Delta\, Price} \quad (3)$$

Tracking price elasticity of demand helps businesses set their targets as well as adjust their prices. The higher the price elasticity, the more responsive are consumers to a product's price change and the lower, the less. If price elasticity of demand is greater than 1, it is elastic. That is, demand for the product is sensitive to an increase in price. Price elasticity of demand that is less than 1 is inelastic, thus demand for the product does not change significantly after a price increase (Investopedia, 2019).

For the purpose of our analysis, elasticity is an exogenous value, taken from literature studies on the policy application in Europe, while variation in quantity and price are the variables on which the correlation is built (Croci, 2016, p. 259). Thus, an increase of quantity variation impacts price variation directly, positively or negatively according to elasticity's sign. The focus of this study will be to understand this relationship and build a model cities could use to decrease air pollution, leveraging consumers' responsiveness to price changes.

Considering that in this case elasticity of demand is not affected exclusively by road pricing, but also by gasoline and parking price, it is needed to assume the possibility to disregard these values. This assumption is supported by studies on the little effect of gasoline price on demand for traveling and on the elasticity of demand of parking, which tends to 0 (U.S. Energy Information Administration, 2014; Kelly & Clinch, 2009, p. 195).The theory that a congestion charge weights more than the increase in gasoline price or other costs in the perception of drivers is also supported by studies on road pricing itself (Croci, 2016, p. 257).

The first step to build a relationship between air pollution decrease and road pricing is to set some values on which elasticity and variations in price and quantity are based. The elasticity value used for our analysis is -0.5, taken as an approximation of elasticity values of both London and Milan road pricing schemes, respectively -0.46 and -0.66 (Croci, 2016, p. 257).

Using a negative elasticity of 0.5 means that for every X increase in prices (P), there will be a consequent decrease in demand (Q) equals to X times 0.5, as shown in (4).

$$+1\%P = -0.5\%Q \quad (4)$$

Once the relationship between variation in price and variation in quantity has been established, a direct correlation between changes in price and variation in pollutants concentration can be created by joining the correlation formulas between variation in polluting vehicles, pollutants and price in a system, as shown in (5) and (6).

$$\begin{cases} 100\%qPV = 37\%NO2 \\ 100\%qPV = 43\%PM10 \\ 100\%qPV = -50\%P \end{cases} \tag{5}$$

$$\begin{cases} +1\%NO2 = -0.19\%P \\ +1\%PM10 = -0.21\%P \end{cases} \tag{6}$$

Firstly, equation (5) presents the percentage of NO2 and PM10 (%QNO2 and %QPM10) caused by the totality of polluting vehicles (qPV) and the correlation between price (%P) and amount of polluting vehicles (qPV), as an extension of (4).

Equation (6) is obtained by solving the system in (5) and proves that a variation of 1% in NO2 and PM10 corresponds to a direct negative impact on prices equal to -0.19% and -0.21% respectively. Figure 5 is the graphical representation of the system just created. In this figure you can see how percentage price increases impacts on the quantities of NO2 and PM10 concentrations and on polluting vehicles and the linear correlation between the three.

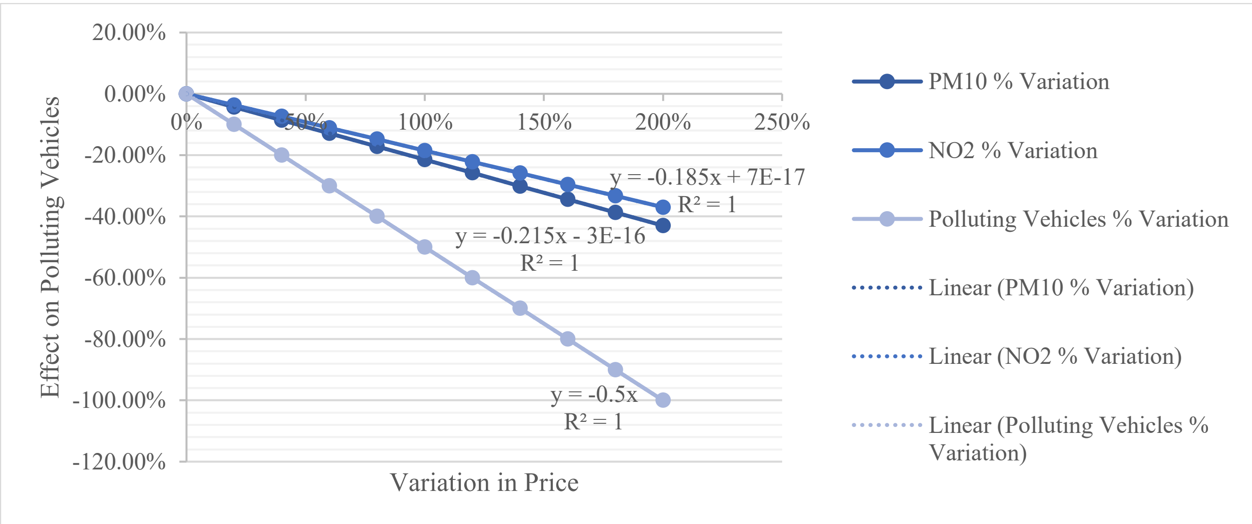


Fig. 5. Effects of variation in price on number of polluting vehicles and air pollutants concentration (in%), own representation

To clarify the applicability of the theoretical findings, a real scenario will be built. This will help the reader understand how to achieve concrete targets, anchoring current concentrations to EU threshold and applying the concrete examples of cities that have implemented road pricing during the last years.

Considering that studies confirm that big cities are the highest source of transport related air pollution, as presented in chapter 2.2.4, the assumption made is that a city average pollution at time 0 aligns with European maximum limit, thus equals to 40ug for both NO2 and PM10. Since the implementation of road pricing in cities as Milan, London and Stockholm has shown that an achievable target in air pollution reduction is -15%, this will be used as a reduction objective for our model, which translates into an averaged target of 34ug. The base price used will be equal to 5€. This is the price the city of Milan has introduced to achieve the aforementioned results in pollution decrease (Muñoz Miguel, de Blas, & García Sipols, 2017, p. 26).

Granted that, as explained in Chapter 4.5, the maximum target achievable is a reduction of 37.1% and 42.9% for NO2 and PM10 respectively, a maximum price will be set. This will be necessary because consumers' responsiveness to price changes after achieving a total ban of cars will be null.

Figure 6. shows a pricing scheme based on (6) which provides the reader with an example of how a road pricing scheme would work in a city with characteristics similar to the ones of Milan for PM10 and NO2 concentrations. Here, to every increase of 1ug in pollution concentrations corresponds a variation in price, which would drive down the number of polluting vehicles and consequently of pollutants concentrations, aiming at the target established for NO2 and PM10. The higher the concentration of pollution registered, the higher the percentage decrease a city aims at to achieve its targets and consequently the higher the set price.

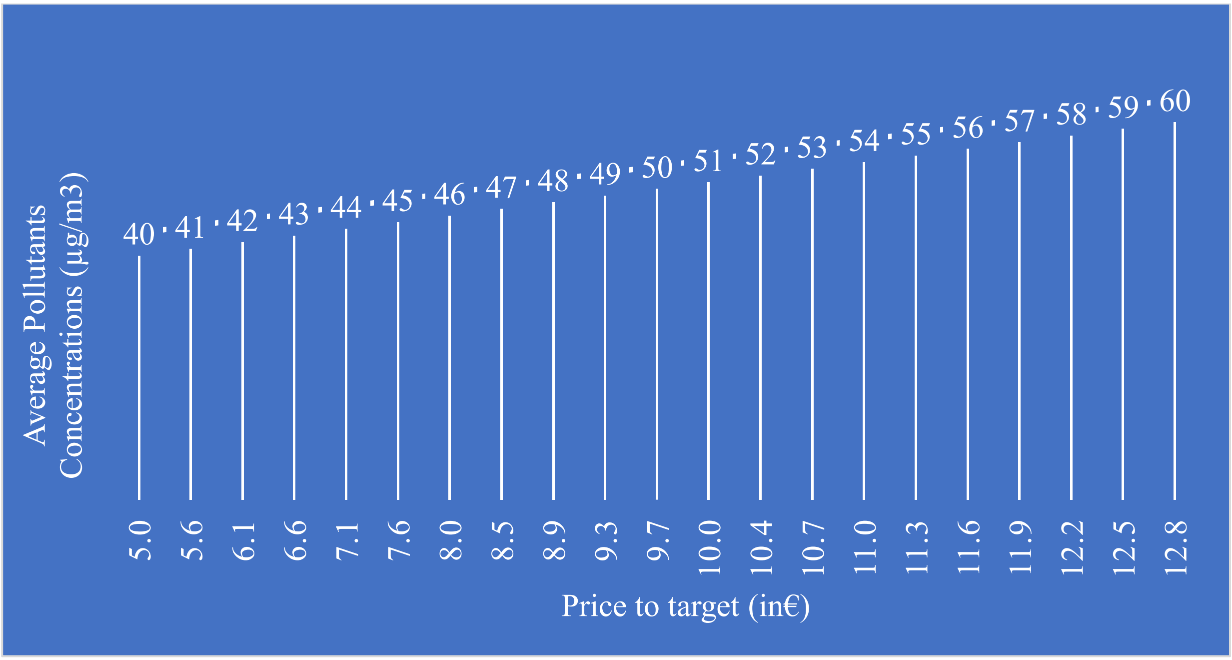


Fig. 6. Average pollutants concentration and consequent price variation for target achievement, own representation

The way in which this road pricing simulation would work is the following: air quality sensors detect the concentration of an air pollutant in a specific area of the city. Collected data are analyzed and an estimation of the average for a longer period is created. According to the computed average, corrective actions are taken in road pricing, which consists in increasing or decreasing the price according to the estimation. City halls will decide autonomously how to communicate the price to drivers accessing the area. Fees start from a base price, in this example equal to 5€, which guarantees the achievement of the initial target, here equals to -13% for NO_2 and -15% for PM10. To the base price a mark-up will be allocated, which varies according to the increase in air pollution concentration with the final aim of achieving the target. This should allow a city hall to achieve outstanding results in the fight against air pollution, as successful examples for the cities of London, Stockholm and Milan have shown (Muñoz Miguel, de Blas, & García Sipols, 2017, p. 26).

4.7 Cost-Benefit Analysis of a Road Pricing Scheme Based on Air Pollution

This chapter will focus on a cost-benefit analysis in order to assess the value of a road pricing scheme and to understand the business opportunity coming from its implementation, on one side for city halls/governments and on the other for additional entities which might benefit from externalities, as bus passengers, drivers, private parking owners and the society.

A cost-benefit analysis is a systematic approach to estimate the strengths and weaknesses of alternatives used to determine options which provide the best approach to achieve some benefits white preserving savings (David, Ngulube, & Dube, 2013). The scope of this analysis is to determine if the investment is sound, if benefits outweigh or not project's costs and by how much. Calculi will be handled in a time span of 5 years, in order to highlight costs and benefits over the years after the system implementation and its initial investment costs.

Given that the presented policy would be based on a dynamic and flexible pricing scheme, revenues are not expected to differ from what presented in literature studies on the cities of London and Stockholm. Additionally, externalities coming from the implementation of a road pricing system will be highlighted, in order to understand what effect these may have on other stakeholders.

4.7.1 Costs Analysis for City Halls

As explained in chapter 4.3, implementing a road pricing system with air quality sensors is not highly costly. However, this depends on the infrastructures already present in a city (Croci, 2016). This study will focus exclusively on cities that had to implement a brand-new advanced technology traffic management system, as in the case of Stockholm and London. These cities will be taken as two examples, in order to show potential costs and benefits of cities with diverse size, population and different initial and operational costs and revenues models.

Initial investment for a brand-new ICT system varies from €203.5 mln. (London) to €207.2 mln. (Stockholm). Moreover, according to interviewed experts, adding a set of air pollution sensors to an ICT system would approximately impact on costs of an additional 20%, which translates into €20.4 mln for London and €20.7 mln for Stockholm. Therefore, total initial investment costs are €223.9 mln. for London and €227.9 mln. for Stockholm (Croci, 2016).

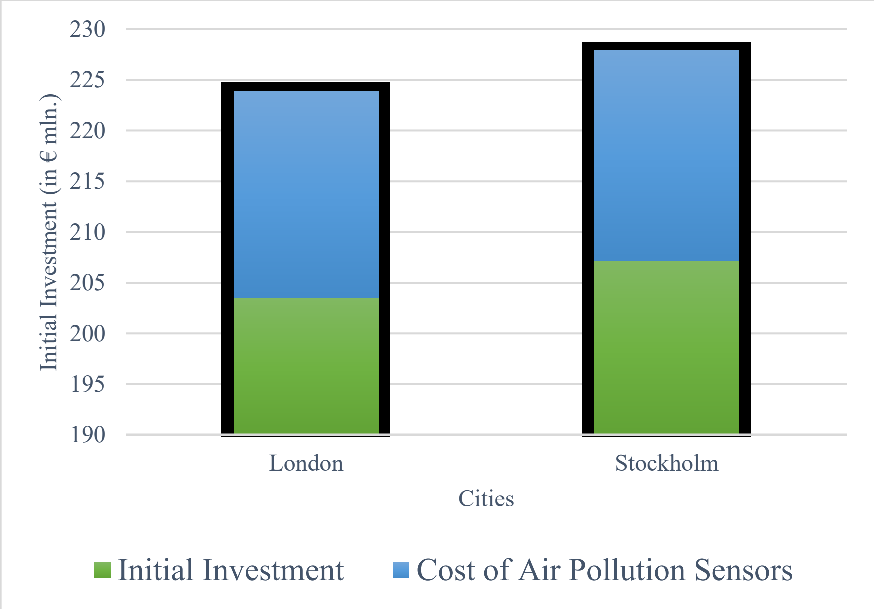


Fig. 7. Initial investment breakdown for London and Stockholm, own representation based on Croci (2016)

Initial investment costs consider cost of cameras, sensors and IoT infrastructure and vary according to the technology used, the number of gates to access the area, the way in which access is charged (i.e. access to area or crossing of the area) and thus to the number of devices needed for a road pricing system to work smoothly. However, the size of the area in which the policy is implemented should not affect costs, as no correlation between the section of the city affected by road pricing and initial investment has been found and because a bigger area could have a small number of checkpoints to access it (i.e. Stockholm) and vice versa.

Yearly operating costs for road pricing systems vary from €23.9 mln in Stockholm to €114.4 mln in London. These costs include any expense a city incurs to let the system work properly and additional costs incurred to increase additional parallel services (i.e. public transport reinforcement) (Croci, 2016, p. 260).

In the next subchapter, economic benefits for city halls and governments in the years following the system implementation will be highlighted, in order to understand if these would cover the maximum outlay of money just presented, which includes initial investment and operational costs, on the medium and long term.

4.7.2 Benefits Analysis for City Halls

According to interviewed experts, expected benefits coming from such a system are expected to be high and to outweigh costs on the short-medium term. Benefits of such a system come from direct sources, such as charges and traffic reduction, and from indirect sources, such as decrease in pollutants concentration, which leads to health benefits, travel time savings and higher road safety (Zhang & Batterman, 2013, p. 308). In this section the focus will be only those benefits which affect city halls or local governments and to each of them a monetary value will be allocated, in order to further proceed with the analysis of the revenue and potential benefit. Indirect benefits and any other positive externality will be analyzed at a later stage, since the entities benefitting from them are others.

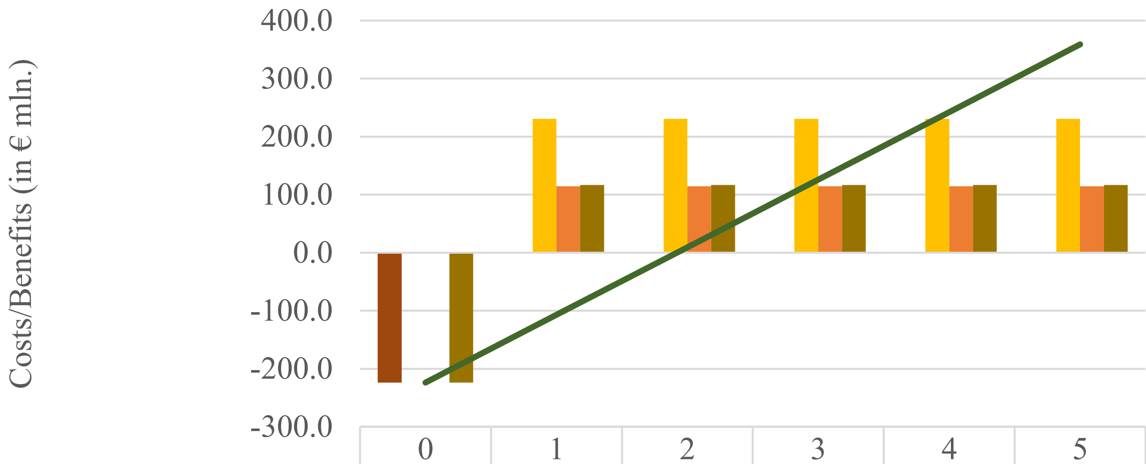
The first direct benefit is traffic congestion reduction. Cities that have implemented this system have experienced between 14% and 21% traffic decrease per year. This led to indirect benefits such as decrease in travel times, more reliable and safer traffic and a decrease in emissions, with the respective effects on human health, which create positive externalities for other entities (Croci, 2016, p. 255).

Another direct benefit and the fastest source of cash-flow is the revenue coming from road charges and fines for infringements. In the cases of London, fees revenues amount on average to €138 mln. per year while fines revenues to €22 mln., with €160 mln. of total revenues. For what concerns Stockholm, this separation is not performed by traffic management entities and total revenues amount on average to €84 mln (Croci, 2016, p. 255)

4.7.3 Cost-Benefit Analysis

In this section, costs and benefits presented in chapter 4.6.1 and 4.6.2 will be joint in a cost-benefit analysis. Figures 8 and 9 show how long would it take for a city following the road pricing schemes of London and Stockholm to recover initial investments and how much profits it would generate afterwards annually and as a cumulative calculation.

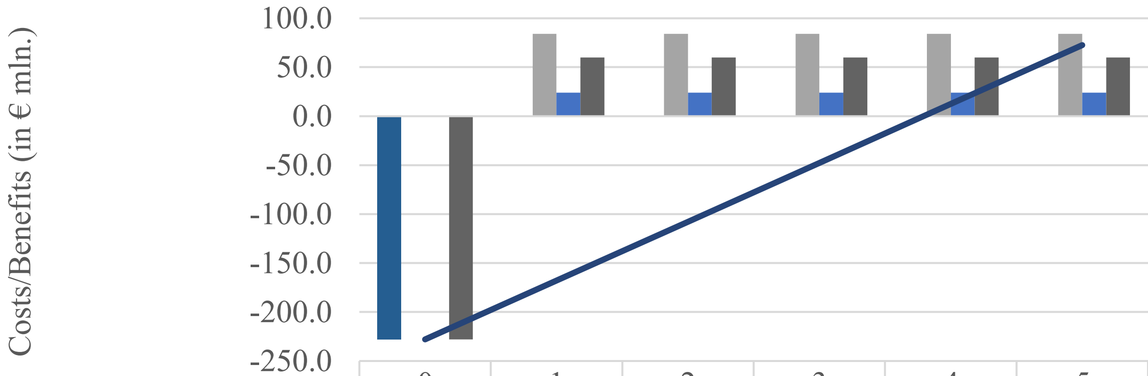
London would start generating positive profits from the second year after the implementation, benefitting from high profits, which almost doubles the ones of Stockholm. The Swedish capital, instead, would start generating profits only from the fourth year after implementation, due to the proportionately higher initial investment made at year 0.



	0	1	2	3	4	5
Initial Investment	-223.9	0.0	0.0	0.0	0.0	0.0
Direct Revenues	0.0	231.0	231.0	231.0	231.0	231.0
Operating Costs	0.0	114.4	114.4	114.4	114.4	114.4
Profit / Year	-223.9	116.6	116.6	116.6	116.6	116.6
Profit (Compounded)	-223.9	-107.3	9.3	125.9	242.5	359.1

Years after Implementation

Fig. 8. Cost-benefit analysis of road pricing in London up to 5 years after implementation, own representation



	0	1	2	3	4	5
Initial Investment	-227.9	0.0	0.0	0.0	0.0	0.0
Direct Revenues	0.0	84.0	84.0	84.0	84.0	84.0
Operating Costs	0.0	23.9	23.9	23.9	23.9	23.9
Profit / Year	-227.9	60.1	60.1	60.1	60.1	60.1
Profit (Compounded)	-227.9	-167.8	-107.7	-47.6	12.5	72.6

Years after Implementation

Fig. 9. Cost-Benefit Analysis of Road Pricing in Stockholm up to 5 years after implementations, own representation

Once the cost-benefit calculation is set, it is now possible to compute the Operating Expense Ratio (OER) for both scenarios. OER is useful to compare the periodical costs to the revenues generated. The higher the ratio, the smaller the profit created. This formula has been used in several research papers analyzing the financial impact of road pricing.

In the case of London, OER is equal to 49.6%, while for Stockholm it is equal to 28.5%. These values show that that in proportion, the road pricing scheme of Stockholm is more profitable, given the fewer operating costs. However, in both cases, it is easy to notice not only its positive economic impact over time, but also how many indirect benefits are hidden behind the mere numbers, first and foremost related to a general increase in quality of life for citizens, justified by the lower concentrations of air pollution and related health issues, the decrease of travel time and an increase in road safety.

4.7.4 Externalities from Road Pricing Schemes Implementation

As shown in the previous chapter, implementing a road pricing scheme in a city with high polluting levels has proven to be a cost-benefit efficient policy for city councils and local governments. In the cases of London and Stockholm, both cities showed the positive impact road pricing policies might have on cashflow, besides the different costs and benefits structures of the two systems. However, the introduction of such policy would cause additional positive and negative externalities.

An externality is a cost or a benefit an activity imposes on a third party, which did not choose to incur that cost of benefit (Varian & Espáriz, 2015). In this case, entities being affected by the policy implementation, besides the positive effects shown on the government, are car, van and goods vehicle users, bus passengers, private parking owners and the society as a whole. In Figure 10 and 11 all additional stakeholders are presented for the cities of London and Stockholm, together with externalities generated by the road pricing scheme introduction and its economic quantification for each category.

		London				
		Travel time and reliability	**Operating costs**	**Other resources and surpluses**	**Financial impact**	**Total**
Car, Van and Goods Vehicle Users	**Business**	198.2	20.2	-16.8 (compliance cost)	-167.8 (user charges)	33.8
	Individuals	72.8	11.2	-6.7 (compliance cost)	-85 (user chrges)	-7.7
Bus passengers	**Individuals**	48.2	-	-	-	48.2
Private Parking	**Net revenues**	-	-	-	-11.2	-11.2
Society	**Accidents**	-	-	15.7	-	19.0
	CO2	-	-	2.2	-	
	NO2, PM10	-	-	1.1	-	
						82.1

Fig. 10. Quantification of charges externalities in London (in € mln.), own representation based on Transport for London (2007)

		Stockholm				
		Travel time and reliability	**Operating costs**	**Other resources and surpluses**	**Financial impacts**	**Total**
Car, Van and Goods Vehicle Users	**Business**	50.4	7.3	-	-75.6	-17.9
	Individuals					
Bus passengers	**Individuals**	N.A.				-
Private Parking	**Net revenues**	N.A.				-
Society	**Accidents**	-	-	11.8	-	19.9
	CO2	-	-	6.0	-	
	NO2, PM10	-	-	2.1	-	
						2.0

Fig. 11. Quantification of charges externalities in Stockholm (in € mln.), own representation, based on KTH Royal Institute of Technology (2014)

Car, van and goods vehicle users can be split into individual and business users. The first refers to all non-business trips, trips made by individuals for personal reasons, including commuting, while the latter merely to business trips. Business and individual users are positively affected by travel time reduction and higher travel time reliability, estimated at €198.2 mln. and €72.8 mln. respectively for London and at an averaged €50.4 mln. for Stockholm, in addition to the decrease in operational costs (i.e. fuel, engine and tire wear), due to the general decrease in vehicles usage and estimated at €20.2 mln. and €11.2 mln. respectively for the British capital and €7.3 mln for the Swedish one. This group is also negatively affected by compliance costs (i.e. vehicle registration, fee payments), estimated to be around -€16.8 mln. and -€6.7 mln. respectively for London and user charges, respectively of -€167.8 mln. and -€85 mln. for London and averaged at -€75.6 mln. for Stockholm (Transport for London, 2007; KTH Royal Institute of Technology, 2014).

According to the data provided by the city of London, these values translate into an overall positive externality on the business group and a slightly negative externality to individual users. For Stockholm, the lack of specific data let the total as an averaged negative result. However, the effect on individual users depends also on other factors, such as type of user and welfare effects, not considered in this study and which might vary the outcome of the total effect.

Bus passengers benefit from pure positive externalities coming from road pricing policies. This is mainly caused by the higher reliability of and the decrease in travel time and by additional investments made throughout the implementation of the policy by public entities on public transport. For London the positive benefits coming from time savings correspond to €48.2 mln. (Transport for London, 2007). This datum is not available for Stockholm.

Private parking owners located inside the charging zone are hit by negative externalities, mainly due to the decrease in number of vehicles accessing the charged area, which impact directly on their finances. In London the economic impact on this category is -€11.2 mln. However, the policy implementation has a neutral impact on parking lots outside the area affected by the road pricing scheme (Transport for London, 2007). This datum is not available for Stockholm.

Finally, positive externalities for the society, which mainly translate into a higher quality of life, come from a decrease in total number of accidents (up to 9% in London), in greenhouse gases (i.e. CO_2) and the previously studied case of air pollutants, PM_{10} and NO_2 among others. A yearly monetization of environmental benefits and their effect on health is €3.3 mln. for London and €8.1 mln. for Stockholm while the decrease in number of accidents has monetary benefits of €15.7 mln. for the British capital and €11.8 mln for the Swedish one (KTH Royal Institute of Technology, 2014; Transport for London, 2007).

Summing up all of the externalities presented for stakeholders other than governments it can be stated that a road pricing scheme tend to have a positive impact on business users, bus passengers and on population as a whole, while it creates negative externalities on individual users (on average) and on private parking owners. However, the sum of quantified benefits for all stakeholders show a positive result of €82.1 mln. for London and of €2 mln. for Stockholm, to add to the positive results of the cost-benefits analysis performed in chapter 4.6.3.

4.8 Potential Applicability

The previously presented analysis on the road pricing model and its cost-benefit study started from data belonging to existing systems and extrapolated the necessary information in order to provide a model which can be implemented in other European cities. Its ease in implementation is justified by the flexibility of the equation and models presented to be adapted to diverse scenarios, i.e. different pollution levels, elasticities of demand, pricing schemes.

European cities currently facing the biggest issues related to air pollution, where the chances of dying from transport pollution are highest, and that haven't introduced any road pricing scheme are the following (ICCT, 2019):

1. Turin, Italy
2. Stuttgart, Germany
3. Cologne, Germany
4. Haarlem, Netherlands
5. Berlin, Germany

However, the model can be implemented also in cities which are not facing air quality concentrations above EU threshold, as an effective policy to decrease number of cars and to prevent potential air quality issues.

CHAPTER 5: CONCLUSIONS AND LIMITATIONS

This section will sum up the main findings and conclusions to the research questions initially presented and provides an overview of the project limitations and cues for further research on the field.

5.1 Main Findings and Conclusions

Q1. *What is the state of art of IoT systems in European cities?*

The research begins with a study on the status of IoT-powered technology in Europe. The findings show that the market is increasing its presence year by year and that Europe is where most of the investments are made. Furthermore, the research hasn't shown any barriers in terms of technology, cost and time. However, security and privacy issues might be a threat.

Q2. *How can IoT technologies be implemented to reduce air pollution in cities?*

The study continues trying to find a link between IoT and solutions to tackle air pollution issues in traffic management. Through primary data collection it was possible to find several alternatives to answer this question. Among the wide variety of measures to be undertaken, the focus has been on a road pricing project with IoT-powered sensors able to detect air pollution. The solution has been picked as experts in the field commonly agreed on its efficiency, low cost of implementation and high impact. The scheme would be implemented as part of a city's traffic management system and would restrict entrance of polluting vehicles in the city center by applying fees, which varies according to the level of air pollutants concentration registered. Established fees are based on drivers' elasticity of demand, which allows to understand consumers' willingness to pay to access the service. The final goal is proving the existence of profitable and effective policies, which not only reduce the quantity of polluting vehicles circulating on its streets, but also promote the switch to cleaner means of transport. This analysis showed that by implementing the scheme a city would benefit from an evident reduction in key air pollutants, such as PM10 and NO2.

Q3. *Is there a business opportunity coming from the implementation of IoT technologies to tackle air quality-related issues?*

The last section of the study focused on the business opportunity coming from the policy implementation through a cost-benefit analysis and its effects. Findings showed cities would make expensive initial investments to build the ICT infrastructure, but low operational costs and high revenues will allow them to break-even on the mid-term and generate profits afterwards. Furthermore, the implementation of the system causes positive and negative externalities to different stakeholders, with an overall positive impact, obtained firstly quantifying and secondly combining its effects on all stakeholders.

5.2 Limitations and Further Research

Due to the budget and time limitations of a master thesis, this study considers some limitations, from which further research could be conducted, in order to provide a more comprehensive and detailed analysis on the topic of new technologies implementation for air pollution reduction.

The first limitation of the study is the lack of a pricing scheme pilot study on the field, to confirm presented results and provide more detailed data to the analysis. The main reason behind this omission is the lack of expertise in IT, in addition to the general limitations related to time and budget. However, the research tried to use similar schemes introduced in other European cities to back up the outcome of the different analyses.

Furthermore, final results do not consider the policy's potential impact at a bigger scale, disregarding the effects on variables that are not directly or evidently affected by the policy, mainly belonging to geographical factors (i.e. outskirts) or cross-departmental matters (i.e. healthcare and urban planning). In addition to the causes previously presented, this omission is due to the wide range of variables potentially affected by the policy, which could serve as input for independent researches and thus allow a broader analysis of the policy's effects. Further research would be useful to analyze the policy implementation at a large scale and its impact on all city-council stakeholders, in order to make more precise forecasts on its effects.

Another limitation to be highlighted relates to the size and population of the sample chosen to conduct the interviews, as they cannot be considered fully representative. However, the decision made to minimize the impact of this limitation was to select experts belonging to each of the fields under study, namely IoT, environment and traffic management, and with experiences in six different European countries. Moreover, 10 interviews are above the minimum threshold of saturation, as highlighted in Chapter 3, allowing a full understanding of the topics' needs, solutions, opportunities and challenges, and sufficient for the scope of the dissertation.

Lastly, the researcher wishes this exploratory study might serve as input for additional research in the fields of IoT, traffic management and green practices, in order to provide city halls with a set of profitable alternatives to improve citizens' quality of life by impacting positively on the environment.

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APPENDICES

Appendix 1:

Main components of smart cities and respective aspects of urban life, own representation from Lombardi et al. (2012).

Components of a smart city	Related aspects of urban life
Smart economy	Industry
Smart people	Education
Smart governance	E-Democracy
Smart mobility	Logistics & Infrastructures
Smart environment	Efficiency & Sustainability
Smart living	Security & Quality

Appendix 2:

List of interviews participants, including acronyms, area of expertise, current position, organization and country, own representation

Acronym	Area of Expertise	Current Position	Organization	Country
Expert1	IoT	Postdoctoral Researcher	AITech Institute TU Delft	Netherlands
Expert2	Traffic Management	Expert in Traffic Management	Gemeente Rotterdam	Netherlands
Expert3	IoT & Smart City	Chief Innovation Officer	Emergya	Spain
Expert4	City Council	Responsible Investment Funds	Alleans	Italy, UK
Expert5	Environment	Environmental Scientist	PNS	Spain
Expert6	City Council	Project Manager	-	Spain
Expert7	IoT & Smart City	-	-	Germany
Expert8	Smart City & Environment	-	-	Spain
Expert9	IoT & Smart City	Head of Digital Solutions	Group Tera	France
Expert10	Environment	-	REN Portgas Distribuçao	Portugal

Note: some participants have decided not to disclose personal data. Therefore, some information in the table above is missing.

Appendix 3:

Interviews guidelines and questions, own representation

Interview Script for IoT/Smart City experts
Introduction
Please explain your personal experience with IoT / in the context of smart cities What are the issues currently being addressed with the implementation of IoT systems in cities? What solutions are being considered to tackle aforementioned issues?
Air Pollution and IoT
Among the issues to be addressed with IoT, what level of importance is given to air pollution? At the status quo, how can IoT systems help in controlling/decreasing air pollution? What the requirements for such systems to be implemented? Is there any advantage or any disadvantage in the use of IoT systems to tackle air pollution with respect to other technologies? What the limitations? What the benefits?
Traffic Management
Among the issues to be addressed with IoT, what level of importance is given to traffic management? At the status quo, how can IoT help in controlling/decreasing traffic management? What are the projects currently being implemented in European cities showing the best results? What the requirements for such systems to be implemented? Is there any advantage or any disadvantage in the use of IoT systems to tackle air pollution with respect to other technologies? What the limitations? What the benefits?
Interview Script for City Halls/Government
Introduction
Please explain your role in city halls/government. Status quo of adoption of IoT systems in cities: how are they being implemented? Why? [Limitations or benefits compared to similar technologies] What are the main issues being addressed in cities? And how are they currently being addressed?
Air Pollution and IoT
Among the current issues being faced in the context of cities, how relevant is air pollution control/reduction? Why?

What the target to achieve in terms of air pollution control/reduction? How are you planning to achieve it? [Solutions being implemented] What the effects/benefits of this solution? What portion budget is currently being used to tackle this issue? Is IoT a technology being used to address these issues? Why? Why not?
Traffic Management
Among the current issues being faced in the context of cities, how relevant is to get better traffic management? Why? What the target to achieve in terms of traffic reduction? How are you planning to achieve it? [Solutions being implemented] What the effects/benefits of this solution? What budget is currently being used to tackle this issue?

Appendix 4:

Main insights from interviews with experts, own representation

Interviewee	Quote
Expert1	IoT creates new needs, does not only solve existing problems. Air quality monitoring: you have several ways to record air data (bikes, buses) but it comes with some limitations, like unstructured system, short-life device, low quality of registration. It might help other entities to gather more data. Air purification: trade-off of environmental cost and better air quality. What is the environmental cost of the implementation of some devices for air purification in terms of batteries and other components? Is it beneficial for better air quality? Technology implementation should aim at installing durable systems, in order to avoid additional environmental costs other than improvements in air pollution and thus to focus on the trade-off between air-pollution decrease and the environmental impact of the components of measuring devices. Requirements for a good IoT system: Connectivity is essential, but most of the cities already offer the possibility to do so. Widespread presence of devices is a must. Suggestions: Connection to weather systems, to monitor air quality for citizens. Status quo: Complete limitation of group of cars in some areas of the city. i.e. Oslo wants to forbid private cars access within the city center. Downside: electric engines transport should always be allowed, because they don't pollute. Primary goal should be reduction and not containment, thus policies such as road pricing can address the issue and be an answer to the problem.
Expert2	Rotterdam already has smart traffic lights system. Gathered data can be used to provide with time data. There are still privacy limitations though. In Rotterdam, for example, traffic is managed with smart traffic lights, which change green/red time according to the number of cars allowed in a specific street. Air pollution is indeed a big issue, currently trying to be solved, especially in streets close to buildings.

	Another goal is to decrease number of cars overall. Improve traffic lights for pedestrians and cyclists, specifically in the Netherlands, one of countries with most traffic lanes in the world. How? Increasing waiting time for cars drivers, not too much because it might have political repercussion. Air quality is considered mainly a health issue. Addressing such issues is not only a competence of traffic management but also of the health department within the city hall. This means budget can be spread into more divisions than the traffic management only. Measurements on cars traffic and pollution are available and through algorithms, you know how to react. This also allows to understand the effects of specific measures that can be taken, for example less car lanes available, more or less time at green/red light at the traffic lights. Influencing the system according to air pollution records is not a problem. Money is not the biggest issue. In order to implement a system with IoT-sensors in a city-like environment I would add a mark-up of 15 to 25%. Systems implemented should have long terms environmental goals.
Expert3	Cities need platforms, to get a holistic vision of all IoT applications. All data should be in the same place, in order to process and analyze data and for politicians to make decisions. Air pollution problems vary a lot from city to city. In Spain, several cities are still lacking sensors, in order to have a holistic system. Nowadays, big investments are being made on IoT-related topics, especially coming from the European Union. Problems to be tackled depend on the size of the city. Several cities have other issues. Tendentially, bigger cities like Madrid have bigger issues related to air pollution. Urban planification is also very important and could help. IoT is definitely the cheapest system and the most efficient, because everything happens in real time. To add sensors to systems previously available is not highly costly. Decisions making can be way quicker than other systems. IoT could be used with Machine Learning to make decisions quickly. For IoT implementation in cities, it is a matter of time. Cities are currently implementing such systems.

Expert4	Public and private sectors have brand different approaches to the problem. Often the private sector is more willing to develop and invest in new technologies, because it foresees the huge return it might have. Smart city is a concept that incorporates different sectors, from energy to transports and from waste management to health. Often the biggest problem is the coordination between these. IoT systems might be introduced also as part of other changes in a city, for example within streetlamps. An alternative system would be to have dynamic tariffs in the city-centers, instead of shutting down entire areas to cars. You can access but tariffs change, according to the time of the day in which the area is more or less polluted. Bad traffic management in city-centers do not only have negative economic effects (cities could increase their revenues with dynamic tariffs), but there are also social costs included, related to health costs, for example. If one can prove that these systems are not only beneficial for cities, but also to the government budget overall, it can be very easy to propose such systems to city halls. Sensors have very low cost of implementation, but data analysis might be more costly. There are no better systems in terms of cost/benefits. EU has started several projects related to IoT, like Jupiter, Jessica, and opened several organizations like "Mayors deal", to share best city practices all over Europe. The forecast for the next years is the introduction of IoT systems in several sectors of a city and the creation of State-cities, which autoregulate according to their needs
Expert5	Currently, a system to decrease air pollution in certain areas is to create superblocks (*superillas*), which aims at decreasing cars access by imposing strict limits in speed, giving pedestrians the priority. For these mini villages, the strategy isn't to ban cars completely. Instead, a nine-block perimeter is drawn where "traffic, freight, and city buses" must drive. Inside the perimeter, local vehicles may only drive on one-way loops, at maximum speed of 10 mph. The first stage of the project is to reduce speeds, and the second is to remove curbside parking completely. The goal was analyzing the status quo in terms of air pollution before and after the implementation of such system.

	The outcome in some cases has been a decrease in number of cars and thus in air pollution (NO_2, COx), without a proportional increase in the number of cars in the neighboring streets. A decrease in traffic would mean also an improvement in public transport, so step by step one factor will impact on the other. If cars do not cross cities, the results are evident, as in this period (COVID19 restrictions). This shows that cars are the first contaminant of a city, together with port activities and flights. Road pricing would be a valid and efficient alternative to such systems, as it could obtain similar or even better results, mainly due to the pricing factor. However, a problem with air pollution in cities as Barcelona (Spain) is that they never surpass EU limits in terms of air pollution, but they are constantly a few points below it, polluting but never enhancing the alarm level. The problem here is that often times, once European goals are achieved, there is little to no political will to make further improvements. Urban planning is also an important factor to take into account when considering measures to improve air quality.
Expert6	Valladolid (Spain) is a smart city. Even if the size of the city is reduced with respect to big metropoles, the city-council focuses on innovative projects to improve citizens' quality of life, mainly through sustainable city urban development. The city has started to implement measures to reduce speed limits in the city center, avoid the use of cars in the city center and raise awareness among the population. Road pricing policies are known for being very efficient measures, but initial investment might be high, especially if a city is new to IoT usage. To guarantee a good air quality-related system, you need to make sure air quality is properly measured and that sensors are precise in detecting air pollution.
Expert7	IoT has very good use cases to enable air pollution control and management through the connection with other systems. At the same time, IoT does not come at a very high cost for the environment, especially from an air pollution perspective.

	Everything in a city must work together as a conglomerate, in order to maximize the possible results of IoT in a Smart City. Every city must have an overall vision to become smart, clear goals and a strategy. Only afterwards a city could really benefit from IoT implementation. The cost does not only consist of sensors: the biggest expense is allocated for what's behind its implementation, such as infrastructure, architecture and consulting. It might not be the cheapest technology, however if joint with some EU funding, benefits would definitely be exponential with respect to costs. If you implement an IoT system in traffic management, consider the downsides of data collection: data security. The user might be against it and some laws might not allow you to fully collect data. However the topic of data security can easily be solved when it is considered from the implementation phase. The biggest problem comes from the cost and the weak impact of tackling privacy issues once a project has been implemented Avoid customer built specific software, because these are very complex and not flexible. Furthermore, this would force you to stick to this only provider and thus to passively get hit by the decision of this provider. The best solution would be to have one open source platform, in which all systems of different cities are connected and thus create a real network of smart cities.
Expert8	There are several new projects available in the market trying to address the topic of air pollution, some are very simple and start as citizens' initiatives (*cities-health* project), while some others are more complex projects, aim at a systematic improvement of air quality (*superilla*s in Barcelona). However it is essential to raise awareness among citizens, when it comes to implement new measures within a city. If you have their cooperation, it becomes easier to achieve established results. Road pricing schemes are becoming more and more popular and efficient to fight the problem of air pollution in cities. In Spain, Madrid has started to work on a project related to it. If you link it to air pollution measurements, it might become even more effective.

	However IoT has some limitations. Privacy is a real concern, so when implementing an IoT system it is necessary to make sure that data are protected.
Expert9	In the market you can find several types of sensors for air quality detection of any size and differing in quality and detection methods. In Europe, thanks to European funds, a lot of sensors have been developed. A big project in which sensors developed by the company I am working for will be deployed is DIAMS. A part of the project consists in introducing hundreds of portable devices for citizens to detect air quality and behave more responsibly. The project will be implemented in Marseille area, France, where almost 2 million people live and aims mainly at reducing NO2. It is not very complex to develop a sensor, but to get certifications it might be. Often it is easier to use sensors previously developed than create one of your own.
Expert10	Air quality is indeed an issue in cities, but you need to make sure you are addressing the problem in the right way. Measuring air pollution is not always very easy, due to chemical factors which do not allow a static analysis: air pollution in different areas of the same cities can present completely different levels and variables as weather can influence a lot on the recordings. However, if a problem affects most of the city and thus if the problem is chronic and widespread, sensors can be a useful tool to detect air quality. The target to achieve in terms of air pollution is similar all over Europe: decreasing air pollution concentrations, letting them fall below limits established by EU, in order to avoid trials and the eventual issue of expensive fines. Linking road pricing to sensors to detect air pollution might be a good way to tackle the issue and to limit the access of vehicles in a city. Paying a fee could be a good deterrent for drivers to avoid the area or even switch to alternative means of transport, especially if during this period, in which COVID has shed a light on the potential effect of reducing drastically vehicles usage.