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iSCAPE

Guidelines to Promote Passive Methods for Improving Urban Air Quality in Climate Change Scenarios

D1.2

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Short Description	*This report is the results of the work described in Task 1.2 of the iSCAPE project as an output Deliverable D1.2. The report aims to review and discuss the available passive control system in order to produce guidelines that accounts for local settings, by considering the fundamental design of urban areas and the potential for low cost retrofits for some passive methods in existing areas in the built environment, as well as, to assesses*

	also the potential of expected benefits from urban deployments.		
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ARL	Academy for Spatial Research and Planning
BLUE AP	Bologna Local Urban Environment Adaption Plan for a Resilient City
BMUB	Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit
CD	Canopy density
C_d	drag coefficients
CFD	computational fluid dynamics
CV	Crown volume fraction
DMC	Distance between source and plume's maximum concentration
EC	Elemental carbon
EEA	European Environment Agency
EPA	United States Environmental Protection Agency
EU	European Union
FUA	Funktional Urban Area
GAIA	Green Area Inner-city Agreement
GIS	Geo-Information System
H/W	aspect ratio
HSL	Helsingin Seudun Liikenne
IGEAT	Institut de Gestion de l'Environnement et d'Aménagement du Territoire
iSCAPE	Improving the Smart Control of Air Pollution in Europe H2020 project
Koop.-G. LEP B-B	Kooperationsgemeinschaft Landesentwicklungsplan Berlin-Brandenburg
LAD	leaf area density
LAI	Leaf area index
LBW	Low Boundary Wall
LES	large eddy simulation
MEWHBW	Ministry of Economy, Work and Housing of Baden-Württemberg
MKULNV	Ministerium für Klimaschutz, Umwelt, Landwirtschaft, Natur- und Verbraucherschutz des Landes Nordrhein-Westfalen
MVI	Ministerium für Verkehr und Infrastrukturen
NUTS	Nomenclature of territorial units for statistics
OECD	Organisation for Economic Co-operation and Development

PNC	particle number concentrations
RANS	Reynolds averaged Navier Stokes
SeUN	Stadtentwässerung und Umweltanalytik Nürnberg
TPER	Trasporto Passeggeri Emilia-Romagna
TSP	Total suspended particles
UBA	Umweltbundesamt
UFP	ultrafine particles
UHI	Urban Heat Island
v_d	Deposition speed

1 Executive Summary

For several years, regulatory authorities have based their strategies of improving air quality on emission reduction strategies. These strategies have furnished till 2010 the maximum potential of achieving true reductions without shifting the blame to other areas or technological sectors. Since achieving further direct emission reduction is practically difficult, it is inevitable now to endeavour in examining the potential of passive interventions. As such interventions, in this report, we examine the potential of physical passive controls (low boundary walls or noise barriers), green infrastructure (trees, hedges, green walls and/or roofs), the utilisation of photo-catalytic coatings (in road tiles or walls) and the possibilities of achieving less atmospheric pollution with intelligent urban design (transport, settlement structure, green and blue spaces). Since all these domains have a long-term potential, the interventions on existing components in the built environment, implementing or relocating these structures provides a potentially low-cost option compared to other "direct" regulatory methods that were tried until now.

With this report, we aim not only to examine the potential of these passive interventions we review the state of science in passive control systems and its characteristics. Furthermore, we review how, when and where these strategies will have benefits in urban areas. We provide conclusions about the validations, strengths and limitations. We also guide the regulatory authorities on how low-cost retrofits for some passive methods might lead to gains in urban air quality either by lowering the presence of primary air pollutants or by improving the climate parameters that are responsible for setting the background concentrations in the periphery of main anthropogenic agglomerations. In the end, we with give final remarks, recommendations and guidance for which pollutants might be successfully handled passive interventions.

2 The State of Science

2.1 Physical Passive Control Systems

2.1.1 Characteristics of the physical Passive control systems

A significant amount of research has been carried out in the last decade on physical passive methods that can improve urban air quality, with each method presenting a unique solution to the problem. However, as this research area is a relatively new area of research, this report outlines the future potential for these methods for improving urban air quality and suggests how they can be incorporated in future urban planning strategies with the link of iSCAPE challenges, this report adjacent to iSCAPE deliverable 1.4 together aims to provide a thorough and neutral assessment of existing and future challenges and opportunities for the cities with respect to air quality (in this report) and climate change (Deliverable 1.4), This report addresses primarily air pollution reduction strategies and interventions. However deliverable 1.4 address the interactions with the local and global climate and related effects such as urban heat. Physical passive methods to improve urban air quality provide a potential long-term solution to the urban air pollution (Gallagher et al., 2015). As most of the physical passive structures are existing components in the built environment, implementing or relocating these structures provides a potentially low-cost option compared to other methods, which iSCAPE tries to examine the different case studies and challenges.

Solid structures or physical systems as used in this report covers all types of solid physical structures and barriers that are used in the built environment. Noise barriers, low boundary walls (LBWs) and parked cars present distinct solid barriers in the built environment that can influence air flow, pollutant deposition and dispersion in several ways. Before going into the details of individual physical passive control systems, it is important to understand common characteristics of the systems, which affect air quality. These include physical dimensions (such as height, length, thickness and spacing), surface roughness etc.

Noise barriers are commonly placed on major high-speed motorways to reduce noise pollution for surrounding areas, but these barriers can also influence localised dispersion and have been shown to improve downwind air quality. The primary differences between a noise barrier and the other solid barriers are (Gallagher et al., 2015): (i) height difference: a noise barrier is typically in excess of 4-5 m tall, compared to a LBW or parked car of 1-2 m or less in height, respectively, and (ii) LBWs and parked cars are often adjacent to low-speed roadways while noise barriers are often located along high-speed highways. Parked cars present a non-continuous and temporary barrier in comparison to the other solid barriers examined in this study. Detailed classification, characteristics and explanations around the use of noise barrier as a passive control system to improve air quality are given in studies (Bowker et al., 2007, Hagler et al., 2011a, Finn et al., 2010, Baldauf et al., 2008).

A Low Boundary Wall (LBW) is presented as a scaled down alternative to a noise barrier in an urban street canyon setting, which influences local dispersion and can improve air quality. LBWs are currently not as prevalent in the built environment. LBWs' characteristics such as height and roughness can have an influence on the air quality in urban street canyons. Detailed classification, characteristics and explanations around the use of LBWs as passive control systems to improve air quality are discussed in the following studies (King et al., 2009, McNabola et al., 2009, McNabola et al., 2008, Gallagher et al., 2013a, Gallagher et al., 2012). In general, benzene, CO, $PM_{2.5}$ or NO_x are used by the mentioned studies as single pollutants to quantify the impact of LBWs on air quality in urban street canyons.

Parking spots and areas are a common feature in the built environment. Parked cars can be considered as obstacles to the natural air flow patterns in a typical street canyon. Some modelling and field studies have been carried out in order to assess the effects of parked cars, as a physical passive control system, on the air quality of the surrounding areas to date. These studies and investigations consider CO and NO_x as a pollutant to help calculate the impact of parked cars on air quality in an urban street canyon. Parked cars provide a transient passive method of pollution reduction, as the parked cars move in and out of parking spots at different times each day, and that totally depends on the activates in the surrounding areas. Generally, the parked cars are located directly adjacent to vehicle lanes and thus provide a barrier between the pollutant source and human receptors on the footpaths (Gallagher et al., 2011, Gallagher et al., 2013a, Gallagher et al., 2015). Parked cars can affect the pollutant dispersion and influence the development of vortices in the street canyon, detailed classification and explanations around the use of parked cars as passive control systems to improve air quality are discussed in such the following studies (Gallagher et al., 2013b, Gallagher et al., 2011, Abhijith and Gokhale, 2015).

2.2 Green infrastructure

2.2.1Characteristics of green infrastructures

Urban vegetation or green infrastructure as used in this report covers all types of vegetation such as trees, hedges or vegetation barriers, green walls, and green roofs. The trees are widely employed as an environmental tool to improve urban outdoor climate and are planted and/or managed as part of urban landscaping along streets, parks, and other common accessible spaces. They are usually placed along both sides street like avenue or single tree stand in the middle. Hedges or hedges rows consists of shrubs and bushes which grow less in size compared to trees. They are usually planted along boundaries to serve as fencing or living boundary wall. The shape of the hedgerows well maintained to a cuboidal or another definite shape (such as cuboidal bottom and spherical top), in a heavily built-up area where as these are allowed to grow with less pruning and maintenance along sides of major highways. Hedges have comparatively less height and thickness than trees but higher density.

Green walls and green roofs are ways of incorporating vegetation into buildings. Green walls are vegetated vertical surfaces where plants are attached to the surface through various mechanisms. Green walls are broadly classified into green facades and living wall. In Green facades system plants or hanging pot or shrubs are directly attached to the wall (direct green façade) or plants are attached to the wall using special supporting features (indirect green facades or double skinned green facades) like cables, ropes, mesh and modular trellises. In Living walls plants as well as growing media are attached to the vertical wall and this relatively new technique is subdivided into continues living wall and modular living walls. Detailed classification and explanations are given in studies (Manso and Castro-Gomes, 2015; Pérez et al., 2014, 2011; Susorova, 2015).

Green roof as vegetation planted on the roof of a building. Plants are cultivated on growth media isolated from the building and it consists of diverse vegetation mosses to small trees, growing substrate, filter and drainage material, root barrier, and insulation. These are classified as extensive, semi-intensive and intensive green roofs. The commonly used system is an extensive system which has a thin substrate layer with smaller plants such as grasses and mosses, low capital cost and low weight with least maintenance. Whereas intensive system requires high maintenance because of the thick substrate layer which can accommodate plants bigger as small trees, and it also needs more investment. The semi-intensive system comes between the above two with the moderately thick substrate, maintenance, and capital cost. Further, detailed information on components and materials are provided in reviews (Berardi et al., 2014; Vijayaraghavan, 2016). Green roof helps in reducing energy consumption and noise pollution, managing runoff water, mitigating urban heat island, air pollution mitigation and noise pollution and enhance Ecological preservation (Berardi et al., 2014; Castleton et al., 2010; Czemiel Berndtsson, 2010; Oberndorfer et al., 2007; Saadatian et al., 2013; Vijayaraghavan, 2016).

Before going into the details of individual urban built environment conditions, it is important to understand common characteristics of green infrastructure, which affect near-road air quality. These include vegetation density, physical dimensions (such as height, length, thickness and spacing), and species-specific characteristics (such as leaf thickness, the presence of hairs or wax on a leaf, seasonal variations, vegetation emissions and air pollution tolerance index).

On one hand, urban vegetation removes gaseous pollutants permanently by absorbing them through leaf stomata or plant surfaces (Escobedo and Nowak, 2009; Fantozzi et al., 2015; Salmond et al., 2016; Vesa Yli-Pelkonen, Heikki Setälä et al., 2017). Particulate air pollutants can also get deposited on vegetation, and then get either re-suspended to the atmosphere, or washed off by precipitation, or transferred to soil and other vegetation parts (Nowak et al., 2014). On the other hand, some plant species emit particulates as well as gaseous pollutants in the air (Benjamin and Winer, 1998; Leung et al., 2011). Furthermore, vegetation canopy has an influence on the nearby pollutant concentration by altering the wind flow around it depending upon built environment and meteorological conditions (Ries and Eichhorn, 2001). Vegetation canopy can either reduce or increase the wind velocity and turbulence, causing an accumulation or dilution of pollutants in the surrounding area. For example, a few studies observed an increase in pollutant levels in street canyon with trees as compared to those without trees (Salmond et al., 2013, Buccolieri et al., 2009; Gromke and Ruck, 2009, 2007). Whereas other studies showed a reduction in pollutant levels with hedges planted along highways and street canyon as compared to vegetation-free conditions (Al-Dabbous and Kumar, 2014; Gromke et al., 2016 Lin et al., 2016). Thus, natures of vegetation effects are controlled greatly by the built environment geometry.

Pollutant dispersion and deposition on vegetation are affected by the vegetation density. A detailed explanation on the dispersion and deposition caused by vegetation was given by Janhall (2015). Studies have characterised vegetation density using different parameters such as leaf area index (LAI), porosity, pressure drop, canopy density, and crown volume fraction and shelter belt porosity. Leaf area index (LAI) is defined as the amount of vegetation surface area per m^2 of ground area, and the leaf area density (LAD) is defined as the leaf area per unit volume, $m^2\ m^{-3}$ or $m^2\ m^{-1}$. Similarly, street tree canopy density (CD) is defined as ratio of the projected ground area of tree crowns to the street canyon ground area, (Jin et al., 2014), and crown volume fraction (CVF) is defined as the volume occupied by tree crowns within a street canyon section (Gromke and Blocken, 2015). Likewise, in open road conditions, some studies used shelter belt porosity which is the ratio of perforated area to the total surface area exposed to the wind (Islam et al., 2012). It can be defined as the ratio between light penetrating trees in a specific vertical section and the area of this vertical section (Yin et al., 2011). It can be calculated by digital image processing of vegetation pictures taken by the digital camera (Chen et al., 2015; Islam et al., 2012). Low porosity (or high-density) vegetation has an effect similar to a solid barrier, which forces the air to flow above and over it; whereas high porosity (or low-density) vegetation allows air to pass through it. Porosity and drag force can also change with wind velocity (Gromke and Ruck, 2008; Tiwary et al., 2005). On one hand, when wind speed increased, a decrease in porosity of broad-leafed trees and drag force on trees were observed by Gromke and Ruck, (2008) and Tiwary et al., (2005) respectively. On the other hand, an increase in porosity was noticed in conifers and no change in porosity up to some threshold value was shown by hedges (Tiwary et al., 2005).

Physical dimensions of vegetation affect neighbourhood air quality. Larger size vegetation lead to higher concentration levels in street canyon (Wania et al., (2012), Abhijith and Gokhale, (2015)); whereas thicker and denser vegetation improve roadside air quality along open roadways (Islam et al., 2012; Morakinyo and Lam, 2015; Neft et al., 2016; Shan et al., 2007). Vegetation species with thick leafs show less deposition but leafs with hairs and or waxes observed more deposition (Sæbø et al., 2012). Likewise, urban vegetation with less seasonal variations i.e. no change in foliage is preferred (Islam et al., 2012). There are studies suggesting for prior evaluation of air pollution tolerance index of vegetation before planting them in an urban area (Pandey et al., 2015).

2.3 Photocatalytic coatings

Photocatalysis mimics the well-known photosynthesis in nature and in principle aims to transform harmful substances for human health into inert salts not directly affecting human respiration. The chemical process that underlies this transformation is a fact based on oxidation that occurs on specific coatings due to the combined action of light (solar or from UV electric lamps) in the presence of air. This process creates on coated surfaces with Titanium Dioxide (TiO_2) hydroxyl radicals and super-oxide ions, which are highly reactive electrons. These highly reactive electrons aggressively combine with other elements in the air, such as bacteria and Volatile Organic Compounds and many other common atmospheric and produce harmless gaseous and liquid by-products.

Several manufacturers already are promoting coating in the form of paints or minerals at the external surface of bricks, windows or pavement tiles that could be used both outdoors and indoors. These natural minerals contain calcium carbonate and titanium dioxide that can reduce classical gaseous urban pollutants in many light coloured pastel paints. These coatings allow the covered areas to self-clean, make painted surfaces reflective to sunlight hence enhance cooling considerably during summer months (energy saving), protects and repels aero disperse particulates and make the exterior surfaces resistant to extreme weather conditions. For indoor uses the can have anti-bacteria and anti-mold action.

Several deployments of such types of products have been carried out in Japan, Italy, France, UK and US and in this section, we describe the potential of this technology as a source of passive measures that could be utilized for improving the air quality and for the estimating the potential in the domains that are part of the iSCAPE project.

2.3.1 The relevant principles of photocatalysis and the links with urban atmospheric pollution

Photocatalysis is a natural phenomenon whereby a substance, called a photocatalyst, through the action of light (natural sunlight or light produced by special UV lamps) modifies the speed of a chemical reaction. In the presence of air and light, a strong oxidation process is triggered that leads to the decomposition of organic and inorganic pollutants that come into contact with these surfaces.

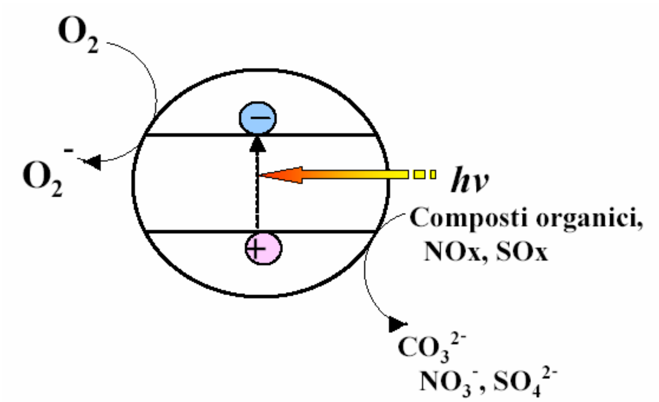

Figure 1: The light and components of air when contact with the coating of surfaces.

The light and components of air when in contact with the coating of surfaces, in the figure above, promote the creation of electron–hole pairs, which generate free radicals (e.g. hydroxyl radicals: •OH) able to undergo secondary reactions. Its practical application was made possible by the discovery of water electrolysis by means of TiO_2, as shown in the figure above. It is worth pointing out that this is a surface reaction and so any air in the atmosphere, containing these pollutants. As such the first generation of these proposed materials had important limitations and dependencies that were later improved by latest nanostructures and enhancements as are presented in the subsequent sections of this report.

This process creates hydroxyl radicals and super-oxide ions, which are highly reactive electrons that aggressively combine with other organic and inorganic elements in the air breaking them down into harmless carbon dioxide and water molecules, drastically improving the air quality.

Such substances are essentially all soot particles (including PM_{10}), microbes, nitrogen oxides, polycyclic aromatic condensates, benzene, sulphur dioxide, carbon monoxide, formaldehyde, acetaldehyde, methanol, ethanol, benzene, ethylbenzene etc. The toxic atmospheric substances as shown in the figure below, are transformed, in sodium nitrate ($NaNO_3$), sodium carbonate $(Ca(NO_3))_2$ and limestone ($CaCO_3$), harmless small quantities measured in parts per billion (ppb). The result is a significant reduction in toxic pollutants from cars, factories, domestic heating and other sources.

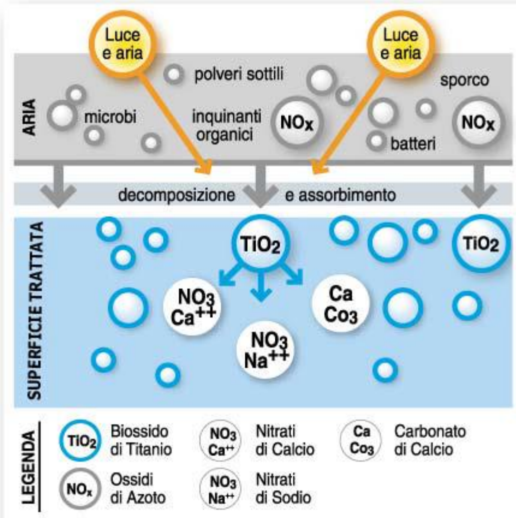

Figure 2: The air pollutants that can be transformed by photocatalytic coatings.

There are two types of photocatalysis:

1) Homogeneous photocatalysis where the reactants and the photocatalysts exist in the same phase. The most commonly used homogeneous photocatalysts include ozone and photo-Fenton systems (Fe^{+} and Fe^{+}/H_2O_2). The reactive species is the •OH which is used for different purposes.

2) Heterogeneous catalysis when the catalyst is in a different phase from the reactants and includes a large variety of reactions: mild or total oxidations, dehydrogenation, hydrogen transfer, $18O_2$–$16O_2$ and deuterium-alkane isotopic exchange, metal deposition, water detoxification, gaseous pollutant removal, etc. Most common heterogeneous photocatalysts are transition metal oxides and semiconductors, which have unique characteristics. Unlike the metals which have a continuum of electronic states, semiconductors possess avoid energy region where no energy levels are available to promote recombination of an electron and hole produced by photoactivation in the solid.

The air pollutants that can be transformed by photocatalytic coatings are:

- Nitrogen Oxides (NO_2 and NO) that are the precursor's formation of ground-level ozone and major components of acid rain.

- Sulphur Oxides (SO_2) contributing to acid rain and responsible for the formation of many harmful sulphates.

- VOCs such as benzene and toluene.

- Ammonia (NH_3) responsible for climate changes.

- Carbon monoxide (CO) with harmful respiratory effects.

- Organic chlorides, aldehydes, polycondensate aromatics and soot.

2.3.2 Operating potentials for which gases under seasonal variations

The effectiveness of the photocatalytic reaction, depends primarily on the contribution of UV rays in the range between 300 and 400 (μm) and occurs at it is maximum value during the hours of greater solar irradiation, and at its minimum in the hours of darkness. The reaction, of course, continues in areas with suitable lighting with lamps emitting UV rays so that efficiency of the reaction continues.

The scientific literature in recent years has been stimulated by the research and development of several products manufactured by several industries that focused primarily in analysing the actual validity of photocatalysis proliferating the deployment of photocatalytic surfaces while promoting the increased potential to reduce pollution in urban areas, through numerical simulations. The CNR in Italy during 2003 provided an estimate of a number of pollutants that a photocatalytic surface is able to destroy, starting from the amount deposited at the surface of the coating and due to the photocatalytic reaction, itself.

"... An active surface of one square meter may have the potential to purify to 90% a cubic meter of air in 45 seconds. Which is translated in that 1 km^2 of the active photocatalytic surface area may remove from the atmosphere 32 tonnes of pollutant per year. This is a very significant purifying capacity subtended that in the course of an hour such purification may be extended to 3600/45 = 80 m^3, i.e. an active surface of 1 m^2 removes 90% of the pollution content of 80 m^3 of air in just 1 hour ... from this observation was born the idea of using the coating by means of photocatalytic cement (containing chemical compounds able to react very quickly with some pollutants) will be able to reduce urban pollution simply by direct absorption. For example, in the typical Milan urban canopy, it is estimated the annual emissions are about 13,000t/ (in 1998), it appears that the covering of all urban area with coatings it may eliminate of nitrogen oxides up to levels compatible with air quality standards".

Similar conclusions were made by the University of Urbino also in Italy, which states that "... 'use of photocatalytic cement mortars, mortars containing chemical compounds that can very easily react with some pollutants causing its removal for direct absorption with quick reactions. In these materials, exposure to ultraviolet radiation (UV at a λ <400 nm wavelength) causes the formation of particles which catalyse oxidation and reduction reactions respectively. These reactions transform pollutants generating a new chemical species with low environmental impact ... ". In this study, the best result was obtained for a water-based paint photocatalytic that was capable of breaking down the nitrogen monoxide (NO) by about 90% after one hour and in a total way after about two hours.

These findings are also in agreement with other studies carried in Northern countries although there UV radiation is not so abundant and with during seasonal variations annually.

2.3.3 Estimate of expected potentials in North and South Europe

There is no doubt that photocatalysis is going to play an increasingly important role in reducing the products of harmful anthropogenic processes and in promoting environmental improvements with targeted control activities. In recent years, scientific and technical interest for photocatalysis applications has grown exponentially.

It can, for example, be cited the photocatalytic degradation of derivatives of herbicides (Singh et al., 2003), the nitrobenzene (Bhatkande et al., 2003), volatile organic compounds (VOC) airborne (Wu and Chen, 2003) and bisphenol (Fukashori et al., 2003). Wu and Chen report that the efficiency of the titanium dioxide for curing of the photolysis of benzene, the xylene, n-heptane, methanol, acetone, ethyl ether, formaldehyde, trichloroethylene and perchloroethylene, it was of the order of more than 80% in 5 minutes (excluding formaldehyde), with mercury lamp irradiation. The same authors report the efficiency variations in relation to different quantities and types of Titanium Dioxide, intensity and type of ultraviolet (UV) and other related aspects. The patents application based on photocatalytic products are so far more than two thousand and Japan claims so far the lion's share. Consider that the photocatalysis market in Japan, scheduled for 2005, is 10 billion dollars. Currently the Japanese market is made up 61% in outdoor products, 18% products for interior, 11% products for road paving, 9% filters, 1% other applications but the development of applications will always give more space to the crucial water treatment that will win in the next few years a third of the total market.

Several European research projects on photocatalysis have been since 2003 and a project that was based on limited products was named PICADA (Photocatalytic Innovative Coverings Application for De-Pollution Assessment). It lasted for three years and the focus area was the applications of innovative photocatalytic coatings for the clean-up assessment. Aimed to partially furnish a better understanding of the clean-up process, the evaluation cost and durability of the materials used, in addition to the development and commercialization of the product. It expected that these materials will allow achieving the goal of reducing the levels of nitrogen oxides below 21 ppb until 2010 which was the target year of all European Commission strategies for achieving compliance below to air quality limit values set by WHO). Since then several products had emerged and in iSCAPE we are planning the utilisation of PURETi.

Research performed in Southern California University using UV-PCO for cleaning the air with roof tiles (lab experiments by Sean Nealon https://ucrtoday.ucr.edu/22621) has shown that 28.75 sqft of material treated with PURETi removes 1 lb of NOx over the course of a year. Since EPA reports that a typical US passenger vehicle emits annually 18.32 lbs of NOx (http://www.epa.gov/otaq/consumer/420f08024.pdf) this means by treating in South California an average 2,000 sqft residential roof with PURETi would offset the NOx produced by almost 4 vehicles.

PURETi is a 3rd generation advance in PCO technology that is covered by nine patients and represents a true solution of water and TiO2 that is remarkably adhesive of its own accord. PURETi technology bonds to virtually any building surface more clearly and more thinly and with more crystals of TiO2 than any known competitor. As a result, PURETi requires less light to work, delivers greater photocatalytic benefit and is more cost effective than any known competitor. Any 1st or 2nd generation PCO product can be produced with greater photocatalytic power and at lower cost with a simple spray application of PURETi.

PURETi is applied to manufactured building materials and fixtures in factories or to the interior or exterior of the built environment. In factories, PURETi is typically applied at the end of the production line via robotically controlled spray, coating or printing methods. In the built environment, PURETi is applied by trained and certified applicators using specialised spray equipment to deposit a super thin film that dries in seconds and cures in hours to form an invisible polymeric like a ceramic film that is durably bonded to the treated surface.

UV light bounces and is reflected around just like visible light, so reflected or ambient light works fine to activate PURETi. The light needed by PURETi depends if the application of this coating is indoors or outdoors.

Outdoors – PURETi claims a self-cleaning and air purifying benefits that require only require 0.1 mW/cm^2 of UV-A light. Direct sunlight delivers over 1 mW/cm^2 and the north side of buildings – even in the shade – receive more than 0.001 mW/cm^2 of UV-A light.

Indoors – PURETi claims a more limited, but still powerful and highly marketable, set of odour eliminating and IAQ, respiratory health improving benefits. These functionalities only require 0.001 mW/cm^2 of UV-A light – one-hundredth the amount of light required for full self-cleaning. This level of light is found at window surfaces and light fixture surfaces.

In the following table are indicated the various forms that this coating is manufactured and the areas of application that could be tested for passive deployment in this project.

Product Name	Description	Uses
PURETi Clean & Fresh	Window Cleaner & Air Cleaner in One	Auto interior glass Hospitality Commercial facility maintenance Residential
PURETi Clear	One step professional application for glass or dark, shiny surfaces	Exterior building maintenance Indoor Air Quality improvement Solar panels
PURETi Coat	One Step Application for concrete, stucco, or cement	Stadiums, roadways, building facades
PURETi Clean	A highly photocatalytic top coat for any opaque surface. Applied on top of Base.	Roofing Infrastructure
PURETi Basecoat	Primer: Promotes adhesion and protects underlying substrates	Any opaque or organic surface where durability is at a premium
PING: PURETi Inorganic Nano Glue	An amorphous titania film former	Immobilization of nano particles Metal oxide film formation

Table 1: Various forms of PURETi coating.

2.4 Spatial perspective

Regarding air quality and urban heat, there are several spatial parameters, which can impair or improve a city's bioclimatic situation. The intensity of private transport (and emissions from it) is for example highly dependent on the compactness of a city, the travel distances between different land-uses and their functions (housing; working; leisure) and the availability of public transport opportunities.

The aim of the planning-related subchapters of this Deliverable is, therefore:

- to gather the state of science on spatial parameters influencing air quality and urban heat (subchapter 2.4),
- to operationalise these spatial parameters by selecting appropriate indicators (subchapter 2.4),
- to apply the indicators to the iSCAPE Living Lab cities in form of a spatial analysis (subchapter 3.4)
- to validate the methodological approach, the parameter and indicator selection (subchapter 4.4) and
- to develop transferable guidelines and recommendations on how to approach improvements in air quality and urban heat from a spatial planning perspective (subchapter 5.4).

In the following, spatial parameters influencing air quality (see subchapter 2.4.1) and urban heat (see subchapter 2.4.2) are gathered. While these subchapters solely focus on the administrative boundaries of cities, subchapter 2.4.3 takes the perspective of city-regional interrelations, introducing the concept of Functional Urban Areas (FUAs).

2.4.1 Spatial parameters influencing air quality

In the following, the parameters ‘transport’, ‘industry and trade’ as well as ‘urban green and blue spaces’ are introduced as spatial parameters influencing air quality. Each parameter is equipped with several indicators, which help estimate a city’s air quality situation.

2.4.1.1 Parameter ‘transport’

Air pollution in cities strongly results from emissions from low-lying sources, making transport one of the most important parameter of air quality (Timtschenko, 2007; Kuttler, 2008; Brosch et al, 2016). Due to suburbanization and centralisation of the retail sector, schools and companies, spatial structures spread and caused an urban sprawl. This functional segregation of work, leisure and living areas caused longer distances and consequently an increase in private transport utilisation. (Holz-Rau and Scheiner, 2005) Until today, a car-affine spatial development is encouraged through good road transport connections and low transport costs (Becker et al., 2011).

Public transport, on the other hand, is a far less energy consumptive form of mobility than private transport, which is why a shift to public transport is often politically wished for (Holz-Rau and Scheiner, 2005). However, this shift requires a change in mobility behaviour, which can – amongst others – be enhanced through accessible and extended public transport network. Further emission reduction strategies can e.g. be the shift of freight transport from road to rail transport and inland navigation. (MVI, 2014)

The parameter ‘transport’ is investigated through the following indicators (as depicted in the table below). The indicator ‘traffic area’ is gained from spatial data and illustrates the percentage of area covered by roads, rail, airports and associated land. It gives reference to the spatial character of a city, exemplifying long distances and widespread settlement (a large percentage) or rather short distances and compact settlement structures (small percentage).

‘Private transport’ is investigated through two indicators, both drawn from the regional yearbook of Eurostat, a database from a Directorate-General of the European Commission. ‘Commuter outflows' describe the percentage of the employed population commuting out of a city's territory for work purposes. A high commuter outflow rate, therefore, indicates increased private transport emissions. Additionally, the 'density of motorways' visualises long-distance transport and gives reference to a city's integration into the regional traffic network.

'Public transport' is approximated by the 'equipment rate for public transport vehicles', measured in a number of buses etc. per 1,000 inhabitants. This indicator illustrates the availability and attractiveness of public transportation services. Additionally, qualitative statements are gathered e.g. from local public transport providers, in order to better estimate the on-site use of public transportation.

Regarding 'freight transport', three indicators are used to approximate the city's local situation. The indicators 'road freight vehicles' and 'density of rail network' are gathered from the Eurostat regional yearbooks. The number of 'road freight vehicles' gives reference to a city's road freight pollution load while the 'density of rail network' indicates the availability of rail freight transport. Additionally, the presence of either an airport or a freight port (or both) is identified in order to gain knowledge on further emission loads.

The following table summarises the indicators used for the parameter 'transport' and gives both a short description as well as the data basis.

	Indicator	Description	*Data Basis*
Transport	**Traffic area (%)**	*Percentage of area covered by roads, rail, airport and other associated land*	*Spatial data; Urban Atlas Data / CORINE Data*
	Private Transport		
	Commuter outflows	Percentage of employed population commuting outwards for work purposes	*Eurostat Regional Yearbook 2016; NUTS2*
	Density of motorways;	Amount of km per 1,000 km² of total area	*Eurostat Regional Yearbook 2015; NUTS2*
	Public Transport		
	Equipment rate for public transport vehicles	Number of public transport vehicles (buses etc.) per 1,000 inhabitants	*Eurostat Regional Yearbook 2016; NUTS2*
	Qualitative statements	Quotes illustrating the local public transport situation	
	Freight Transport		
	Road freight vehicles	Number of road freight vehicles (in 1,000)	*Eurostat Regional Yearbook 2013; NUTS2*

	Density of rail networks	Amount of km of railway line per 1,000 km² of total area)	*Eurostat Regional Yearbook 2014; NUTS2*
	Presence of airport and/or freight port	Presence of airport and/or freight port as major sources of air pollution	*Google maps*

Table 2: Indicators of parameter 'transport'

2.4.1.2 Parameter 'industry and trade'

One main pollutant straining a city's air quality situation is industrial land use (SeUN, 2012). The emission load of this parameter results from both, industrial production as well as from transport from and to industrial or commercial units, as these areas are often located at the periphery (Becker et al., 2011).

In the spatial analysis, the indicator 'industrial area (%)' is used to operationalize the parameter 'industry and trade', giving reference to the amount of area covered by industrial or commercial units. Although the indicator simplifies the complex local situations, it is a valid indicator for the approximation of a generally higher/lower emission load from the sectors of industry and trade.

	Indicator	Description	*Data Basis*
Industry and trade	**Industrial area (%)**	*Percentage of area covered by industrial or commercial units or port areas*	*Spatial data: Urban Atlas Data / CORINE Data*

Table 3: Indicator of parameter 'industry and trade'

2.4.1.3 Parameter 'urban green and blue spaces'

Generally speaking, urban green spaces and water bodies positively influence air quality, as they function as cold air production areas and are capable of filtering CO_2. These characteristics of urban green and blue spaces are also valid for a city's local climatic situation. Due to evaporation and opacity/shading, urban green and blue spaces have a cooling effect, able to mitigate potential heat loads in urban heat islands (Bruse, 2003; Kuttler, 2008).

In the following, the parameter 'urban green and blue spaces' is understood to embrace all types of green and blue spaces within a city. These can e.g. be parks, cemeteries, sports grounds, but also nature conservation areas, water bodies or forests (BMUB, 2015).

As 'urban green and blue spaces' positively influence both air quality and local climate, it is to be considered a strong parameter for the spatial analysis. The operationalization embraces separate indicators on 'forests', 'urban green', 'agriculture' and 'water bodies', all measured in percentages of area covered by these land uses. Additionally, the indicator 'green and blue areas (%)' sums up the individual land-use categories and illustrates the share of climate-comforting green and blue spaces.

	Indicator	Description	*Data Basis*
Urban	Green and	*Percentage*	*Spatial data: Urban Atlas Data / CORINE Data*

green and blue spaces	blue areas (%)	*of area covered by green of blue areas (sum of forests, urban green, agriculture and water bodies)*	
	Forest (%)	*Percentage of area covered by various types of forests*	*Spatial data:* *Urban Atlas Data / CORINE Data*
	Urban green (%)	*Percentage of area covered by urban green (parks etc.)*	*Spatial data:* *Urban Atlas Data / CORINE Data*
	Agriculture (%)	*Percentage of area covered by agricultural land use*	*Spatial data:* *Urban Atlas Data / CORINE Data*
	Water bodies (%)	*Percentage of area covered by water bodies*	*Spatial data:* *Urban Atlas Data / CORINE Data*

Table 4: Indicators of parameter 'urban green and blue spaces'

2.4.2 Spatial parameters influencing urban heat

In the following, the parameter 'settlement structure' is introduced as the major spatial parameter [besides 'urban green and blue spaces' (see subchapter 2.4.1.3)] influencing urban heat.

The phenomenon of urban heat may be explained as follows. In comparison to a more rural surrounding, cities have an annual average elevated temperature of 1-2 degrees Celsius (Matzarakis et al., 2008; Kuttler, 2011). This gradient results from the radiative and thermal conditions that differ between built-up and undeveloped areas, i.e. the "absorption ability, the heat capacity, the heat conductivity, and the evaporation ability of the underlying ground"

(MEWHBW, 2012). This distinct temperature difference of surface temperatures is called an ‘urban heat island’ (UHI) (EPA, 2008).

2.4.2.1 Parameter ‘settlement structure’

Temperature gradients in cities and the development of UHI largely depend on the degree of ground sealing (Kuttler, 2008; adelphi et al., 2015; Knieling et al., 2012). Sealing increases both the average annual temperature of an area and engraves the daily temperature differences (MEWHBW, 2012). Additionally, sealed ground is air- and watertight, which impedes rainwater infiltration and restricts gas exchange between ground and atmosphere (UBA, 2013). Furthermore, a high degree of ground sealing in combination with a low proportion of vegetation leads to higher physical stress during heat waves (Kuttler et al., 2013; MKULNV, 2011).

Building density is defined by the proportion of built-up area to undeveloped land in a certain area. The more compact settlement structures are, and the less ventilation there is, the more increased is the UHI potential. A compact settlement structure that nonetheless has proper ventilation is understood as an ideal spatial design concept (Kuttler, 2008).

In the following, the indicators ‘sealed ground (%)’ and ‘population density’ are used for an approximation of the parameter ‘settlement structure’. The indicator ‘sealed ground (%)’ contains the percentage of sealed ground and is derived from spatial data basing on different degrees of sealing according to each land-use category. Additionally, the indicator ‘population density’ is illustrated in map excerpts taken from the Eurostat regional yearbook 2016. The excerpts depict the number of inhabitants living per km^2 and visualise the core housing areas of a city, potentially being affected by urban heat.

	Indicator	Description	***Data Basis***
Settlement Structure	Sealed ground (%)	*Percentage of sealed ground on the basis of total city area*	*Spatial data: Urban Atlas Data / CORINE Data*
	Population density	A number of inhabitants living per km^2.	*Eurostat Regional Yearbook 2016.*

Table 5: Indicators of parameter ‘settlement structure’

2.4.3 The concept of Functional Urban Areas

When approaching the subject of air quality from a spatial perspective, taking a city-regional viewpoint is inevitable because the city-region has become one of the most significant functional levels of urban and regional systems (Antikainen, 2005). Nowadays, the core centres of an urban region and their suburban area (the “fringe areas”) have formed an intertwined and interactive functional area, which is not bound to any administrative levels (Van der Laan, 1998). So while the previous subchapter 2.4.1 and 2.4.2 concentrated on parameters related to the administrative boundaries of cities, this subchapter centres city-regional interrelations by introducing the concept of Functional Urban Areas (FUAs).

The European Commission in cooperation with the Organisation for Economic Co-operation and Development (OECD) facilitated the FUA concept in 2011, aiming at developing an EU-inherent definition of ‘a city’ based on population size and density (Dijkstra and Poelman, 2015). In the simplified description of FUAs, cities are defined as densely populated local administrative units with at least 50,000 inhabitants, of which more than 50 % live within an urban centre (Eurostat, 2015a). The urban centre may be composed of one or more municipalities (Antikainen, 2005; OECD, 2013). In case the urban centre stretches out beyond the city's boundaries, a 'greater city' area is approximated (see e.g. chapter 3.4.3 Dublin) (Eurostat, 2015b). Last, commuting zones are calculated on the basis commuting shares, displaying "the surrounding travel-to-work areas of a city where at least 15 % of their employed residents are working in this city" (Eurostat, 2015c). Together, cities and commuting zones form an FUA (Eurostat, 2015d).

The OECD gives a more detailed description of the FUA definition and calculation, also discussing exceptions and particularities. In a polycentric structure, it may e.g. be the case, that urban areas hold more than one high densely inhabited core, which is in fact physically separated but economically connected. To distinguish between two separate cores and integrated cores within a polycentric structure, the relationship among the urban cores needs to be looked at, using the information included in the commuting data (OECD, 2013). "Two urban cores from the same polycentric metropolitan area are considered integrated if more than 15 % of the residence population of any of the cores commutes to work on the other core." (OECD, 2013) Furthermore, 'the hinterlands', the municipalities surrounding the urban cores need to be calculated in order to identify the integration of labour market. By OECD definition urban hinterlands are municipalities with at least 15 % of their working population commuting to their workplace located in a certain urban core. In other words, hinterlands are "worker catchment areas" of the urban labour market, outside the densely-inhabited centre (OECD, 2013).

Functional urban areas can be categorised into four types according to population size (OECD, 2012):

- small urban areas, with a population below 200,000;
- medium-sized urban areas, with a population between 200,000 and 500,000
- metropolitan areas, with a population between 500,000 and 1.5 million
- large metropolitan areas, with a population of 1.5 million or more.

2.4.3.1 Functional Urban Areas of the iSCAPE Living Lab cities

The FUA concept is useful whenever a comparison of regions of similar size across countries is needed (cf. Antikainen, 2005; OECD, 2012), as envisaged in this deliverable. Therefore, as an introduction, the six iSCAPE Living Lab cities are classified and shortly described according to the FUA concept.

Name of FUA	FUA Classification	Source
Bologna, Italy	Metropolitan area	OECD, 2016
Bottrop (Gelsenkirchen-Bottrop)[1], Germany	Medium-sized urban area	OECD, 2016; IGEAT et al., 2007,

[1] The city of Bottrop is listed as 'Gelsenkirchen-Bottrop' in the OECD report. Apparently the cores of both cities are integrated and count as one core FUA.

		pp. 53, 162
Dublin, Ireland	Metropolitan area	OECD, 2016
Guildford, United Kingdom	Small urban area	IGEAT et al., 2007, p. 119
Hasselt, Belgium	Small urban area	IGEAT et al., 2007, p. 157
Vantaa, Finland	no classification	IGEAT et al., 2007

Table 6: Functional Urban Areas in iSCAPE

Bologna is one of the several densely inhabited cores along with San Marino, Modena and others located close to the Apennine Mountains. It is not only an important railway hub of the national railroad network but also holds an important international airport. As a university town, Bologna has a strong education market. Due to its education and labour market, workforces from surrounding municipalities commute to Bologna, making it a metropolitan area according to the OECD FUA classification (OECD, 2016).

Bottrop is part of a polycentric system in the Ruhr Area; therefore, a lot of urban cores of similar or bigger size are located close to the city. It is well connected with the regional transport system and easily reachable from surrounding cities. Compared to other cities in the Ruhr Area, Bottrop offers lesser workplaces and no university; hence more people from Bottrop commute to other cores than the other way around (OECD, 2016).

As the capital of the Republic of Ireland, **Dublin** is the biggest and most densely inhabited core in the region. It has a strong influence on the commuting workforce from the surrounding and even distant municipalities due to the city's strong labour and education markets. Dublin not only holds many jobs but also universities. In addition, the city is one of the most important national and international transport nodal points, due to the fact that it has one of the biggest international airports in Europe (OECD, 2016).

Guildford is located close to the economically strong capital London, which influences swaths of its region offering great labour and education markets. Nevertheless, Guildford is the core of a functional urban area itself, because it holds (amongst others) a university and many jobs in the technological field, so people of surrounding municipalities commute to Guildford (IGEAT et al., 2007).

Hasselt is a small urban area surrounded by further smaller municipalities, from which labour force party commutes to Hasselt. Bigger cities nearby are Brussels or foreign cities like Aachen and Maastricht. The city is well connected in the regional transport network. Hasselt holds a university as well as an administrative and trading centre with regional influence. The city is also located at the Albert-Canal, which connects various inland cities to the North Sea (IGEAT et al., 2007).

Vantaa, as well as Espoo, is part of Greater Helsinki, the metropolitan area of the capital of Finland. Many people from Vantaa and Espoo commute to Helsinki. Simultaneously, Vantaa itself offers a great labour market (e.g. headquarter of Finland's main airlines) as well as a university, resulting in commuter flows from surrounding municipalities to Vantaa (IGEAT et al., 2007).

3 Air pollution reduction strategies

3.1 Physical PCS

A few Physical barriers have been identified and investigated as potential physical passive methods to improve air quality in the urban environment. Noise barriers, LBWs and parked cars present distinct solid barriers in the built environment that can influence air flow and pollutant dispersion in different ways.

In this report, a review of some key studies around the different three physical passive control systems, mentioned earlier, has been conducted, table 7 summarises some of the discussed studies in this section.

Recently, Gallagher et al. (2015) published a review that synthesises the methods that have demonstrated an ability to influence air flow patterns to reduce personal exposure (on footpaths) in the built environment, a number of passive methods are split into two distinct categories: porous or solid barriers. These methods include trees and vegetation (porous) as well as noise barriers, low boundary walls and parked cars (solid). Those passive methods have been investigated through experimental and modelling studies, which have provided an understanding of the potential for these barriers to improve air quality under varying urban geometrical and meteorological conditions.

Passive method	Study type					Pollutant^{s}				References
Barrier type	Measurement	Modelling	Wind Tunnel	Combined		PM	CO^b	NO_x	VOCs	
Noise barrier	✓	✓	✓	✓		✓	✓		✓	(Bowker et al., 2007, Baldauf et al., 2008, Finn et al., 2010, Ning et al., 2010, Hagler et al., 2011b, Steffens et al., 2013, Steffens et al., 2014, Jeong, 2014, Schulte et al., 2014, Hagler et al., 2012)
Low boundary wall	✓	✓		✓		✓	✓	✓	✓	(McNabola et al., 2008, McNabola et al., 2009, King et al., 2009, Gallagher et al., 2012, Gallagher et al., 2013a)
Parked cars	✓	✓		✓			✓	✓		(Gallagher et al., 2011, Gallagher et al., 2013a, Abhijith and Gokhale, 2015)

Table 7: Summary of the research studies undertaken for different physical passive methods for improving air quality (adapted after, (Gallagher et al., 2015)).

3.1.1 Noise barriers

Many studies have investigated the influence of the noise barriers on the air quality in the built environment, see Table 8. The effects of a noise barrier on air quality and pollutant dispersion are studied in the USA as part of a modelling and measurement study of different roadside barriers (Bowker et al., 2007). This study considered the impacts of a barrier on UFP concentrations along a busy highway and allowed for the assessment of a barrier versus no barrier in a real-world environment. The measurements results provided by (Baldauf et al., 2008) for PM and CO illustrated that the using of a noise barrier reduced pollutant concentrations behind the barrier by around 15% but at times reached 50%. With the inclusion of a barrier, the modelling results demonstrated that a reduction in pollutant concentrations would be achieved further downwind (Bowker et al., 2007).

Reference	Location/methods	Findings
(Steffens et al., 2014)	Wind tunnel experiments, USA	In general, the inclusion of multiple roadways features often result in lower downwind pollutant concentrations than those with single roadway features; however, adding features typically offers diminishing returns in concentration reduction.
(Schulte et al., 2014)	Semi-empirical dispersion models, USA	The suggested models overestimate pollutant concentrations near the barrier during unstable conditions.
(Jeong, 2014)	FLUENT computational fluid dynamics (CFD) model, China	The findings of this study show that the double noise-barrier decreases normalized average concentrations of leeward positions, ranging from 0.8 (H/W=0.1, wake interface) to 0.1 (H/W=0.5, skimming flow) times lower than that of the no barrier case, at 10 x/h downwind position; and ranging from 1.0 (H/W=0.1) to 0.4 (H/W=0.5) times lower than that of the no barrier case, at 60 x/h downwind position.
(Hagler et al., 2012)	This study measured ultrafine particle (UFP) concentrations using an instrumented mobile measurement approach, collecting data on major roadways and in near-road locations for more than forty sampling sessions at three locations in central North Carolina, USA.	At 10 m from the road, UFPs measured using a mobile sampling platform were lower by approximately 50% behind the brick noise wall relative to a nearby location without a barrier for multiple meteorological conditions.
(Baldauf et al., 2008)	This field study provided an opportunity to evaluate the near-road air quality with no barriers, with a noise barrier only, and with a	The results show that the presence of the barrier structures often led to pollutant concentration reductions behind the barrier during meteorological conditions with winds directionally from the road.

	noise barrier and vegetation adjacent to the road. Pollutants measured under these scenarios included carbon monoxide (CO) and particulate matter (PM), USA.	
(Bowker et al., 2007)	This study examined the effects of roadside barriers on the flow patterns and dispersion of pollutants from a high-traffic highway in Raleigh, North Carolina, USA, using the Quick Urban & Industrial Complex (QUIC) model.	Results indicate that air pollutant concentrations near the road are generally higher in open terrain situations with no barriers present; however, concentrations for this case decreased faster with distance than when roadside barriers are present. The presence of a noise barrier and vegetation resulted in the lowest downwind pollutant concentrations, indicating that the plume under this condition is relatively uniform and vertically well-mixed.
(Finn et al., 2010)	A roadway toxics dispersion study was conducted at the Idaho National Laboratory (INL) to document the effects on concentrations of roadway emissions behind a roadside sound barrier in various conditions of atmospheric stability, using the atmospheric tracer (SF_6) from two 54 m long line sources, one for an experiment with a 90 m long noise barrier and one for a control experiment without a barrier.	Key findings of the study are: a concentration deficit developed in the wake zone of the barrier with respect to concentrations at the same relative locations on the control experiment at all atmospheric stabilities. The lateral dispersion was significantly greater on the barrier grid than the non-barrier grid. The barrier tended to trap high concentrations near the “roadway” (i.e. upwind of the barrier) in low wind speed conditions, especially in stable conditions.
(Hagler et al., 2011b)	A 3-dimensional computational fluid dynamics (CFD) 6-lane road model has been developed to simulate roadside barrier effects on near-road air quality and evaluate the influence of key variables, such as	Under winds perpendicular to the road, CFD model simulations show that roadside barriers reduce the concentration of an inert gaseous tracer (χ), relative to a no-barrier situation, vertically up to approximately half the barrier height and at all horizontal distances from the road. At 20 m (3.3H, where H = 6 m) from the road, barriers of heights ranging from 0.5H to 3.0H reduce the maximum concentrations by 15–61% relative to a no-barrier case, with the location of the maximum shifted to occur near the top of the barrier.

	barrier height and wind direction. The CFD model matches an existing wind tunnel road model and comparison with the wind tunnel data guided the selection of the optimal turbulence model (Realisable k–ε turbulence model with a Schmidt number of 1.0)	
(Ning et al., 2010)	This study investigated two highly trafficked freeways (I-710 and I-5) in Southern California, with two sampling sites for each freeway, one with and the other without the roadside noise barriers, USA.	The results showed the formation of a "concentration deficit" zone in the immediate vicinity of the freeway with the presence of roadside noise barrier, followed by a surge of pollutant concentrations further downwind at 80–100 m away from the freeway.
(Steffens et al., 2013)	Comprehensive Turbulent Aerosol Dynamics and Gas Chemistry (CTAG) model are utilised to simulate the spatial gradients of SF6 concentrations behind a solid barrier under a variety of atmospheric stability conditions collected during the Near Road Tracer Study (NRTS08), USA.	This study suggests that advanced simulation tools can potentially provide a variety of numerical experiments that may prove useful for roadway design communities to intelligently design roadways, making effective use of roadside barriers.

Table 8: Key studies related to the use of noise barriers as a passive control system.

Ning et al. (2010) measured the size distribution of particulate concentrations and several other pollutants in two case studies of urban freeways. Very similar results were noted in this study for PM, with reductions in the 45-50% range downwind of the barrier. Tracer pollutant investigations reported by Finn et al. (2010) illustrate the potential for noise barriers to improve air quality by over 50% downwind of the barrier during certain meteorological conditions such as stable atmospheres. The results of a modelling study by Hagler et al. (2011b) ranging from 15 to 61% and dependent on the physical dimensions of the barrier especially the height (higher the barrier, the greater the downwind pollutant reduction).

Many papers have illustrated how a noise barrier traps the pollutants on the upwind side of the structure and this may lead to higher concentrations in this location (Bowker et al., 2007, Finn et al., 2010, Steffens et al., 2014, Ning et al., 2010, Gallagher et al., 2015). Finn et al. (2010) reported that trapping of the pollutants on the upwind of the structure occurs during low wind speeds. The simulations results from Hagler et al. (2011b) illustrated that the on-road pollutant concentrations increased by a factor of 1.1 to 2.3, increasing as the barrier height increased. Ning et al. (2010) illustrated that the barrier creates an impact zone for traffic emissions. A simulation study by Steffens et al. (2013) specified a recirculation zone in the wake of the barrier, that affected on pollutant transport in the road area, the results show that pollutant concentrations from upwind sources may lead to higher pollutant concentrations, although questions still remain on whether turbulence created by traffic on the roadway may limit these effects for the on-road environment.

The reviewed studies show some evidence of potentially higher pollutant concentrations further downwind of the barrier (approximately 150 m), which is mainly reported by Ning et al. (2010) compared with the control case of no barrier exist. A modelling study by Bowker et al. (2007) found that this is due to the re-attachment of the plume downwind of the barrier, this study also report that concentrations at 150 m from the road are approximately 35% higher than with no barrier; although it is also suggested that these concentrations are significantly lower at this distance, both with and without the barrier, compared to the high concentrations closer to the highway with no barrier exists.

Gallagher et al. (2015) reported the review study that the potential of noise barriers to affect pollutant transport and dispersion is influenced by the size and layout of the barrier, wind direction and turbulence conditions (Hagler et al., 2011b, Jeong, 2014, Schulte et al., 2014, Steffens et al., 2013, Finn et al., 2010, Steffens et al., 2014). As mentioned earlier, the measurements reported by Hagler et al. (2011b) show reductions in pollutant concentrations of up to 61%, with improved air quality conditions associated with an increase in the barrier height.

The physical characteristics of the noise barrier can affect the air quality in the built environment, the impact of wall height on both noise and air quality is noted by King et al. (2009) and Steffens et al. (2014) who consider a number of road and barrier configurations. The barrier height is shown to have the greatest influence on pollutant concentrations near the barrier and on atmospheric stability downwind of the barrier (Schulte et al., 2014).

Finn et al. (2010) reported measurements of barrier-induced turbulence and pollutant concentrations around a noise barrier. A number of flow conditions are modelled by Schulte et al. (2014), the simulations find that overestimations of pollutant concentrations are made in unstable, turbulent conditions. Wind speed and direction are specified as factors that influence air pollutant concentrations in the barrier surrounding area. Jeong (2014) demonstrated how wind conditions significantly impact the influence of noise barriers on air quality, using different wind flow scenarios. Measurement studies have illustrated the potential of noise barriers as a physical passive system and their effects on air quality for different pollutants (Bowker et al., 2007, Baldauf et al., 2008, Ning et al., 2010, Finn et al., 2010). More recent modelling investigations have provided a deep understanding of pollutant dispersion for different barrier configurations and in a range of flow conditions (Steffens et al., 2013, Hagler et al., 2011b, Steffens et al., 2014), however more measurements studies are needed to verify the results of the many conducted modelling studies.

3.1.2 Low boundary walls

A number of studies have been implemented in order to study the effects of the LBWs as a passive control system to improve air quality, Table 9. Using LBWs has been investigated first by initial studies, which are implemented in along a boardwalk in Dublin, Ireland (McNabola et al., 2008, King et al., 2009). Those studies investigated the influence of a boundary wall constructed between a boardwalk and an adjacent road with three lanes of one-directional traffic in Dublin city centre. McNabola et al. (2008) concluded that an LBW acted as a baffle, that when located on the outer edge of footpaths or in the centre of the street canyon, altered pollutant dispersion in a street canyon. A follow-on study by King et al. (2009) reported that the effect of the boardwalk on air and noise pollution is that the segregation of human and vehicular traffic increased the distance between the source and the receptor.

Reference	Location/methods	Findings
(McNabola et al., 2008)	Air quality samples were taken along the length of a boardwalk in Dublin city to study whether pedestrians using the boardwalk would have a lower air pollution exposure than those using the adjoining footpath along the road. The same case has been modelled using CFD to provide more understanding.	The results of the study show significant reductions in pedestrian exposure to both traffic derived particulates and hydrocarbons along the boardwalk as opposed to the footpath.
(King et al., 2009)	This study offers a combined analysis of pedestrian exposure to noise and air pollution within a specific urban setting in Dublin, Ireland.	The results show that the boardwalk has reduced pedestrian exposure to air and noise pollution and that further reductions may be achieved by more strict segregation of pedestrian and road traffic in urban areas.
(McNabola et al., 2009)	The impact of low boundary walls on the dispersion of air pollutants in street canyons has been brought forward in this investigation study using CFD modelling, again in Dublin, Ireland.	The results of this study show that a low boundary wall located in the central median of the street canyon creates a significant reduction in pedestrian exposure on the footpath. Reductions of up to 40% were found for perpendicular wind directions and up to 75% for parallel wind directions, relative to the same canyon with no wall.
(Gallagher et al., 2012)	This numerical modelling study assessed the spatial distribution of concentrations of	The percentage difference in concentrations induced by the presence of footpath LBWs

	a tracer pollutant in a street canyon as a result of introducing of passive controls in asymmetrical street canyons to reduce personal exposure to air pollutants on footpaths.	ranged from an increase of up to 19% to a reduction of 30% on the leeward footpath, with reductions between 26% and 50% on the windward footpath with varying H1/H2 ratios.
(Gallagher et al., 2013a)	This study investigates the potential real world application of passive control systems to reduce personal pollutant exposure in an urban street canyon in Dublin, using both modelling and measurement approaches.	The results indicate that lane distribution, fleet composition and vehicular turbulence all affect pollutant dispersion, in addition to the canyon geometry and local meteorological conditions. The paper suggests that the use of passive controls displayed mixed results for improvements in air quality on the footpaths for different wind and traffic conditions.

Table 9: Key studies related to the use of LBWs as a passive control system.

McNabola et al. (2008) performed an air quality sampling study, which measured reductions of between 35% and 57% in personal pollutant exposure for pedestrians walking along the boardwalk as opposed to the adjacent footpath. Following the field sampling study McNabola et al. (2009) performed a generic computational modelling study to model the case and again reductions in personal pollutant exposure of up to 40% and 75% in perpendicular and parallel wind conditions, respectively have been calculated. Gallagher et al. (2012) in a later study found that footpath LBWs models ranged from a 19% increase to a 30% reduction on the leeward footpath and reductions of 26% to 50% on the windward footpath. Gallagher et al. (2013a) took the same case forward and assessed LBWs in a real study and reported reductions in pollutant concentrations of up to 35% to a maximum increase of 25% on the footpaths in varying wind conditions. Regarding the effects of the LBW physical characteristics, King et al. (2009) concluded that the height of the LBW impacted the effectiveness of the barrier on air flow and pollutant concentrations on the footpath. Also, McNabola et al. (2009) reported that the location of the LBWs impacted the results for pollutant concentrations. The street layout, limited wind conditions and omission of vehicular turbulence are noted to provide inaccuracies in the results compared to real case conditions (McNabola et al., 2009). The simplification in the emissions models generated errors, which were accounted to be more influential in model results for low wind speeds in the street canyon (Gallagher et al., 2012, Gallagher et al., 2015). A study by Gallagher et al. (2013a) adopted a semi-empirical equation for a real LBW case study to calibrate the models and account for factors such as vehicular turbulence, in addition to the fleet composition in the street canyon. The study reported that the omission of vehicular turbulence decreases the street level dispersion. The turbulence effects of LBWs is dependent on site-specific characteristics: street geometry, wind conditions and vehicular turbulence (Gallagher et al., 2013a, McNabola et al., 2008). In perpendicular wind conditions, reductions and increases in pollutant concentrations are evident in the footpaths LBW models, with reductions reported on both footpaths for all central LBW models (McNabola et al., 2009). The footpath LBWs provided the best results in parallel wind conditions, however, improvements in air quality are found for both LBW configurations.

3.1.3 Parked cars

Parked cars impact pollutant dispersion and influence the development of vortices in the street canyon (Gallagher et al., 2015). The first modelling investigation by Gallagher et al. (2011) investigates three common parking bay configurations, while a followed investigation by Gallagher et al. (2013a) examine a real case scenario with parallel parked cars in a street canyon in Dublin city centre, Ireland. However, it is concluded that some configurations could be detrimental to air quality on adjacent footpaths in certain wind conditions (Gallagher et al., 2011).

Reference	Location/methods	Findings
(Abhijith and Gokhale, 2015)	This study investigates the passive-control-potentials of trees and on-street parked cars on pedestrian exposure to air pollutants in a street canyon using three-dimensional CFD.	The results show that tree crown with high porosity and low-stand density in combination with parallel or perpendicular car parking reduced the pedestrian exposure considerably.
(Gallagher et al., 2013a)	Using a combination of field measurements and numerical modelling this study assessed the implementation of parked cars as a passive control system in Dublin.	Parked cars demonstrated the most comprehensive passive control system with average improvements in the air quality of up to 15% on the footpaths.
(Gallagher et al., 2011)	An investigation is carried out to establish the effectiveness of parked cars in urban street canyons as passive controls on pedestrian pollutant exposure. A numerical model of a generic street canyon is developed using a large eddy simulation (LES) model to compare personal exposure on the footpath with and without the presence of parked cars (Dublin)	The fraction of parked cars influence the level of reduction of pollutants on the footpaths with steady reductions in perpendicular winds, the reductions are only evident for occupancy rates greater than approximately 45% in parallel wind conditions.

Table 10: Key studies related to the use of parked cars as a passive control system.

The results from Gallagher et al. (2011) show that the parallel parking demonstrated the best overall simulated results in air quality, with an average modelled reduction in pollutant concentrations between 31% and 49% on both footpaths for varying wind conditions. Gallagher et al. (2013a) compared the results from the CFD modelling study to a real case scenario and the comparison show an improvement in the air quality of up to 15% when the parking bays are fully occupied. And the study suggests that is due to:

- the parking bays not taking up the full length of the street.
- the parking bays only existing on one side of the street.

Gallagher et al. (2011) reported that perpendicular and central parking bays demonstrated improvements and deteriorations in air quality for different wind conditions, unlike parallel parking. The occupancy rate and the spacing between cars in the parking bays affect air quality on the footpaths and the development of the vortex in the street (Gallagher et al., 2011). Gallagher et al. (2013a) examine the effects of canyon geometry and include local traffic and meteorological conditions through the models, a semi-empirical equation has been used to calibrate the model. Similar to other methods, street geometry and meteorological conditions are predominant factors on the ability to alter localised dispersion patterns and improve air quality (Gallagher et al., 2011, Gallagher et al., 2013a, Gallagher et al., 2015).

Abhijith and Gokhale (2015) have recently simulated five different parking systems with three different wind directions. The used five parking conditions are parallel, perpendicular parking, and inclined at (30, 45, and 60) degrees, see figure 3. The parallel and perpendicular parked cars showed a significant reduction in pollutant exposure compared to the reference case, whereas angled-parked cars showed mixed results. The 0 and 90 degrees parked cars reduced the pollutant concentration by about 20% and the passive control was the least in 45^o winds with concentrations close to that in the reference case. The 30^0 angled parking cars resulted in the maximum increase in pollutant exposure in parallel and oblique winds as found along the wall of a footpath. The concentrations were reduced when the parking angle changed to 45^0 and least concentrations were in 60^0. In perpendicular winds, the least exposure was for 30^0 parked cars and the worst for 60^0 and the windward side showed a reverse trend in exposure levels.

Abhijith and Gokhale (2015) concluded that the parallel parking system is the most effective, which show the best passive control. The results are in line with those of Gallagher et al. (2011). Table 10 summarises some key studies that address the use of parked cars as a passive control system to improve air quality in the built environment.

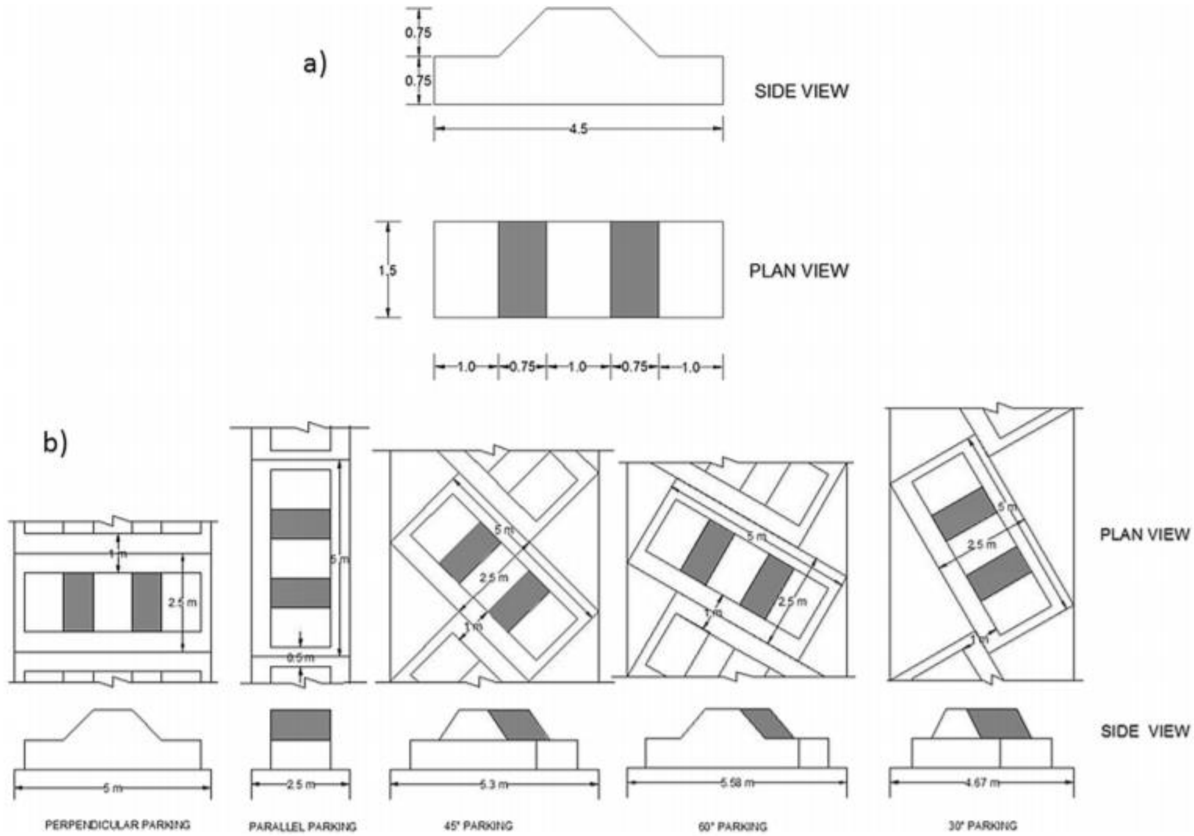

Figure 3: Dimensions of the car (a) and car parking configuration (b), which are used by (Abhijith and Gokhale, 2015).

3.2 Green infrastructure

The urban forest or greenery has been identified as one of the solutions for improving air quality. These urban infrastructures include street trees, vegetation barriers or hedges, green (or living) walls, and green (or living) roofs. These vegetation act as porous bodies which influence the local dispersion patterns and aids deposition of particulate matter (Janhall, 2015). Apart from air pollution reduction, urban greenery provides benefits such as urban heat island mitigation, reduction in energy consumption and noise pollution, better storm water management and climate change mitigation and adaptation (Berardi et al., 2014; Gago et al., 2013; Pérez et al., 2014).

Recent studies investigated air pollution abatement performance of various types of green infrastructure individually or in combination under different urban environments (Gallagher et al., 2015). This urban greenery can be implemented as passive air pollution control measures in future as well as in existing cities with limited modifications in built environment (McNabola, 2010). The urban environments considered in these studies were either near an open road or urban street canyon with high traffic volume. For example, the impact of trees in street canyons were examined by several studies (Abhijith and Gokhale, 2015; Amorim et al., 2013; Buccolieri et al., 2011, 2009; Gromke et al., 2008; Hofman et al., 2016; Li et al., 2013; Moonen et al., 2013; S. M. Salim et al., 2011; Salmond et al., 2013; Vos et al., 2013; Wania et al., 2012) . These studies pointed out the presence of trees in street canyon increases the pollution levels. The other studies investigated the pollutant exposure in street canyon with hedges, reporting that the low hedgerows reduce pollutant levels along the footpath. Likewise, a few studies investigated air pollution removal potential of vegetation along the busy urban highways, reporting vegetation barriers and trees along roads were able to reduce the roadside pollutant levels (Brantley et al., 2014; Hagler et al., 2012; Lin et al., 2016; Tong et al., 2016). A few studies also examined the air pollution removal potential of green roofs and green walls (Joshi and Ghosh, 2014; Ottelé et al., 2010; Pugh. et al., 2012) or the combinations of green infrastructure with other passive methods (Baldauf et al., 2008; Bowker et al., 2007; Ton g et al., 2016;Baik et al., 2012; Tan and Sia, 2005Baik et al., 2012; Tan and Sia, 2005). Overall, a general conclusion was from these studies was that the green infrastructure has a both positive and negative impact under different urban environments.

As summarised in Table 11, previous review articles on this topic have discussed particulate matter removal by vegetation (Janhall, 2015), suitability of passive methods to reduce pollutant exposure (Gallagher et al., 2015), and deposition on plant canopies (Litschike and Kuttler, 2008; Petroff et al., 2008). Furthermore, other reviews have focused on benefits of urban infrastructure such as urban heat island mitigation of trees (Gago et al., 2013), thermal performance of green facades (Hunter et al., 2014) and energy aspects of green roofs (Saadatian et al., 2013). Recently, Berardi et al. (2014) published a state of art of review on air pollution mitigation by green roofs. In addition, Salmond et al. (2016) summarised key ecosystem services provided by urban street trees.

Review	Description
Salmond et al. (2016)	Reviewed ecosystem services provided by street trees
Gallagher et al. (2015)	Reviewed effectiveness and suitability of each passive methods for reducing air pollution exposure
Janhall (2015)	Reviewed particulate matter removal by vegetation through deposition and dispersion
Berardi et al. (2014)	An extensive review of environmental benefits of green roofs covering energy conception reduction, air pollution mitigation, noise reduction, heat island effects etc.
Mullaney et al. (2015)	Listed social, environmental and economic benefits of street trees and challenges associated with growing.
Gago et al. (2013)	Review various heat island mitigation strategies and pointed out vegetation can reduce heat island effect
Hunter et al. (2014)	Reviewed thermal performance of green façade. This study listed thermal modulation of different types of climbing plants.
Pérez et al. (2014)	Vertical greenery systems, which include green walls and facades, were reviewed considering their potential for saving energy.
Saadatian et al. (2013)	This study reviewed energy aspects of green roofs.

Petroff et al., (2008)	Reviewed particulate matter deposition on urban vegetation
Litschike and Kuttler (2008)	Reviewed dry deposition on vegetation canopies

Table 11: presents a comprehensive summary of past studies on different green infrastructure.

3.2.1Trees

As described in section 2.2.1 trees are planted along streets and based on urban built environment urban trees can be subdivided into trees in street canyons and trees along open roads. This section is focused on local air quality impact of design characteristics of trees which are close to traffic emissions either in a street canyon or open road.

3.2.1.1 Trees in street canyons.

The street canyon is a common urban built area feature which consists of the tall building along both sides of the street. Tree rows are planted on either side of the road or a single row in the middle. The spacing between trees varies and the physical dimensions' changes with species. It has been observed that trees have an adverse effect on air quality within the street canyon. Trees in street canyon reduce the wind speed in street canyon resulting less air exchange between air above the roof and within the canyon and this leads to accumulation of pollutants inside the street canyon. Thus, pollutant levels in street canyon with trees are high compared to tree free street canyons. Apart from common vegetation characteristics listed in the previous section, other unique factors to the street canyon, affecting pollutant exposure are aspect ratio, wind direction and its speed, spacing between trees and the sectional area occupied by trees of the street canyon.

Limited field measurements or real world investigations have been accounted pollutant exposure of trees configurations in street canyons (Kikuchi et al., 2007; Hofman et al. 2013; Salmond et al. 2013; Jin et al. 2014), Another category of studies evaluated impacts of trees on street level pollutant exposure through combined measurement and modelling studies (Amorim et al., 2013; Buccolieri et al., 2011; Hofman et al., 2016). In addition, wind tunnel (Gromke and Ruck, 2012, 2009, 2007) and modelling studies have extensively evaluated pedestrian pollutant exposure in street canyons with trees (Balczó et al., 2009; Buccolieri et al., 2011, 2009; Gromke and Blocken, 2015; Gromke et al., 2008; Li et al., 2013; Moradpour et al., 2016; Ng and Chau, 2012; Ries and Eichhorn, 2001; Salim Mohamed Salim et al., 2011; S. M. Salim et al., 2011; Vos et al., 2013; Vranckx et al., 2015; Wania et al., 2012). A detailed summary of these studies is provided in tables 12 and 13.

In general all categories of studies reported reduced wind velocities and rise in pollutant concentration in street canyon with trees (Amorim et al., 2013; Buccolieri et al., 2011; Gromke and Ruck, 2012; Hofman et al., 2016; Jin et al., 2014; Kikuchi et al., 2007; Ries and Eichhorn, 2001; Salmond et al., 2013; Vranckx et al., 2015). Pollutant concentration was reduced with an increase in wind velocity (Hofman and Samson, 2014; Wania et al., 2012). Wind directions which are perpendicular (90^0), parallel (aligned, 0^0) or oblique (45^0) to the street canyon and induced pollutant distribution within canyon were mainly investigated in these studies. Isolated street canyon studies recorded higher concentrations along leeward and decrease in windward side of the street canyon under perpendicular flow. Whereas, oblique wind and parallel flow reported an increase in pollutant levels on both sides and increasing pollutant concentration towards the outer end of canyon respectively. Out of these perpendicular flow is most investigated and oblique flow was identified as critical wind flow as it cause accumulation on both sides (Abhijith and Gokhale, 2015; Buccolieri et al., 2011; Gromke and Ruck, 2012). Contradictorily following studies showed different pollution distribution in street canyon. The parallel wind flow showed 16% improvement compared to tree free scenario (Amorim et al., 2013). The Higher concentration in parallel wind direction and lower concentration in the perpendicular wind were observed. This was due to channelling of high pollutant emission from intense traffic corridor at the end of the canyon during parallel wind condition and when the wind direction changed to perpendicular, wind flow blocked this high emission entering street canyon (Hofman and Samson, 2014). Higher changes in concentration were observed in street canyon aligned with wind direction than street canyon with perpendicular wind direction (Gromke and Blocken, 2015). These variations show surrounding built environment have a significant impact on pollutant distribution within the street canyon.

As specified earlier, aspect ratio affects pollutant dispersion substantially. Deeper canyons have worst air quality even without trees. For same LAD higher concentration was noted in higher aspect ratio street canyons (Moradpour et al., 2016), although the percentage change in concentration with tree free scenario decreased with increase aspect ratio (Ng and Chau, 2012) Interesting conclusions were made by Buccolieri et al., (2011), under perpendicular wind direction larger concentration increase is observed in vegetated street canyon with regular aspect ratio (*H/W* =1, regular) than lower aspect ratio (*H/W* =0.5, shallow). However, under inclined wind direction larger concentration increase is observed in the vegetated shallow street canyon than a regular street canyon. This abnormality was partially cleared by Moradpour et al. (2016) through studying combinations of different densities of vegetation and aspect ratios. The study observed larger regions of higher concentrations in street canyons with aspect ratios of H/W of 0.5, 1.0, and 2 were of trees with LAD 2.0, 1.5, and 1.0, respectively. The present review finds combinations of wind flow direction, aspect ratio and LAD create critical scenarios.

A comprehensive review by Janhall, (2015) remarked about ambiguity in choosing LAD or porosity for dispersion and/or deposition among previous studies which leads to difficulties in the comparison between studies. There is a need for standardisation on the selection of these density parameters in future studies on deposition and dispersion. Studies on air quality impact of trees in the street canyon have LAD and porosity ranged from 0.2 to 5.12 m^2m^{-3} and 96% to 99% respectively. Studies noticed increase in pollutant concentration with increase in LAD (Abhijith and Gokhale, 2015; Balczó et al., 2009; Buccolieri et al., 2009; Gromke and Ruck, 2012; Kikuchi et al., 2007; S. M. Salim et al., 2011; Salim Mohamed Salim et al., 2011; Vos et al., 2013; Wania et al., 2012). Other important parameters are tree spacing (stand density) and cross-sectional covered by trees. Increasing the spacing between the crown and smaller canopy sizes lowered concentration levels (Abhijith and Gokhale, 2015; Buccolieri et al., 2009; Gromke and Ruck, 2007; Ng and Chau, 2012). However, the rate of change of pollutant concentration with spacing was predominant in wider canyon and least in deeper canyons (Ng and Chau, 2012). Similarly, a numerical investigation showed 1% increase in pollutant concentration per percentage increase in CVF (Gromke and Blocken, 2015).

Seasonal and annual variations of pollutant exposure were studied. In summers (leaves on periods) higher concentrations were reported in street canyon with deciduous trees but in winter presence of evergreen trees resulted in worst air quality scenario (Gromke and Blocken, 2015; Jin et al., 2014; Salmond et al., 2013; Vranckx et al., 2015). Non-foliated deciduous trees had no effect on pollutant concentration in winter seasons (Jin et al., 2014; Salmond et al., 2013). Vranckx et al., (2015) simulated the annual average change in concentration with trees in a shallow street canyon for various wind directions considering background concentration and emission strength in a street canyon in Antwerp, Belgium. Annual average change in pollutant concentration ranged from 0.2% to 2.26% for PM_{10} and 1% to 13% for elemental carbon (EC) with respect to various types of vegetation with different leaf area densities (LAD), deposition speeds v_d and drag coefficients C_d. Presences of trees caused a lesser increase in the concentration of PM_{10} compared to EC and NO_2 (Vos et al., 2013) and (Vranckx et al., 2015) made a similar observation by comparing EC and PM_{10}.

Reference	Findings
Jin et al. (2014)	$PM_{2.5}$ distribution in six symmetrical street canyons with trees was measured. They observed high vertical concentration distribution in tree street canyons compared to tree free scenario. Percentage changes in average concentration near breathing height (1.5 m) were ~6% increase in both spring and summer as well as ~9% concentration increase in winter with evergreen trees; no change in concentration with deciduous trees during winter was noted. Lower wind speed was noticed in street canyons with tree compared with those without trees. They reported that CD, LAI, the rate of change of wind speed, pruning intensity and species mainly influenced the diurnal $PM_{2.5}$ changes in street canyons. This work showed a deciduous tree with no leaves had little effect on pollutant distribution in winter.
Salmond et al. (2013)	Vertical distribution of NOx concentration was measured during different seasons from street floor to canopy level in a street canyon with a same deciduous tree. During summers, which are a leaf on period, a higher concentration was observed below canopy level. Differences between leeward and windward concentration were less. Like Jin et al. (2014), this study also revealed identical impacts of trees (same species) in street canyon measuring gaseous and particulate pollutants.
Kikuchi et. al, (2007)	NOx concentration was measured in street canyons of different tree densities, one with two rows of deciduous trees and other with four rows of a bigger canopy. High pollutant concentration was noticed along leeward side than windward side in both canyons and denser trees had higher concentration levels compared to less dense tree streets
Hofman and Samson, (2014)	the study had tested a new validation tool which employed magnetic bio-monitoring of particle deposited on tree leaves for validation a CFD model ENVI-met (Hofman and Samson, 2014) and it found concentration decreases with increase in

	wind speed. They showed surroundings can alter usual pollutant dispersion patterns in street canyon as they reported higher concentration in parallel wind direction and lower concentration in perpendicular which is contradictory normal observation. These abnormal concentration profiles resulted by channelling of high pollutant emission from intense traffic corridor at the end of the canyon, during parallel wind condition and when the wind direction changed to perpendicular, wind flow blocked this high emissions entering canyon.
Amorim et al., (2013)	An average increase in CO concentration about 12% was found in a street canyon compared to roof level atmosphere (Lisbon) when wind direction was approximately 45^0. On contrary, an average reduction in CO concentration about 16% was found in another street canyon (Aveiro) when wind direction was aligned to the street. Aerodynamic effect of trees reduced pollutant exchange rate between canyon and above roof level with 45^0 wind flow whereas with parallel wind flow (0^0) trees enhanced ventilation and aided dispersion.
Buccolieri et al., (2011)	This study extended idealised street canyon wind tunnel and modelling study into a real junction of street canyons with and without trees under different wind conditions. They illustrated excluding vegetation in the model can result in a discrepancy between modelled and measured date. Interesting conclusions were made by this work, under perpendicular wind direction larger concentration increase is observed in vegetated street canyon with regular aspect ratio (*H/W* =1) than lower aspect ratio (*H/W* =0.5, wide), but under inclined wind direction larger concentration increase is observed in vegetated street canyon with lower aspect ratio (*H/W* =0.5, wide) than regular aspect ratio (*H/W* =1).
Moradpour et al., (2016)	NOx-O_3 dispersion in street canyons of three different aspect ratios and with various canopy densities was investigated. This study noted tree scenarios had higher concentrations than tree free. Deep street canyon turned out to be critical of the same leaf area density. A significant disclosure made by this work was the combination different densities of vegetation and aspect ratios determined the critical exposure condition at breathing height in street canyon rather than denser vegetation led worse air quality. They

	observed larger regions of higher concentrations in street canyons with aspect ratios of H/W of 0.5, 1.0, and 2 were of trees with LAD 2.0, 1.5, and 1.0, respectively.
Vranckx et al., (2015)	They simulated the annual average change in concentration with trees in a wide street canyon (*H/W* = 0.5) for various wind directions considering background concentration and emission strength in a street canyon in Antwerp, Belgium. A total of seventy scenarios were created by taking seven wind directions with 150 intervals the annual average change ranged from 0.2% to 2.26% for PM_{10} and 1% to 13% for elemental carbon (EC) with respect to various types of vegetation with different leaf area densities (LAD), deposition speeds v_d and drag coefficients Cd. Representative Western European tree characteristics include an average leaf area density of 1.0m2m−3, a drag coefficient of 0.24 and a deposition velocity of 0.8 cm s−1 which showed an annual average EC increase of about 8% and a PM_{10} increase of about 1.4%.
Gromke and Blocken, (2015)	They investigated pollutant exposure at breathing height (2 m) in an urban neighbourhood consisting of six street canyons intersecting each other. Seven avenue-tree layouts consisting various CVF were compared to tree free scenario. Study revealed 1% increase in pollutant concentration per one percentage increase in CVF and more changes of concentration was observed in street canyon aligned with wind direction than street canyon with perpendicular wind direction
Abhijith and Gokhale, (2015)	They simulated concentration profile at breathing height (1.7 m) in street canyon with trees of various porosities, canopy dimensions, configurations and tree spacing under different wind conditions. They reported higher concentrations in presence of trees in all wind directions and lower concentration increase was observed in trees with smaller dimensions, higher porosity, and higher tree spacing. An arrangement of single tree row along windward side resulted in the least increase in concentration under 90^0 and 45^0 wind conditions.
Vos et al., (2013)	Air quality impacts of various tree configurations in the street canyon were studied through modelling and they noticed the deterioration of air quality along the footpath at breathing height with trees. This study reported trees influence was more on

	concentrations of NO_2 and EC than PM_{10}.
Li et al., (2013)	CO_2 concentration modifications done by trees in a street canyon under varying traffic intensity were studied. They found, during day time trees reduced CO_2 concentration up to certain emission rates, then trees led to higher concentration levels
Gromke and Ruck, (2012)	They studied concentration variations due to the presence of trees under three wind directions in street canyons of different aspect ratio. This study focused on influences of aspect ratio, tree crown porosity and tree stand density. The study observed higher pollutant concentration with street canyon with trees and in 900 wind direction higher concentration along leeward side and slight decrease along windward side whereas in 45^0 wind direction concentration increased on both sides. The rise in pollutant concentration was visible with an increase in tree stand density (spacing) and decrease in crown porosity. It identifies the highest exposure in the street canyon under oblique wind directions with an increase of 146% compared to tree-free.
Wania et al., (2012)	They studied the impact of trees in street canyon by modelling different aspect ratio and changing crown densities under various wind directions and speed. This Study revealed concentration increased with a decrease in wind velocity, increase in aspect ratio and increase in density of foliage. It recommends avoiding dense foliage continues trees in street canyons with aspect ratio 0.5 or more.
Ng and Chau, (2012)	They studied pollutant exposure in the deep street canyon with tree planting found the influence of aspect ratio and spacing between crowns. The magnitude of pollutant concentration increased with an aspect ratio in both tree free and tree conditions. Trees showed higher pollutant exposure at 1.5 m height compared to tree free street canyons, although the percentage change in concentration with tree free scenario decreased with increase aspect ratio. The increase in spacing between crown lowered concentration levels but the rate of change of pollutant concentration with spacing was predominant in wider canyon and least in deeper canyons.
Salim et al., (2011a); **Salim et al., (2011b)**	Studies compared LES and RANS modelling techniques and observed LES had better agreement with wind tunnel and higher

	concentration in presence of trees.
Balczó et al., (2009)	They observed higher pollutant exposure in street canyon with trees under 900 wind direction and concentration increased with increase in LAD. Similar result was observed by Gromke and Ruck, (2009) and higher porosity led to less increase in concentration
Buccolieri et al., (2009)	This study investigated the effect of trees in street canyon of aspect ratio 0.5 under perpendicular wind direction. Trees resulted in higher concentration compared to leeward. Under perpendicular wind directions lower aspect ratio, low porosity, high stand density and lower wind velocity yielded higher concentration
Gromke et al., (2008)	They reported trees in street canyon increased traffic exhaust pollutants inside canyon and reduced wind velocity
Gromke and Ruck, (2007)	They investigated the effect of trees in street canyons with traffic induced turbulence through wind tunnel study. This study noticed the presence of trees reduced wind flow leading to higher concentrations and lower crown diameter and more gaps between trees reduced the pollutant concentration. Traffic turbulence-induced mixing and homogenous mixing of exhaust emissions yielding low average concentration. Ries and Eichhorn, (2001) observed high concentration with trees in street canyon.

Table 12: Detailed summaries of past studies showing the effect of trees in street canyons on pollutant concentrations.

Wind direction	Aspect ration	Pollutant	LAI/porosity	Changes in concentration with trees	Studies
Perpendicular 90^0	H/W <0.5	SF_6	96%	+21%	Buccolieri et al., (2011)
		SF_6	97.5%, 96%	+71% Leeward –35% windward	Buccolieri et al., (2009
		$NO-NO_2-O_3$.	0.5-2 m^2 m^{-3}	Higher concentration with tree at LAD=2	Moradpour et al., (2016)
		SF_6	97.5%, 96%	+27 to 105% leeward side -3 to -19% windward side	Abhijith and Gokhale, (2015)
		EC, $NO-NO_2-O_3$.	0.7 m^2 m^{-3}	Increase in concentration on	Vos et al., (2013)

		PM_{10}.		both sides	
		PM_{10}.	0.2- 2 m^2 m^{-3}	Higher concentration than tree free	Wania et al., (2012)
		NO_2	-	Increase in concentration on both sides	Salmond et al., (2013)
		SF_6	97.5%, 96%	+41% maximum wall average change	Gromke and Ruck, (2012)
	0.5< H/W<1.5	$PM_{2.5}$	1-5.12 m^2 m^{-3} 0 m^2 m^{-3}	+8.92% - 6.32%(other seasons) -0.58%(winter)	Jin et al.,(2014)
		SF_6	96%	+36%	Buccolieri et al., (2011)
		NO-NO_2-O_3	0.5-2 m^2 m^{-3}	Higher concentration with tree at LAD= 1.5	Moradpour et al., (2016)
		CO_2	1.095 m^2 m^{-3}	-2.47 % to +4.33% with various vehicles/min	Li et al.,(2013)
		SF_6	97.5%, 96%	+58% maximum wall average change	Gromke and Ruck, (2012)
		SF_6	97.5%, 96%, 0%	Higher concentration than tree free	Salim et al., (2011,a) Salim et al., (2011b) Gromke et al., (2008) Gromke and Ruck, (2007)
		SF_6	97.5%, 96%	+41%to + 58% at leeward −37% to -49% at windward	Gromke and Ruck, (2009)
		SF_6	0.25 - 4.25 m^2 m^{-3}	+20% - 40%	Balczó et al., (2009)
		SF_6	97.5%, 96%	+42% at leeward -32% at windward	Buccolieri et al., (2009)
		Arbitrary	--	+20%	Ries and Eichhorn, (2001)

		CO	96%	+43%	Ng and Chau, (2012)
		PM_{10}	0.2- 2 m^2 m^{-3}	Higher concentration than tree free	Wania et al., (2012)
	H/W<2	CO	96%	+39% H/W=2 +17% H/W=4	Ng and Chau, (2012)
		NO-NO_2-O_3	0.5-2 m^2 m^{-3}	Higher concentration with tree at LAD= 1	Moradpour et al., (2016)
Oblique 45^0	H/W<0.5	SF_6		+96%	Buccolieri et al., (2011)
		CO	1 m^2 m^{-3}	+12%	Amorim et al., (2013)
		SF_6	97.5%, 96%	+2 to 119% in leeward side +34 to 246% in windward side	Abhijith and Gokhale, (2015)
		EC, NO-NO_2-O_3. PM_{10}.	0.7 m^2 m^{-3} 0.2- 2 m^2 m^{-3}	Increase in concentration on both sides Maximum increase than other wind direction	Vos et al., (2013) Wania et al., (2012)
		SF_6	97.5%, 96%	+146%	Gromke and Ruck, (2012)
	0.5< H/W <1.5 (~1)	SF_6	97.5%, 96%	+91%	Gromke and Ruck, (2012)
		SF_6	96%	+66%	Buccolieri et al., (2011)
		PM_{10}	0.2- 2 m^2 m^{-3}	Maximum increase than other wind direction	Wania et al., (2012)
	H/W <2				
Parallel 0^0	H/W <0.5	NO-NO_2-O_3	0.5-2 m^2 m^{-3}	Higher concentration with tree at LAD=2	Moradpour et al., (2016)
		SF_6	97.5%, 96%	+38% wall average	Gromke and Ruck,

					(2012)
		PM_{10}	0.2- 2 m^2 m^{-3}	Higher concentration than tree free	Wania et al., (2012)
	0.5< H/W <1.5 (~1)	CO	1 m^2 m^{-3}	-16%	Amorim et al., (2013)
		$NO-NO_2-O_3$	0.5-2 m^2 m^{-3}	Higher concentration with tree at LAD=1.5	Moradpour et al., (2016)
		SF_6	97.5%, 96%	+40% wall average	Gromke and Ruck, (2012)
		PM_{10}	0.2- 2 m^2 m^{-3}	Higher concentration than tree free	Wania et al., (2012)
	H/W <2	$NO-NO_2-O_3$	0.5-2 m^2 m^{-3}	Higher concentration with tree at LAD=1	Moradpour et al., (2016)

Table 13: Changes in concentration with trees to tree free at street canyons and key finding of past studies.

3.2.1.2 Trees in open streets

Studies have focused effect of trees on near-road exposure in open street conditions. Open street is an urban built environment feature in which both sides of traffic corridor are open with less packed buildings and other manmade structures. In open street conditions, trees as well as other vegetation such as hedges, shrubs etc. are planted and maintained along both sides of heavily trafficked urban corridors as green belts which have a significant role in noise reduction, heat island and aesthetics. In open road or free traffic way conditions, trees act differently than in street canyon. Tree rows and other vegetation belts act as a barrier to the pollutants coming to pedestrian or nearby residential dwelling. This barrier effect creates a high concentration region windward side of trees (upwind or in front of tree rows) which is traffic corridor and force polluted air low over vegetation or pass through vegetation depending upon porosity and physical dimensions of vegetation (Tong et al., 2016). If porosity is the high majority of air flows through vegetation whereas, high density (lower porosity) leads to no infiltration through vegetation. Downwind of vegetation (behind vegetation), a wake zone is created and pollutant concentration decrease along the increase in distance from the street. The formation and extend of wake zone, pollutant concentration profile before and after vegetation, and pollutant deposition and dispersion within barrier are controlled by wind direction and speed, position of vegetation, physical characteristic of green belt (dimensions-mainly thickness and height, porosity, etc.), temperature, relative humidity, physical characteristics of leafs etc.

Opposite to the street canyon investigation, most of the studies accounted pollution exposure in open areas with trees followed experimental approach (Chen et al., 2016, 2015; Fantozzi et al., 2015; Grundström and Pleijel, 2014; Islam et al., 2012; Shan et al., 2007; Tong et al., 2016, 2015). Only a limited study employed modelling methodology (Morakinyo and Lam, 2015; Neft et al., 2016). Detailed summaries of past studies are given in Table 14. Some of the studies analysed the effect of the combination of other vegetation types with trees and those will be discussed in detail in coming sections. Air quality impact of trees can be positive or negative; positive means a reduction of pollutant concentration along the footpath and negative opposite. Literature showed positive effect of trees on air quality at street scale (Chen et al., 2015; Islam et al., 2012; Tong et al., 2016), mixed and limited effects (Chen et al., 2016; Fantozzi et al., 2015; Grundström and Pleijel, 2014), and negative effects (Tong et al., 2015) and details are given in Table 14. Significant physical characteristic altering near road pollution exposure is thickness and density of green belt (Islam et al., 2012; Morakinyo and Lam, 2015; Neft et al., 2016; Shan et al., 2007). The increase in thickness resulted in a reduction of pollutant concentration (Neft et al., 2016; Tong et al., 2016) and filtration efficiency increased linearly with increase in thickness (Neft et al., 2016). Morakinyo and Lam, (2015) proposed a technique to find optimum thickness, location and height of the vegetation barrier. They used the distance between source and plume's maximum concentration (DMC) and recommended to place tree rows or vegetation barrier close to the source or behind the DMC, thickness enough to cover DMC and height close to plume height. Similarly, 5 m thickness as optimum for TSP removal and 10 m thickness for 50% removal of the 20 nm particle were recommended by Islam et al., (2012) and (Neft et al., 2016) respectively. In addition Shan et al., (2007) recommended a minimum thickness of 5m and an optimum thickness of 10m for 50% or more TSP removal. These recommendations show further investigation on the relation between the thickness and emissions strength could produce a practical recommendation on the thickness of vegetation barrier with respect to the quantity of emissions from streets.

Densities of trees were expressed in LAD, canopy density CD, and shelterbelt porosity. Pollutant removal percentage was increased with increase in CD and LAD and decreased with increase in shelter belt porosity (Chen et al., 2016; Islam et al., 2012; Shan et al., 2007; Tong et al., 2016). An optimum canopy density of 70-85% was recommended for 50% or more TSP reduction and for maintaining healthy green belt (Shan et al., 2007). Increasing canopy density over 85% decreases removal percentage (Shan et al., 2007). Optimum shelter belt porosity proposed by studies were 20-40% and 10-20% for TSP and PM_{10} (Chen et al., 2016; Islam et al., 2012) respectively. Shan et al., (2007) observed below 25% shelter belt porosity TSP removal percentage was stable and recommended an optimum shelter belt porosity of 25-33% for 50% or more pollutant removal. Gray relation analysis revealed the highest impact on PM_{10} removal was exerted by relative humidity, then wind speed and least by temperature (Chen et al., 2015). Similarly high NO_2 concentration was observed with high relative humidity and low temperature (Fantozzi et al., 2015). These clearly indicate the importance of relative humidity in local air pollutant exposure analysis. Another interesting observation was warmer climate regions (China, Bangladesh, Italy) showed significant pollutant concentration reduction with these barriers (Chen et al., 2016, 2015; Fantozzi et al., 2015; Islam et al., 2012) and colder northern regions showed limited or no change in pollutant concentration with vegetation (Grundström and Pleijel, 2014; Setälä et al., 2013). Highest concentration reduction with trees occurred in summer seasons (Fantozzi et al., 2015; Islam et al., 2012; Shan et al., 2007) and deciduous trees had no effect on particulate removal in winters. Evergreen trees are promoted to plant along open road conditions for ensuring pollutant reduction in all seasons (Islam et al., 2012; Shan et al., 2007).

Reference	Findings
Chen et al., (2016)	Particulate matter deposition on different specifies seen along traffic corridors and vertical and horizontal reduction of particulate matter by vegetation belts were measured. Total suspended particle deduction was observed by all configurations of green belts whereas shrubs (hedges) and combinations of

	tree-grass showed a better reduction of $PM_{2.5}$ concentrations. Trees showed positive deduction in TSP and negative deduction in $PM_{2.5}$. The combination of tree-shrub-grass turned out to be the worst considering removal of $PM_{2.5}$.Species deposition study revealed highest deposition occurred on trees, moderate on shrubs. A major limitation of this study was it only accounted washable PM on leafs, leaving PM captured in waxes. This study recommended two vegetation types as effective PM filters, Lianas as suitable vertical and roof greening and shrubs along streets even though further investigations are required.
Neft et al., (2016)	Aerosol filtration of vegetation was studied by simulating vegetation of different LAD values. They observed roadside vegetation of few meters' thickness with < 5 m^2/m^3 LAD didn't filter significant amount of particles larger than 20 nm. The study found Filtration efficiency increases with a thickness linearly. They suggested for model validation and application in real world.
Tong et al., (2016)	Particulate matter (5 nm to 253 nm) reduction by tree rows as a vegetation barrier alone and combination with the solid wall was investigated through modelling study considering both deposition and dispersion. The study analysed six configurations and varied vegetation parameters such as LAD, height, thickness etc. study recommended wide tree rows (two tree rows-conifers) for reduced downwind pollutant concentration. Higher LAD, increase in width can reduce behind barrier concentration levels whereas the change in height had a slight effect on concentration. Concentration change with respect to a change in LAD was non-linear.
Chen et al., (2015)	PM_{10} removal efficiencies of green belts consisting of different combinations of arbour, shrub and grass were investigated at 1.5 m near open roads having various traffic densities. Combination of shrubs small trees and combination of trees-shrubs-grass produced maximum removal efficiency in arterial roads, and sub-arterial roads respectively. They proposed planting parallel tree grows in low traffic roads even though these combinations didn't show a significant change in PM_{10} concentration. They observed higher canopy density leads to higher removal efficiency and maximum removal efficiency occur at 15% shelterbelt porosity. Gray relational analysis revealed the impact of relative humidity, wind speed and temperature on PM_{10} removal efficiency.
Morakinyo and Lam, (2015) ENVI-met	Dispersion and deposition related benefits of vegetation barrier on near road condition were analysed by a simulation study. They used the distance between source and plume's maximum concentration (DMC) as a tool for finding the optimum distance of vegetation barrier and optimum thickness of vegetation barrier which can enhance benefits from both dispersion and deposition. They recommendation were position vegetation barrier close to street or place behind DMC, porosity should be suitable for both dispersion and deposition, height and thickness of vegetation barrier should be close enough to full plume height, and extend to cover DMC respectively.
Tong et al., (2015)	$PM_{2.5}$ transport downwind of open highway was studied and changes made by trees were compared with open areas. The presence of tree caused higher $PM_{2.5}$ concentration than open transects. They observed steep decay in concentrations in open field and less steep decay with trees. An interesting observation was the presence of tree eliminated concentration spikes and they pointed out in local exposure is governed by the aerodynamics of trees than

	deposition surface of trees.
Fantozzi et al., (2015)	Long-term monitoring of NO_2 O_3 using passive samplers showed lower NO_2 concentration levels at 5 m and 10 m from the road in tree transect compared to an open area in all seasons. O_3 concentration was higher in presence of trees except in October 2013. Near road concentration (at 1 m) was higher in tree transect compared to tree free area.
Grundström and Pleijel, (2014)	NO_2 and O_3 concentration were measured inside and outside of mixed deciduous trees (broadleaf) canopy near to a heavy traffic corridor using passive samplers. They found a limited effect of forest canopy on NO_2 concentration and canopy reduced concentration by 7%. They observed the effect of canopy on O_3 was insignificant
Islam et al., (2012)	TSP removal percentage by a green belt which consisted of shrubs and trees were measured and seasonal variations were recorded. They found significant TSP removal which was highest in summer season and least was in the winter season. They recommended a minimum thickness of 5 m and they observed an increase in removal percentage with canopy density and reduction in removal percentage with an increase in shelter belt porosity.
Shan et al., (2007)	TSP removal percentages were calculated in six green belts comparing to vegetation free case. The found reduction in all cases and recommended to have a green belt at latest 5 m wide and 10 m as optimum width. They observed planting shrubs in front and followed by trees results in the higher removal of TSP. canopy density should be maintained 70-85% for higher percentage removal and for the healthy green belt.

Table 14: Detailed summaries of past studies showing effect of trees in street canyons on pollutant concentrations

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3.2.2Hedges

3.2.2.1 Hedges in street canyon

Similar to trees in street canyons, hedges are planted along both sides of streets or a single row in the middle. Thickness and height of hedges in street canyons are lesser than that of open roads. As seen in Table 15, only a few studies examined the air pollution reduction potential of hedges in street canyon (Gromke et al., 2016; Li et al., 2016; Vos et al., 2013; Wania et al., 2012). Studies observed hedges reduced pollutant exposure in footpath area in street canyon, although Vos et al., (2013) reported opposite to that. Matching to the effect of trees on wind velocity in street canyons, hedges reduced wind velocity in street canyon (Gromke et al., 2016; Li et al., 2016; Wania et al., 2012) but the effect of hedge on wind is lesser than trees (Wania et al., 2012). Hedges diverted air pollutant reaching footpath area by generating vortices (Gromke et al., 2016; Li et al., 2016). Low permeable and higher (2.5m) hedges showed more pollutant reduction in footpath area and central single hedgerow had maximum concentration reduction compared to hedgerows along both sides (Gromke et al., 2016). The optimum height of hedge about 2 m was obtained through simulation assessing its sensitivity to wind velocity and aspect ratio for both regular and shallow street canyon (Li et al., 2016). Gromke et al.,(2016) observed a maximum reduction in pollutant concentration with a hedge of 2.5m height in the shallow street canyon.

Reference	Findings
Gromke et	Gaseous pollutant reduction by hedgerows of different height, permeability,

al., (2016)	spacing and arrangements in the street canyon were studied through simulation studies. Overall hedges improved air quality in street canyon. They recorded low permeability and higher hedgerows in the centre of the street had a maximum reduction in pollutant concentration along the pedestrian area. Discontinues hedge resulted in the least improvement.
Li et al., (2016)	CO concentration reduction by hedge was investigated by comparing street canyon with trees and hedges to a street canyon with the only tree. The study analysed the sensitivity of wind speed, the height of hedge and aspect ratio. They observed a significant reduction in concentration with the presence of hedges under perpendicular wind and optimum heights and ranges were recorded.
Vos et al., (2013)	Different vegetation types were analysed to ascertain the impact on personal exposure in the built-up area. Hedges showed deterioration in air quality
Wania et al., (2012)	PM_{10} concentration in the street canyon was studied in presence of trees and hedges. They found hedges resulted in the least reduction in wind velocity and caused less accumulation of pollutants compared to trees.

Table 15: Detailed summaries of past studies showing the effect of hedges in street canyons on pollutant concentrations.

3.2.2.2 Hedges in Open roads

Most of the studies investigated pollutant concentration behind hedges and vegetation barriers through measurements (Al-Dabbous and Kumar, 2014; Brantley et al., 2014; Hagler et al., 2012; Lin et al., 2016; Tiwary et al., 2008) or combined measurement and modelling (Morakinyo et al., 2016; Tiwary et al., 2005) than pure simulation (Morakinyo and Lam, 2016; Tiwary et al., 2005). Pollutant reductions observed were positive in the majority of studies (Al-Dabbous and Kumar, 2014; Brantley et al., 2014; Lin et al., 2016; Tiwary et al., 2008, 2005) and negative (Morakinyo et al., 2016) and mixed (Hagler et al., 2012). Pollutant accumulation in front of the hedge was observed (Al-Dabbous and Kumar, 2014). Morakinyo and Lam, (2016) reported pollutant removal/ reduction of hedges can be positive or negative and it is not uniform across height and length of the barrier. Supporting to this, Hagler et al., (2012) observed lower, higher and nearly same concentration levels behind vegetation barrier compared to open area. In addition, Lin et al. (2016) reported the difference in concentration levels at the different height of the hedge. Morakinyo and Lam, (2016) proposed the design of thickness and location of the hedge, from DMC-distance to maximum concentration from source (traffic) for positive reduction. Studies noticed an increase in pollutant concentration with increase in speed (Brantley et al., 2014; Morakinyo et al., 2016). Higher thickness, volume and LAD of hedge resulted in higher pollutant removal (Morakinyo and Lam, 2016; Steffens et al., 2012). Seasonal variations in pollutant concentration were captured by field assessments. These studies remarked vegetation barrier with deciduous plants had no effect on pollutant removal and concentration levels were similar to an open area with no trees (Hagler et al., 2012; Lin et al., 2016). Key findings of studies investigated the effect of vegetation barriers in the open area are summarised in Table 16.

Reference	Findings
Morakinyo and Lam, (2016)	PM deposition and dispersion benefits of vegetation barrier were studied through modelling study. They observed Pollutant reduction is not

	uniform across height and length of vegetation barrier and pollutant removal efficiency can be positive, partially positive and negative. They proposed -Distance to maximum concentration (DMC) (definition is the calculated distance between the downwind maximum concentration and the source region) for calculation of vegetation barrier thickness with positive removal efficiency. Sensitivity analysis showed it increased increase in breathing height and slight variation with LAD and particle size. They claimed this technique can be an applicable to particle size range (1–10 μm) and common LAD of 1–4 m^2/m^3. They recommended placing vegetation after DMC or extended thickness beyond DMC for positive removal efficiency and both resulted in positive pollutant removal in all wind directions.
Lin et al., (2016)	CO and UFP concentration reduction behind vegetation barrier were measured using stationary and mobile instruments in different seasons. They reported pollutant reduction behind the barriers expects at a location with the majority of deciduous trees in winter. They observed significant differences in concentration (>20%) measured by mobile and stationary methods which were measured pollutant levels at a different height from ground (1.5 m, 3 m).
Morakinyo et al., (2016)	$PM_{2.5}$ concentration behind hedge was measured and modelled under various wind flow conditions. Higher concentration was observed behind the vegetation barrier at all wind directions and concentration level reached zero after a certain distance. They observed deterioration in air quality in higher speeds.
Al-Dabbous and Kumar, (2014)	Nanoparticle reduction potential of evergreen vegetation barrier was investigated near busy traffic corridor. They observed accumulation in front of the hedge and reduction in PNC behind the hedge in all wind direction and velocity. The minimum reduction in PNC was observed in perpendicular winds.
Brantley et al., (2014)	Black carbon and particle number concentrations were measured behind vegetation barrier under various wind speed and directions. They evaluated diurnal variation and effect of the width of vegetation barriers. They found vegetation barriers reduced pollutant concentrations and higher concentration peak was observed with high wind

	speed and same time or near to traffic peak. They observed a gradual decrease in pollutant concentration behind vegetation barrier which may lead to increase concentration levels far behind areas with respect to clear area.
Steffens et al., (2012)	UFP concentration tree row was analysed using modelling technique and found increasing LAD can increase deposition but the relation is not linear. They observed variation in wind speed resulted in dissimilar change in concentration of particles with different sizes.
Hagler et al., (2012)	UFP concentration behind an evergreen and deciduous vegetation barriers were measured under varying wind conditions in leaf on and off seasons. They observed the concentrations behind barriers were higher or lower or same as that of open area. In winter season vegetation barrier location and with vegetation showed same concentration levels.
Tiwary et al., (2008)	The pm_{10} removal efficiency of the hedge was measured in field experimental study. An average reduction of 34% was recorded by the study.
Tiwary et al., (2005)	Particulate matter removal efficiency was investigated through modelling and measurement study. They studied three species with different porosity, and they found denser hedge force pollutants to flow over and have less particle collection within hedge.

Table 16: Detailed summaries of past studies showing effect of hedges in Open Street on pollutant concentrations

3.2.3 Green walls

Only a few studies assessed air pollution reduction of green walls at local scales of urban built environment conditions (Joshi and Ghosh, 2014; Ottelé et al., 2010; Sternberg et al., 2010) and these are documented in Table 17. Pollutant reduction along a footpath in open street conditions (Morakinyo et al., 2016; Tong et al., 2016) and a considerable reduction in the street canyon were reported (Pugh. et al., 2012). Moreover, other studies on green wall reported effective collection of pollutants by vegetation on the green wall (Joshi and Ghosh, 2014; Ottelé et al., 2010; Sternberg et al., 2010). A city scale study showed significant improvement in air quality with the green wall (Jayasooriya et al., 2016) but reductions were lesser compared to trees (Jayasooriya et al., 2016; Tong et al., 2016). In open road conditions, green wall resulted in dispersion patterns similar to the solid wall as a high concentration region in front of barrier (on road) and reduction behind the green wall (Morakinyo et al., 2016; Tong et al., 2016). In addition, vegetation cover on wall removed pollutants by deposition (Joshi and Ghosh, 2014; Morakinyo et al., 2016; Tong et al., 2016). In street canyon conditions, green wall turned out to be beneficial in improving air quality with different aspect ratio (H/W=1 to 2) and reduction up to 40% in NO_2 concentration and 60% in PM_{10} concentration were observed (Pugh. et al., 2012). Common climbing plants such as ivy (UK) and Lianas species (in China)were found suitable for vertical gardening (Chen et al., 2016; Ottelé et al., 2010; Sternberg et al., 2010). The removal potential of the green wall was influenced by street canyon geometry, wind speed, humidity and LAI (Joshi and Ghosh, 2014; M. et al., 2012, further details in Table 12Table (Ottelé et al., 2010). Samples from a different height of green wall near traffic corridor showed no variations in deposited particles (Pandey et al., 2014). The study suggest measuring air pollution tolerance before selecting species (Pandey et al., 2014).These observations are made from limited studies and further investigation is required to produce recommendations as well as better understanding of the impact of the green wall on air quality.

Reference	Findings
Jayasooriya et al., (2016)	Air quality improvements of green infrastructures (trees, green wall, and green roof) in an Australian city were quantified by applying i-Tree Eco software. They found comparatively lower air quality improvement by green roofs and green wall than trees but these could provide significant pollution reduction in urban built up area with less space. They also observed combinations of green wall and green roofs were a lesser air quality improvement than other combinations which included trees.
Morakinyo et al., (2016)	$PM_{2.5}$ concentration behind the green wall was modelled under various wind flow conditions. They found maximum pollutant reduction behind the green wall at pedestrian height. The increase in wall thickness had little effect on pollutant removal and wall accumulates pollutants upwind (near the road) as well as transports to the vertical direction. They remarked green walls are favoured against the solid wall as vegetation can remove some pollutants by deposition.
Tong et al., (2016)	Ultrafine Particulate matter (5 nm to 253 nm) reduction by a green wall along the open road was investigated through modelling study considering both deposition and dispersion. They observed significant reduction behind the green wall as pollutants were deflected above the wall which increased on street pollution levels. They remarked green wall showed similar concentration profile to solid walls and vegetation cover on the wall showed less reduction as it had lesser leaf surface area than trees stands.

M. et al., (2012)	NO_2 and PM_{10} deposition on the green wall and green roof of the street canyon were investigated through modelling and these green infrastructures showed reduction up to 40% in NO_2 concentration and 60% in PM_{10} concentration was observed. They observed green walls are more effective in reducing street-level pollution than green roofs and reduction were depended on street canyon geometry and wind speed. Contrary to trees in street canyon greening of walls of deeper (higher aspect ratio) street canyons resulted in higher reduction as an increase in aspect ratio reduced wind speed, enhancing residence time, and yielded more deposition. Lower wind flow showed higher deposition rates.
Ottelé et al., (2010)	Compared leaf samples of near road and woodland and found a fine and ultra-fine particle of human origin were deposited near road green wall. They observed samples from different height had shown no variations in deposited particles. This study showed potential of green walls to improve air quality and proposed greening of noise barrier for collecting anthropogenic particles from traffic
Sternberg et al., (2010)	This study analysed particulate particle deposition on climbing vegetation ivy and they observed the effective collection of a particle in high trafficked areas.
Joshi and Ghosh, (2014)	SO_2 removal by green façade was modelled and they found significant removal by vegetation. The removal rate was influenced by humidity and LAI.
Pandey et al., (2014)	Air pollution index was calculated for various climber plants.

Table 17: Detailed summaries of past studies showing the effect of hedges in green walls on pollutant concentrations.

3.2.4 Green roofs

Even though, many studies examined various aspects of green roof, limited research emphasised on air quality improvement of the green roofs (Baik et al., 2012; Berardi et al., 2014; Currie and Bass, 2008; Li et al., 2010; Rowe, 2011; Speak et al., 2012; Tan and Sia, 2005; Yang et al., 2008). As documented in Table 18, all studies noticed significant pollutant removal by green roofs. Pollutant removal by green roofs are inferior to trees was observed by both local scale (Speak et al., 2012) studies and city scale studies (Currie and Bass, 2008; Jeanjean et al., 2015). This was due to low surface roughness and longer distance from pollutant source (Speak et al., 2012). 2% cooling intensities of a green roof in street canyons resulted in a reduction of pollutant concentration about 32% at breathing level. Because of enhanced canyon vortex and higher dispersion which arose from downward moving cool air (Baik et al., 2012). Whereas, M. et al., (2012) recorded marginal pollutant removal by green roof without accounting the cooling effect. Roofs near traffic corridor exhibited a significant improvement of air quality (Speak et al., 2012) and a fine particle of traffic origin of size less than 0.56 µm decreased by 24%(Tan and Sia, 2005). Removal rate of green roofs were influenced by wind velocity, season of year, plant condition, leaf features or pollutant removal ability of specific species, position of green roof, and type of plant used in green roof (Currie and Bass, 2008; Li et al., 2010; Speak et al., 2012; Yang et al., 2008). Intensive green roofs can further increase pollutant removal (Currie and Bass, 2008; Yang et al., 2008).

Study	Findings
Baik et al., (2012)	The study evaluated the effect of cooling intensities of green roofs on air quality of generic street canyon of aspect ratio one and applied in real urban morphology under different wind direction using CFD. Temperature varied from 18 ^{0}C to 30 ^{0}C with 2 ^{0}C interval, set 2 m/s wind velocity at building height, and measured concentrations of NO_X with no chemical reaction. The study observed improvement in air quality at breathing height of 1.5m near the road with green roof cooling than a roof without vegetation. Upwind roof cooling strengthened canyon vortex by combining downward movement of cool air and mechanically driven downward wind resulting increased dispersion and reduction in pollutant concentration. Pollutant reduction increased with increase in cooling intensity. The cooling intensity of 2^{0}C produced 32% reduction in concentration. Testing on a real urban morphology showed the air quality improvement was dependent on wind direction, and 5^{0}C cooling yielded an average reduction in pollutant concentration about 49%.
Speak et al., (2012)	PM_{10} capture by different species used in green roofs in Manchester, UK were studied. Roofs were located near traffic corridor and compared with a control site away from traffic pollution. They found green roof had a significant impact in the removal of pollutants although it was inferior to trees which have more surface roughness and close to the source. They observed leaf surface features had a relationship with deposited pollutants and proposed grasses A.stolonifera and F.rubra than P. lanceolate and the commercial extensive green roof species S. album because of their higher pollutant capturing ability.
Li et al., (2010)	CO_2 absorption by the green roof in Honk Kong with subtropical monsoon climate was studied through measurements, chamber experiment and CFD simulation. They found the considerable removal of CO_2 in the day time by green roof and emission was lower than removal. The removal rate was influenced by plant condition, the position of green roof and wind velocity. They observed 2% reduction in

	pollutant concentration than nearby area by the green roof on a sunny day and reduction can reach up to 9.3% under favourable conditions.
Tan and Sia, (2005)	Air quality changes after installing green roof were examined in the tropical city of Singapore and SO_2, $PM_{2.5}$, and PM_{10} were measured. They observed a reduction in acid gaseous pollutants SO_2 by 37%, increase in $PM_{2.5}$ and PM_{10} by 16%, and 42% respectively after installation. Mass concentration of particles with 0.56 µm and above recorded increase and smaller than 0.56 µm decrease by 24%. Black carbon concentration was lowered and particle number concentration of particulate matter was shrunken by 6%. They suspected, increase in the concentration of heavier particle was of crushed stones, gravel around sides of the green roof and exposed substrates on the green roofs. They also found drought resistant plants were favourable in tropical humid climates.
Currie and Bass, (2008)	Air quality improvement by green roofs and green wall in Toronto city was investigated using UFORE model and they found a green roof and green wall reduced significant air pollutants lesser than trees and shrubs. They observed extensive green roofs can complement other vegetation in air quality improvement whereas intensive green roofs can reduce air pollutants considerably.
Yang et al., (2008)	Air pollution removal by 170 green roofs of Chicago, Illinois USA was evaluated using modelling approach. The plants in the green roof were short grass and other low-growing plants, large herbaceous plants and trees and shrubs covering 63%, 14%, 11%, respectively. They calculated removal of O_3 (52%), NO_2 (27%), PM_{10} (14%), and SO_2 (7%). Snowing period (February) recorded the lowest removal and maximum removal with fully expanded leaves (May). The study showed green roofs can reduce air pollutants and it can be further increased by converting all roof into intensive green roofs.

Table 18: Detailed summaries of past studies showing the effect of hedges in the green roof on pollutant concentrations.

3.3 Photocatalytic coatings

Photocatalytic coatings, although they have consistent technical characteristics as passive measures to control atmospheric pollution in urban areas, they have limitations due to the uncertainty of the presence of light and humidity in the areas of deployment. In the last 17 years, the gains from the photocatalytic destruction of pollutants have improved, nevertheless, the reduction strategies should not raise expectations that are disproportional to other mitigating interventions. It should be emphasised here that such coatings have no secondary effects on the environment for their life-cycle analysis of their deployment.

3.3.1 Assessment of maximum expected reductions in cities

So far, the following are theoretical evaluation for the potential of reduction of urban NO_2 by photocatalytic coating based on TiO_2,

Removal of atmospheric NO_2 by:	TREES	Pavements with cement incorporating TiO_2
Occupied Area	30000 m^2	30000 m^2
NO_2 absorption in 12 h per m^2		1.5 Million molecules= 0.069 g
Annual absorption assuming 12 hours of UV radiation	670	365*0.069*30000= 755 kg

Table 19: theoretical evaluation for the potential of reduction of urban NO_2 by photocatalytic coating based on TiO_2.

In the previous table are compared the theoretical potential of photocatalysis in removing NO_2 in comparison to trees for the same area although during winter months the capacity of trees to absorb NO_2 is not the same (deciduous trees will not have leaves and in evergreens, the photosynthesis will be sufficiently reduced).Taking into consideration 1 km of road with the pavements on both sides of 1.5m width results in a potential area of 3000 m^2 that could be covered with photocatalytic coatings. If we also assume that this area is exposed to UV light for 12 hours per day. The following table assesses the maximum expected potential.

Average NOx vehicle emissions per km	8.3 million of molecules = 0.25 g
Absorption from TiO_2 per m^2 in 12 hours	1.5 million of molecules * 3000 m^2 = 4500 mil. molecules
Number of vehicles that produce equivalent NO_x	4500 / 8.3 = 542 vehicles
If the road traffic is 5000 vehicles for the 12 hours of daylight.	The absorption of NO_x from traffic by the pavements will result in savings of 11%

Table 20: the maximum expected potential.

However, there are several parameters that are affecting the photocatalytic efficiency in the real-world paint (Mo *et al.,* 2009). The most critical parameters are:

A) The geographical characteristics of where the coatings are deployed: The effective surface area where photocatalyst coating is applied. The higher surface area of the photocatalyst increases the photocatalytic rate. The wavelength of the incident radiation has to be appropriate in order to excite the electrons of the photocatalyst and initiate the photocatalytic process. The Light intensity: The reaction rate increases with increasing light intensity according to the following figure for NO_2. Similar figures are required for other urban pollutants.

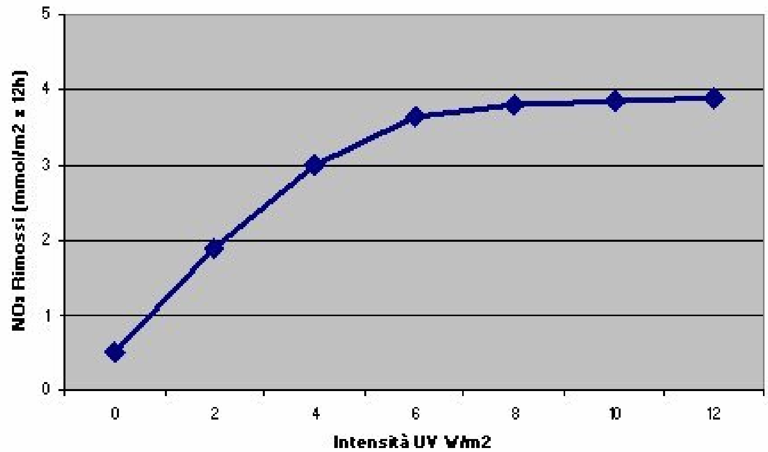


Figure 4: Absorption of NO_2 (millions molecules/m^2 in 12 Hours) at various UV light intensities (W/m^2).

B) The climatic characteristics of the site such as Relative humidity and Temperature: Water molecules adsorbed on the photocatalytic paint seem to enhance the photocatalytic efficiency of TiO_2 through the formation of hydroxyl radicals which, in turn, oxidise the air pollutants. However, an excessive relative humidity (>70%) inhibits the photocatalytic degradation of air pollutants, due to the competition for adsorption sites on the photocatalyst surface (Pichat, 2010). *Temperature:* A rise in the temperature speeds up the kinetics of the reaction between the pollutants and the photocatalyst, while at the same time decreasing the adsorption of the pollutants on the surface of the photocatalytic paint. Since the net photocatalytic reaction rate is a combination of both processes, a maximum photocatalytic oxidation rate is obtained at the optimum temperature (Obee and Hay, 1997).

C) The specificities of the local atmospheric pollution. The relationship between the concentration of the pollutant and the photocatalytic rate is generally governed by the Langmuir—Hinselwood model (Shiraisi *et al.,* 2007), according to which the reaction rate increases with the concentration as described in the equation:

$$R = k\,\frac{A < c >}{1 + A < c >}$$

where R represents the reaction rate, k the rate constant, A the adsorption coefficient of the pollutant on the photocatalytic paint and <c> the pollutant concentration. Also, the presence of mixtures of pollutants is also of concern due to the competition on the adsorption of the different pollutants on the surface of the photocatalyst. The reaction rate for a single component is normally lower in the presence of different kinds of pollutants (Ao et al., 2004; Chen and Zhang, 2008).

D) Paint constituents and interaction with the photocatalyst. Paint constituents such as binder have a considerable influence on the performance of the photocatalytic paint. Aguia et al. in 2010, have been observed that the nature and proportion of the different paint constituents can have a significant effect in terms of enhancing or diminishing the photocatalytic efficiency of the catalyst. Since there was no correlation between the photocatalytic activity of the pure photocatalyst and the corresponding derived paint they concluded that the paint components and the way in which the photocatalyst is mixed in the coating play a crucial role in the photoactivity of the final product.

3.3.2 Optimisation of highest pollution reductions

It is evident from the above that it should be taken into consideration that absorption capacity of coatings is subject to the intensity of the light that is varying significantly during the day and due to the local meteorological conditions.

Figure 5: Variation of light intensity (W/m^2) every 10 min at 35 N latitude in winter.

Such variations are part of the sensor instrumentation deployed for meteorological assessments and long data time series are in consultation for the sites where iScape outdoor experimental campaigns are planned with the deployment of photocatalytic coatings (Bologna, Madrid and Guildford).

Prior to these deployments outdoors, suitable PURETi coatings as those presented in section 1.3.3 will be tested indoors in a chamber for testing the reduction of inorganic pollutants (NO, NO_2, SO_2) and organic pollutants (benzene, toluene). Clean air will be flushed through the chamber where the photocatalytic product is for at least 12 hours prior to the injection of urban pollutants until steady state conditions are reached. It is important to stress that, when evaluating the photocatalytic efficiency of paints, the activation conditions are the critical parameters affecting the time required to reach the steady state, after which the photoactivity of the paint either remains constant or diminishes in the event of inactivation by the adsorption of intermediate products on the active catalytic sites.

The chamber experiments will also assess the presence of intermediate products due to the incomplete photocatalysis or the secondary emissions from by-products (especially since some might be more harmful compared to the original pollutant). Such emissions are formed due to the photo-oxidation of supporting material in which the photocatalyst is embedded.

During the incomplete degradation of pollutants some of the intermediate products such as carboxylic acids will be produced, which are strongly adsorbed on the photocatalyst surface (Huang and Li, 2011). These can reduce the number of active catalyst sites in the photocatalytic paint, which can in critical cases considerably minimise its efficiency. The surface can be regenerated by washing the surface with water (or by UV light). However, these methodologies are not easy to apply and further research will be needed for establishing methodologies to remove adsorbed intermediate products.

As for secondary emissions, the formation of carbonyls has been observed by many types of research while irradiating photocatalytic paints under either UV or visible light. The main source of such carbonyl compounds was assumed to be the photo-induced decomposition of paint binders. The main degradation compounds for most common photocatalytic coatings are formaldehyde, acetaldehyde and acetone. Lower amounts of longer chain carbonyl compounds such as propanal, butanal or hexanal were formed in the initial stages. The reduction in the secondary emissions of photocatalytic paints can be achieved with appropriate selection of paint constituents during the manufacturing of the coatings and/or with prior irradiated with UV light before the commercial distribution of the coatings. In particular, the secondary emission of carbonyl compounds can be considered to be negligible after continuous UV irradiation of about 3 weeks.

3.3.3 Deployment methodologies in existing urban canopies

There are several outdoor experiments have been carried out today. One of first was PICADA, which started in January 2002 and ended in 2005 in the frame of European programme called Competitive and Sustainable Growth. The aim of the PICADA (standing for Photocatalytic Innovative Coverings Applications for De-Pollution Assessments) is to develop a range of materials and to evaluate their effect on a large scale such a typical street canyon and inside a car park in Paris.

The outdoor experimental layout and instrumentation used for emissions from a single engine are shown in the following figure. Experiments were carried during the summer of 2004. Unfortunately, the street canyon dimensions were only 1:5 and the performance of the photocalytical products under real urban conditions were not reported. Although background ozone and NO_x was measured on the simulated canyons the effect of the NO_2 by the coatings on the ozone concentration was not properly assessed. Classical chemiluminescence analysers were used on both sides of the TiO_2 treated surfaces and a rather simplistic numerical model was also used for generalisation under different meteorological conditions.

The results for NO_x recorded concentrations in the TiO_2 canyon were 40 to 80% lower than the ones observed in the reference canyon and the variations were attributed due to differences in pollution source emissions (artificially induced in the centre of each canyon), wind direction and orientation of the walls. For the car-park indoor tests, 322 m^2 ceiling surface was covered with white TiO_2 treated paint while the walls were covered with nylon. Illumination was provided by 20 U.V lamps with total U.V irradiance was $1 W/m^2$. A car was placed outside the test area while its exhaust was connected to a pipe in order to release exhaust gases 4.74m inside the closed area. The maximum NO_2 reduction due to the TiO_2 ceiling was about 20%.

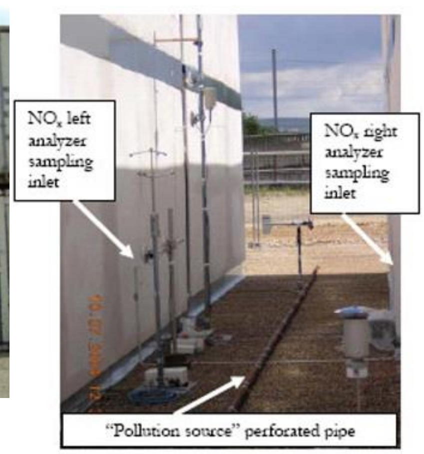


Figure 6: Street canyon and experimental instrumentation as per the project documentation at: http://www.picada-project.com/domino/SitePicada/Picada.nsf?OpenDataBase.

Since then several other real-world assessments were carried out (Marolt et al., 2011; Guerrini, 2012) for the reduction of inorganic pollutants (NO, NO_2, SO_2) and organic pollutants (benzene, toluene) as a result of the application of photocatalytic paints. These studies included:

- Via Porpora (Milan, Italy)
- Umberto I tunnel (Rome, Italy)
- Road pavement at Hengelo (The Netherlands)
- Umberto I tunnel (Rome, Italy)
- Roadway coating in Baton Rouge (Louisiana, US)
- Leopold II tunnel coating (Brussels, Belgium)
- Coating at concrete blocks Vesterbro district (Copenhagen, Denmark)
- Road coatings at Zhonghe Toll station (Tsitsihar, China)

In iSCAPE, the methodology that will be applied is based on the assessment of the area where PURETi material will be employed before and after a testing period of two weeks. We will assess two urban sites with strong photochemical activity in South Europe and one site in North Europe. For measurements, we will use several devices based on sensor technologies with the most accurate technologies. For reference purposes, we will also analyse the concentrations obtained from all surrounding conventional air-quality stations for identifying the cluster of occurring conditions during similar meteorological periods. The local effectiveness will be based on gains from the local measurements with photocatalytic coatings against the values measured during corresponding periods when the coatings were not deployed.

3.4 Spatial perspective

From a spatial perspective, there are several parameters influencing air quality and urban heat (see chapter 2.4). However, air pollution reduction strategies can best be derived when the city-specific air quality situation is known. Therefore, this subchapter gives information on the city-regional and local context in the six iSCAPE Living Lab cities and thereby becomes the basis for chapter 5.4, the development of guidelines and recommendations.

3.4.1City Profile Contents

According to the parameters presented in chapter 2.4, information on air quality and urban heat are gathered and assessed in individual city profiles for the six iSCAPE Living Lab cities (see following subchapters of 3.4.2). City profiles allow a clear and consistent way of presenting information that can easily be compared. A short subsequent description of the gathered information helps understand the presented data.

3.4.1.1 Spatial general maps

Besides the air quality and urban heat parameters, the city profiles are equipped with two maps. The first is the outcome of a geo-information system (GIS) analysis of the current land uses and shall provide a first overview of the spatial proportions (built-up area vs. undeveloped land) within the Living Lab cities[2]. The scale of the maps is 1: 250,000 (resp. 1: 350,000 for Guildford and Vantaa). The database for all Living Lab cities except Hasselt[3] is the Urban Atlas Data of the European Environment Agency (EEA) (EEA, 2014). For Hasselt, CORINE Land Cover Data, likewise of the EEA, are used (EEA, 2006).

The second map included in the city profiles contains the Functional Urban Areas (FUAs) of the iSCAPE Living Lab cities, taken from the Eurostat regional yearbook 2016 (Eurostat, 2016). The European Commission in cooperation with the Organisation for Economic Co-operation and Development (OECD) facilitated the FUA concept in 2011, aiming at developing an EU-inherent definition of 'a city' basing on population size and density (Dijkstra and Poelman, 2015).

According to the FUA concept, cities are defined as densely populated local administrative units with at least 50,000 inhabitants, of which more than 50 % live within an urban centre (Eurostat, 2015a). In case the urban centre stretches out beyond the city's boundaries, a 'greater city' area is approximated (see e.g. chapter 3.4.3 Dublin) (Eurostat, 2015b). Last, commuting zones are calculated on the basis commuting shares, displaying "the surrounding travel-to-work areas of a city where at least 15 % of their employed residents are working in this city" (Eurostat, 2015c). Together, cities and commuting zones form an FUA (Eurostat, 2015d).

3.4.1.2 Land-use information

The below-listed parameters are assessed through land use information taken from GIS datasets. The prevailing dataset is the above-introduced EEA Urban Atlas data (the reference year 2006). The data set contains high-resolution land use and land cover data for FUAs above 100,000 inhabitants. Urban Atlas data are vector data (point surface) with a resolution of 1:10,000. Land-use information gained from Urban Atlas data are marked bold and provided with a star (*). As Hasselt, has less than 100,000 inhabitants, EEA CORINE land cover data (the reference year 2006) are used for the Belgian city. CORINE data are raster data (grid cell surface) derived from satellite images with a lesser spatial resolution compared to Urban Atlas data. Land-use information gained from CORINE data are not printed in bold and provided with two stars (**).

In order to provide maximum comparability, land-use information is provided from both datasets, where possible (Bologna, Bottrop, Dublin, Guildford, and Vantaa).

The following parameters are assessed via spatial data analysis:

Traffic area (%)	**Percentage of traffic area towards total city area**

Calculation (land-use categories):
Urban Atlas: Airports; Fast transit roads and associated land; other roads and associated land; railways and associated land.
CORINE: Road and rail networks and associated land; airports.

[2] Legend/Key can be found in the Annex of this Deliverable.
[3] Urban Atlas Data are only available for large urban zones/FUAs with more than 100,000 inhabitants (EEA, 2014).

Industrial area (%)	Percentage of industrial or commerce area towards total city area
Calculation (land-use categories): ***Urban Atlas: Industrial, commercial, public, military and private units; Port areas.*** ***CORINE: Industrial or commercial units; port areas.***	
Green and blue areas (%)	Percentage of green areas and water bodies towards total city area (sum of sub-parameters)
Forests (%)	Percentage of forested area towards total city area
Calculation (land-use categories): ***Urban Atlas: Forests.*** ***CORINE: Broad-leaved forest; Coniferous forest; Mixed forest; Transitional woodland-shrub***	
Urban green (%)	Percentage of urban green areas (parks) towards total city area
Calculation (land-use categories): ***Urban Atlas: Green urban areas.*** ***CORINE: Green urban areas.***	
Agriculture (%)	Percentage of agricultural area towards total city area
Calculation (land-use categories): ***Urban Atlas: Agricultural + Semi-natural areas + Wetlands.*** ***CORINE: Non-irrigated arable land; Fruit trees and berry plantations; Pastures; Complex cultivation patterns; Land principally occupied by agriculture, with significant areas of natural vegetation; Natural grasslands; Moors and heathland.***	
Water bodies (%)	Percentage of area of water bodies (lakes; rivers) towards total city area
Calculation (land-use categories): ***Urban Atlas: Water bodies.*** ***CORINE: Watercourses; Waterbodies; Estuaries; Sea and ocean.***	

Table 21: Indicators for spatial data analysis

3.4.1.3 Statistical information

Statistical information is used for the parameters private transport, public transport, freight transport and population density. All four parameters are mainly extracted from the Eurostat website, the online appearance of the European Commission's statistical office. Additionally, further information, e.g. from the European Commission's 'Survey on the perception of quality of living' (2010), are given. The following information is listed per parameter:

- Private Transport
    - Commuter outflows (% of total employment): Eurostat regional yearbook 2016
    - Density of motorways (km per 1000 km² of total area): Eurostat regional yearbook 2015
- Public Transport

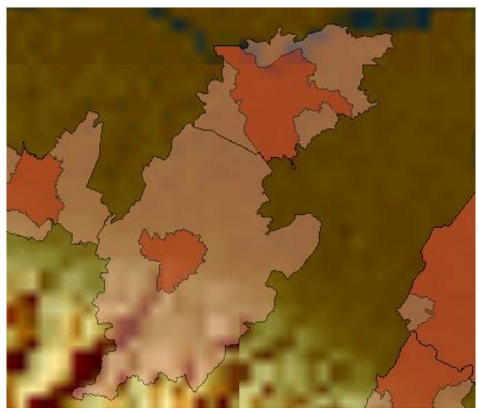
    - Equipment rate for public transport vehicles, e.g. motor coaches, buses and trolleybuses (number of public transport vehicles per 1,000 inhabitants): Eurostat regional yearbook 2016
    - Density of rail networks (km of railway line per 1000 km² of total area): Eurostat regional yearbook 2014
    - Other statements, e.g.
        - European Union (2010): Survey on perception of quality of life in 75 European cities, DG Regional Policy
        - Information from local public transport providers
- Freight Transport
    - Road freight vehicles (thousand vehicles): Eurostat regional yearbook 2013
    - Density of rail networks (km of railway line per 1000 km² of total area): Eurostat regional yearbook 2014
    - Presence of airport and/or freight port
- Population density
    - Population density (inhabitants per km²): Eurostat regional yearbook 2016.

3.4.2 Living Lab City Profiles

3.4.2.1 Bologna, ITALY

Bologna, ITALY

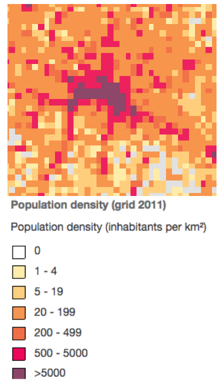
Land use in Bologna (©F. Hurth, Urban Atlas Data)



FUA and City of Bologna (Eurostat, 2016)

Air quality			*Data Basis*
Transport	Traffic area (%)	***14.96****/*5.32***	*Urban Atlas Data / CORINE Data; 76.88 km² total area*
	Private Transport		
	Commuter outflows; % of total employment	Region: Emilia-Romagna 2.8	*Eurostat Regional Yearbook 2016: Commuter Outflows; NUTS2*
	Density of motorways; km per 1,000 km² of total area	Region: Emilia-Romagna 25	*Eurostat Regional Yearbook 2015; Density of motorways; NUTS2*

	Public Transport		
	Equipment rate for public transport vehicles; number of public transport vehicles per 1,000 inhabitants)	Region: Emilia-Romagna 1.4	*Eurostat Regional Yearbook 2016: Equipment rate for public transport vehicles; NUTS2*
	Other statements	"Respondents in Rennes and Bologna were the most likely to complain that public transport was not adapted to their itinerary."	*EU, 2010, 68*
	Other statements	"Everyday more than 340,000 passengers use buses and more than 30,000 regional rail transport."	*TPER, 2016*
	Freight Transport		
	Road freight vehicles; in thousand vehicles	No data available	*Eurostat Regional Yearbook 2013: Road Freight vehicles; NUTS2*
	Density of rail networks; km of railway line per 1,000 km² of total area)	Region: Emilia-Romagna 58.19	*Eurostat Regional Yearbook 2014: Density of rail networks; NUTS2*
	Presence of airport and/or freight port	Aeroporto di *Bologna* - Borgo Panigale "Guglielmo Marconi"	*Google maps*
Industry and trade	Industrial area (%)	***22.55****/*15.11***	*Urban Atlas Data / CORINE Data; 76.88 km² total area*
Urban green and blue spaces	Green and blue areas (%)	***27.92****/*27.92***	*Urban Atlas Data / CORINE Data; 76.88 km² total area*
	Forest (%)	***1.46****/*0.59***	*Urban Atlas Data / CORINE Data; 76.88 km² total area*
	Urban green (%)	***6.78****/*2.07***	*Urban Atlas Data / CORINE Data; 76.88 km² total area*
	Agriculture (%)	***19.43****/*25.26***	*Urban Atlas Data / CORINE Data; 76.88 km² total area*
	Water bodies (%)	***0.25****/*0.00***	*Urban Atlas Data / CORINE Data; 76.88 km² total area*
Urban Heat			*Data Basis*
Settlement	Sealed ground (%)	***40.99****/*29.23***	*Urban Atlas Data / CORINE Data; 76.88 km² total area*

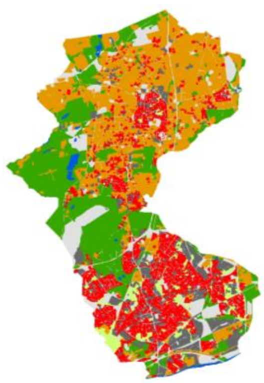
Structure	Population density		*Eurostat Regional Yearbook 2016: Population Density.*

*Based on Urban Atlas Data: http://www.eea.europa.eu/data-and-maps/data/urban-atlas
**Based on CORINE Data: http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2

Table 22: *City profile Bologna, ITALY*.

3.4.2.2 Bottrop, GERMANY

Bottrop, GERMANY

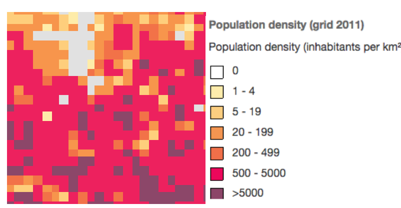


Land use in Bottrop (©F. Hurth, Urban Atlas Data)

FUA and City of Bottrop (Eurostat, 2016)

Air quality		*Data Basis*	
Transport	Traffic area (%)	***5.67****/0.18**	*Urban Atlas Data / CORINE Data; 100.27 km² total area*
	Private Transport		
	Commuter outflows; % of total employment	Region: Münster 16	*Eurostat Regional Yearbook 2016: Commuter Outflows; NUTS2*
	Density of motorways; km per 1,000 km² of	Federal State: North-Rhine Westphalia 65	*Eurostat Regional Yearbook*

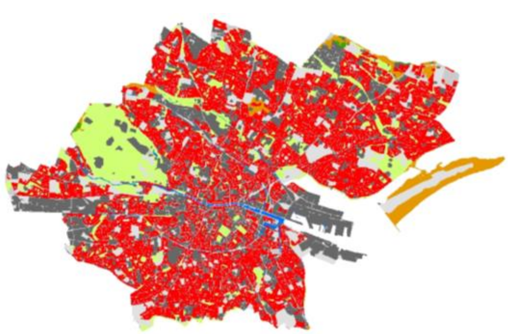
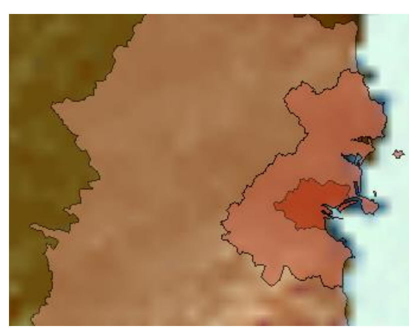
	total area		*2015; Density of motorways; Federal States*
	Public Transport		
	Equipment rate for public transport vehicles; number of public transport vehicles per 1,000 inhabitants)	Region: Münster 1	*Eurostat Regional Yearbook 2016: Equipment rate for public transport vehicles; NUTS2*
	Other statements	"The 'Vestische' is one of the largest traffic enterprises in Europe with about 976 km^2. Every year about 63 million people travel with 'Vestrische'."	*Vestrische, 2016, p.4-5*
	Freight Transport		
	Road freight vehicles; in thousand vehicles	Region: Münster: 122	*Eurostat Regional Yearbook 2013: Road Freight vehicles; NUTS2*
	Density of rail networks; km of railway line per 1,000 km² of total area)	Federal State: North-Rhine Westphalia 158.37	*Eurostat Regional Yearbook 2014: Density of rail networks; Federal States*
	Presence of airport and/or freight port	no	*Google maps*
Industry and trade	Industrial area (%)	***9.08****/*6.69***	*Urban Atlas Data / CORINE Data; 100.27 km² total area*
Urban green and blue spaces	Green and blue areas (%)	***58.04****/*63.71***	*Urban Atlas Data / CORINE Data; 100.27 km² total area*
	Forest (%)	***23.46****/*18.69***	*Urban Atlas Data / CORINE Data;*

			100.27 km² total area
	Urban green (%)	***2.97****/0.64***	*Urban Atlas Data / CORINE Data; 100.27 km² total area*
	Agriculture (%)	***30.60****/43.92***	*Urban Atlas Data / CORINE Data; 100.27 km² total area*
	Water bodies (%)	***1.01****/0.46***	*Urban Atlas Data / CORINE Data; 100.27 km² total area*
Urban Heat		*Data Basis*	
Settlement Structure	Sealed ground (%)	***24.23****/11.06***	*Urban Atlas Data / CORINE Data; 100.27 km² total area*
	Population density		*Eurostat Regional Yearbook 2016: Population Density.*

*Based on Urban Atlas Data: *http://www.eea.europa.eu/data-and-maps/data/urban-atlas*
**Based on CORINE Data: *http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2*

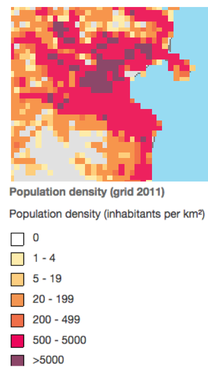
Table 23: City profile Bottrop, GERMANY

3.4.2.3 Dublin, IRELAND

Dublin, IRELAND		

	Land use in Dublin (©F. Hurth, Urban Atlas Data)	***FUA, greater city and city of Dublin (Eurostat, 2016)***	
Air quality			*Data Basis*
Transport	Traffic area (%)	***9.32****/0.20**	*Urban Atlas Data / CORINE Data; 117.52 km² total area*
	Private Transport		
	Commuter outflows; % of total employment	Region: Southern and Eastern Ireland 1.3	*Eurostat Regional Yearbook 2016: Commuter Outflows; NUTS2*
	Density of motorways; km per 1,000 km² of total area	Region: Southern and Eastern Ireland 18	*Eurostat Regional Yearbook 2015; Density of motorways; NUTS2*
	Public Transport		
	Equipment rate for public transport vehicles; number of public transport vehicles per 1,000 inhabitants)	Region: Southern and Eastern Ireland 2.2	*Eurostat Regional Yearbook 2016: Equipment rate for public transport vehicles; NUTS2*
	Other statements	“24 % [of respondents from Dublin] are very satisfied with public transport, 46 % are rather satisfied, 16 % are rather unsatisfied and 10 % not at all satisfied.”	*EU, 2010, 67*
	Other statements	“As with any city, you’ve got options for getting around Dublin. You can hop aboard a Dublin Bus with an extensive network reaching across the county. There’s a coastal train line, the DART, […]. There’s a light rail	*Website Dublin City Council, 2017*

		system, the LUAS, […]. Dublinbikes, the most successful citywide bike hire scheme in Europe, is loved by the locals.”	
	Freight Transport		
	Road freight vehicles; in thousand vehicles	Region: Southern and Eastern Ireland 241	*Eurostat Regional Yearbook 2013: Road Freight vehicles; NUTS2*
	Density of rail networks; km of railway line per 1,000 km² of total area)	State: Republic of Ireland 27.14	*Eurostat Regional Yearbook 2014: Density of rail networks; Countries.*
	Presence of airport and/or freight port	Dublin Airport Dublin Connolly	*Google maps*
Industry and trade	Industrial area (%)	***11.39**** */10.86***	*Urban Atlas Data / CORINE Data; 117.52 km² total area*
Urban green and blue spaces	Green and blue areas (%)	***16.1**** */13.12***	*Urban Atlas Data / CORINE Data; 117.52 km² total area*
	Forest (%)	***0.13**** */0.00***	*Urban Atlas Data / CORINE Data; 117.52 km² total area*
	Urban green (%)	***12.04**** */10.42***	*Urban Atlas Data / CORINE Data; 117.52 km² total area*
	Agriculture (%)	***3.15**** */2.65***	*Urban Atlas Data / CORINE Data; 117.52 km² total area*
	Water bodies (%)	***0.78**** */0.05***	*Urban Atlas Data / CORINE Data; 117.52 km² total area*
Urban Heat			*Data Basis*
Settlement Structure	Sealed ground (%)	***50.20**** */34.02***	*Urban Atlas Data / CORINE Data; 117.52 km² total area*

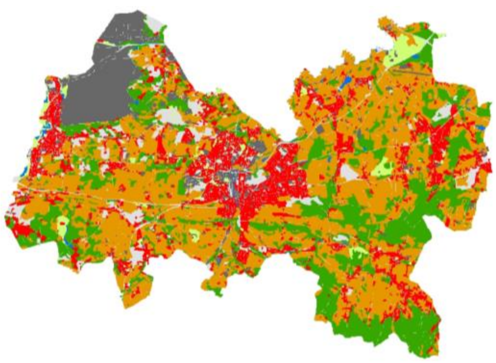
	Population density		*Eurostat Regional Yearbook 2016: Population Density.*

*Based on Urban Atlas Data: http://www.eea.europa.eu/data-and-maps/data/urban-atlas
**Based on CORINE Data: http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2

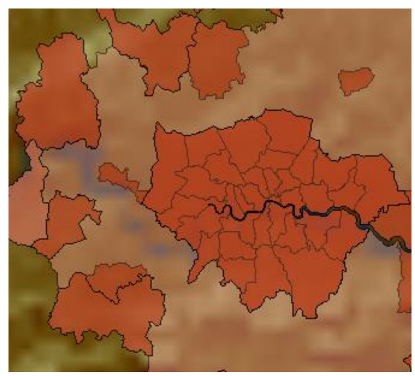
Table 24: City profile Dublin, IRELAND

3.4.2.4 Guildford, UNITED KINGDOM

Guildford, UNITED KINGDOM



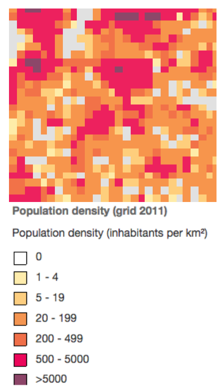
Land use in Guildford (©F. Hurth, Urban Atlas Data)



FUA and city of Guildford (Eurostat, 2016)

Air quality			*Data Basis*
Transport	Traffic area (%)	***3.79****/0.00**	*Urban Atlas Data / CORINE Data; 270.80 km² total area*
	Private Transport		
	Commuter outflows; % of total employment	Region: South East England 18.2	*Eurostat Regional Yearbook 2016: Commuter Outflows; NUTS2*
	Density of motorways; km per 1,000 km² of total area	Region: Surrey, East and West Sussex 21	*Eurostat Regional Yearbook 2015; Density of motorways; NUTS2*
	Public Transport		
	Equipment rate for public transport vehicles; number of public transport vehicles per	Region: Surrey, East and West Sussex 2.2	*Eurostat Regional Yearbook 2016: Equipment rate for public transport vehicles; NUTS2*

	1,000 inhabitants)		
	Other statements	"Guildford offers a range of transport services in order to guarantee that everyone can use public transport. Guildford offers community transport services for those who can't easily use public transport, e.g. senior citizens, citizens with a physical disability or mobility problem, citizens with learning difficulties or citizens who are suffering short or long term ill health. Furthermore, the city offers "Dial-a-ride" which is a door-to-door service, providing transport to a range of locations, appointments and social activities in Guildford and key towns in the surrounding area. Also, Door to Store services, transport to centres for older people, a library service and social trips are offered."	*Website Guildford Borough, 2017*
	Freight Transport		
	Road freight vehicles; in thousand vehicles	Region: Surrey, East and West Sussex 161	*Eurostat Regional Yearbook 2013: Road Freight vehicles; NUTS2*
	Density of rail networks; km of railway line per 1,000 km² of total area)	State: United Kingdom 65.15	*Eurostat Regional Yearbook 2014: Density of rail networks; Countries.*
	Presence of airport and/or freight port	no	*Google maps*
Industry and trade	Industrial area (%)	***8.98****/1.02**	*Urban Atlas Data / CORINE Data; 270.80 km² total area*

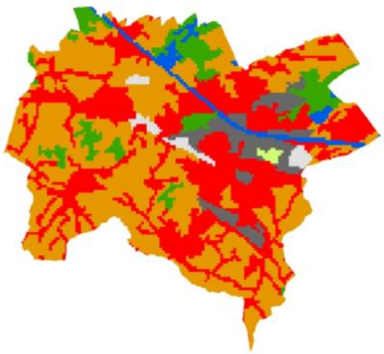
Urban green and blue spaces	Green and blue areas (%)	***65.74****/81.03***	*Urban Atlas Data / CORINE Data; 270.80 km² total area*
	Forest (%)	***21.85****/23.84***	*Urban Atlas Data / CORINE Data; 270.80 km² total area*
	Urban green (%)	***2.47****/0.56***	*Urban Atlas Data / CORINE Data; 270.80 km² total area*
	Agriculture (%)	***40.84****/56.91***	*Urban Atlas Data / CORINE Data; 270.80 km² total area*
	Water bodies (%)	***0.58****/0.00***	*Urban Atlas Data / CORINE Data; 270.80 km² total area*
Urban Heat			*Data Basis*
Settlement Structure	Sealed ground (%)	***13.70****/5.32***	*Urban Atlas Data / CORINE Data; 270.80 km² total area*
	Population density		*Eurostat Regional Yearbook 2016: Population Density.*

*Based on Urban Atlas Data: *http://www.eea.europa.eu/data-and-maps/data/urban-atlas*
**Based on CORINE Data: *http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2*

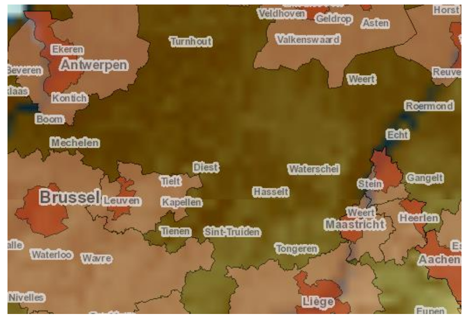
Table 25: City profile Guildford, UNITED KINGDOM

3.4.2.5 Hasselt, BELGUIM

Hasselt, BELGIUM

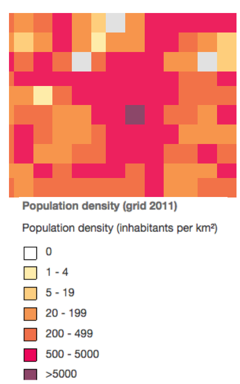


Land use in Hasselt (©F. Hurth, CORINE Data)



No FUA in Hasselt (Eurostat, 2016)

Air quality			*Data Basis*
Transport	Traffic area (%)	*0.94***	*CORINE Data; 102,70 km² total area*
	Private Transport		
	Commuter outflows; % of total employment	Region: Province Limburg 19.1	*Eurostat Regional Yearbook 2016: Commuter Outflows; NUTS2*
	Density of motorways; km per 1,000 km² of total area	Region: Province Limburg 44	*Eurostat Regional Yearbook 2015; Density of motorways; NUTS2*
	Public Transport		
	Equipment rate for public transport vehicles; number of public transport vehicles per 1,000 inhabitants)	Region: Province Limburg 1.4	*Eurostat Regional Yearbook 2016: Equipment rate for public transport vehicles; NUTS2*
	Other statements	“Because of the free public transport, Hasselt got worldwide media attention and has become a success story. Both the number of travellers and the number of routes and buses has increased with time. Until June 1997, there were approximately 1,000 Hasselt bus passengers per day. Ten years later there was an average of 12,600."	*ELTIS, 2014*

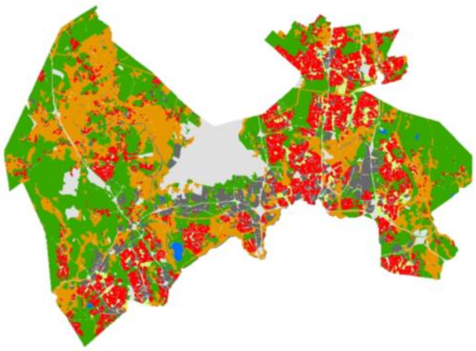
	Freight Transport		
	Road freight vehicles; in thousand vehicles	Region: Province Limburg 73	*Eurostat Regional Yearbook 2013: Road Freight vehicles; NUTS2*
	Density of rail networks; km of railway line per 1,000 km² of total area)	Region: Province Limburg 111.89	*Eurostat Regional Yearbook 2014: Density of rail networks; NUTS2*
	Presence of airport and/or freight port	no	*Google maps*
Industry and trade	Industrial area (%)	*6.20***	*CORINE Data; 102,70 km² total area*
Urban green and blue spaces	Green and blue areas (%)	*56.99***	*CORINE Data; 102,70 km² total area*
	Forest (%)	*7.81***	*CORINE Data; 102,70 km² total area*
	Urban green (%)	*0.34***	*CORINE Data; 102,70 km² total area*
	Agriculture (%)	*46.05***	*CORINE Data; 102,70 km² total area*
	Water bodies (%)	*2.79***	*CORINE Data; 102,70 km² total area*
Urban Heat		*Data Basis*	
Settlement Structure	Sealed ground (%)	*14.63***	*CORINE Data; 102,70 km² total area*
	Population density		*Eurostat Regional Yearbook 2016: Population Density.*

**Based on CORINE Data: *http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2*

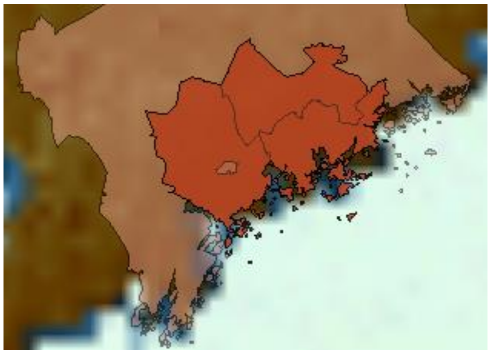
Table 26: City profile Hasselt, BELGIUM

3.4.2.6 Vantaa, FINLAND

Vantaa, FINLAND

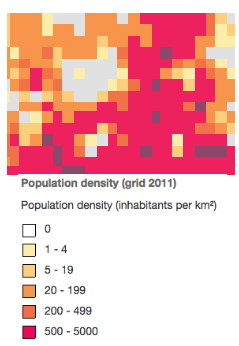


Land use in Vantaa (©F. Hurth, Urban Atlas Data)



FUA and City of Vantaa (eurostat, 2016)

Air quality			*Data Basis*
Transport	Traffic area (%)	***9.97****/*5.27***	*Urban Atlas Data / CORINE Data; 240.33 km² total area*
	Private Transport		
	Commuter outflows; % of total employment	Region: Manner-Suomi 4.2	*Eurostat Regional Yearbook 2016: Commuter Outflows; NUTS2*
	Density of motorways; km per 1,000 km² of total area	Region: Helsinki-Uusimaa 31	*Eurostat Regional Yearbook 2015; Density of motorways; NUTS2*
	Public Transport		
	Equipment rate for public transport vehicles; number of public transport vehicles per 1,000 inhabitants)	Region: Helsinki-Uusimaa 3	*Eurostat Regional Yearbook 2016: Equipment rate for public transport vehicles; NUTS2*
	Other statements	"42 % [of respondents from Helsinki Metropolitan Area] are very satisfied with public transport, 51 % are rather satisfied, only 4 % are rather unsatisfied and 1 % not at all satisfied"	*EU, 2010, 67*
	Other statements	"The aim is to encourage people to reduce driving alone in their cars and increase walking, cycling, use of public transport, car sharing, ride sharing and economic driving. Good public transport	HSL, 2017

		services, town planning and locating services and jobs close to housing reduce the need to use a car on a daily basis."	
	Freight Transport		
	Road freight vehicles; in thousand vehicles	No data available	*Eurostat Regional Yearbook 2013: Road Freight vehicles; NUTS2*
	Density of rail networks; km of railway line per 1,000 km² of total area)	Region: Helsinki-Uusimaa 43.48	*Eurostat Regional Yearbook 2014: Density of rail networks; NUTS2*
	Presence of airport and/or freight port	Helsinki Airport	*Google maps*
Industry and trade	Industrial area (%)	7.10*/8.66**	*Urban Atlas Data / CORINE Data; 240.33 km² total area*
Urban green and blue spaces	Green and blue areas (%)	62.54*/55.1**	*Urban Atlas Data / CORINE Data; 240.33 km² total area*
	Forest (%)	36.42*/32.10**	*Urban Atlas Data / CORINE Data; 240.33 km² total area*
	Urban green (%)	2.74*/2.18**	*Urban Atlas Data / CORINE Data; 240.33 km² total area*
	Agriculture (%)	22.76*/20.59**	*Urban Atlas Data / CORINE Data; 240.33 km² total area*
	Water bodies (%)	0.62*/0.23**	*Urban Atlas Data / CORINE Data; 240.33 km² total area*
Urban Heat			*Data Basis*
Settlement Structure	Sealed ground (%)	17.71*/18.52**	*Urban Atlas Data / CORINE Data; 240.33 km² total area*
	Population density		*Eurostat Regional Yearbook 2016: Population Density.*

*Based on Urban Atlas Data: http://www.eea.europa.eu/data-and-maps/data/urban-atlas
**Based on CORINE Data: http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2

Table 27: City profile Vantaa, FINLAND

4 Validations, Strengths and limitations

4.1 Physical PCS

4.1.1 Strengths and limitations of noise barriers

The potential for the noise barriers to affect pollutant dispersion is found to be affected by the geometry and layout of the noise barrier, and its influence on local air flow regimes and turbulence conditions.

The local meteorological conditions and motorway layout have a significant part in quantifying the impact of noise barriers on local air quality conditions.

The literature reviewing process concluded that a reduction in pollutant concentrations occurs downwind of the barrier. It is also reported that the downwind location may be a densely-populated area, therefore implementing this type of barrier may help improve air quality conditions for urban inhabitants.

For the negative impact side, the reviewed studies have also demonstrated the potential negative impact of increased concentrations of the pollutant on the roadside of the barrier if vehicle turbulence does not increase mixing and dilution.

4.1.2 Strengths and limitations of LBWs

As discussed before LBWs act as a baffle and alter air flow patterns at street level. Currently, limited research projects have been addressed LBWs as a passive control system, so iSCAPE deployment of LBWs is a very important to improve the knowledge. The review process for the available literature shows that LBWs have the potential of enhancing local dispersion in the built environment. The height of the LBW, its location in the street and whether spaces exist in the barrier was found to influence air flow in street canyons.

As same as the noise barriers, it has concluded that LBWs effectiveness is dependent on varying canyon geometry, barrier configuration, wind conditions and vehicular turbulence.

Previous studies provide an understanding of the impact of LBWs in generic and real case settings. However, further studies are required to allow for the extrapolation of findings in other cities. This requires an examination of LBWs in a broader range of climatic conditions and high rise street canyons.

The confined street canyon study needs to be expanded to a city-scale, as the frequency and variation of road characteristics and intersections are not considered in the LBW studies to date. There are some evidence that LBWs could cause deteriorations in air quality for vehicular users and, in particular, pedestrians and cyclists.

LBWs can provide a solution to enhancing dispersion and improving air quality in distinct street canyons settings. Many potential drawbacks of LBWs, as they have the same limitation as noise barriers in as the pollutants concentrations increase in front of the LBWs. Depending on wind direction, street geometry and position of the LBW, it may cause air pollutant concentration to increase behind it, having the opposite effect to its intention. Since wind direction is variable an

LBW may have a positive effect today and negative effect tomorrow, which makes the designing process very hard in terms of city planning, as a result of this we must be very careful in where these are placed.

4.1.3 Strengths and limitations of parked cars

Parked cars do not present a static barrier in the built environment. Although a limited number of studies, that address the parked cars as a passive control system, are available, further research is required to provide more conclusive evidence of their potential in a range of settings.

The height of the physical barriers has been found to impact its effect on air quality and dispersion, parked cars can provide a taller boundary than a LBW and shorter than the noise barrier. The temporary, non-continuous and variable shape or parked cars could be considered as less effective than a narrower and shorter LBW.

Although parked cars are a common element of the built environment, they present a low-cost method of pollution concentration reductions that can be implemented through the simple re-design of parking bays, converting streets with the best layout based on local meteorological conditions.

4.2 Green infrastructure

4.2.1 Validations of Green infrastructures studies

Previous sections have described various green infrastructural interventions used as passive pollutant reduction methods. The air quality improvements of urban vegetation have been investigated through field experimental studies, modelling studies, combined field measurements and modelling studies and wind tunnel studies. Some of the field measurements captured seasonal variations as well as species-specific characteristics some studies only validated the impact of vegetation on air quality in a limited time scale. These studies investigated vegetation considering different climatic and meteorological conditions. It is impossible to replicate field measurements studies as location and other features are different from study site to another. Even though investigations are reported similar trends in pollutant concentration profiles. Another important method is combined field measurements and modelling. In this method, air pollutants are measured at one or more locations in a study area, and then these measurements are used for model validation. Subsequently, the validated model can be used to compute the concentration distribution inside the study area. Moreover, the validated model allows performing what-if analysis by changing locations and parameters of vegetation for finding the vegetation arrangement for least exposure in the study area. The next methods for evaluating air pollution reduction potential of vegetation are modelling and wind tunnel based techniques can also be used to evaluate the air pollution reduction potential of green infrastructures. These techniques are validated by experimental data. It is extremely difficult to compare the above mentioned methods with each other due to differences in built environment geometry, vegetation characteristics, meteorological conditions etc. although some general trends were observed as reported in the previous sections and modelling as well as wind tunnel studies showed similar pollution dispersion characteristics of field measurements. In general trees and hedges have shown improvement open road conditions, whereas in street canyons trees deteriorate air quality and hedges showed betterments of the same. Green walls and green roofs showed potential to reduce air pollution. Their strength and limitation are discussed in coming section.

4.2.2 Strengths and limitations of green infrastructures

Trees showed a negative impact on air quality under street canyon conditions and positive impact on air quality in open street conditions. The impact of trees on pollutant exposure mainly depended on built environment geometry, vegetation characteristics, and meteorological conditions. Trees are considered as important means of urban greening and have a greater influence on air quality than other vegetation types since trees are larger in size resulting in more dispersion and more surface area for deposition. However, limited real world investigated the effect of trees in street canyons than of trees along open roads. From the current status of research on air pollution reduction potentials of trees in street canyon, it is difficult to make guidelines as; street canyon and its surrounding differ largely in cities around the world. Trees combined with other vegetation such as hedges, grasses in open street conditions observed to reduce pollutant concentrations. Preliminary studies indicate trees combination with passive methods like boundary walls and parked cars can effectively lower concentration level and further studies can provide guidelines for implementations.

Hedges improved air quality in both street canyon and open road conditions. Hedges can be placed closer to emission source leading to better pollution removal. Studies have demonstrated optimum dimension and favourable vegetation characteristics for improving air quality in open road conditions, still, these findings should be validated by field measurements. However, only limited studies are available discussing air quality improvements of hedges in street canyons, and findings seem to be promising in improving air quality. Detailed studies are needed for better configurations of hedges in the street canyon under local meteorological conditions. Being smaller in dimensions, this can be incorporated into any built urban environment with fewer difficulties than trees; moreover, the maintenance would be easier compared to other green infrastructure solutions.

Green walls and green roofs: compared to other green infrastructures, limited studies were available to ascertain strength and limitations of green walls and green roofs. Additional investigations are required to produce a better understanding of pollutant reduction potentials of this building envelope greening methods. Limited research showed significant pollutant removal by green walls and green roofs which were comparatively lower than other green infrastructural interventions these interventions require no additional space for planting than trees and hedges which consume larger area in heavily built up areas. Thus, green walls and green roofs can be used as effective methods of passive air pollution control with the less special requirement. Among green wall and green roof, green wall outperformed than green roof by reducing more pollutants. In addition, the green wall can cover a larger area than green roofs. However, detailed investigations are required to assess effective of these interventions in controlling air pollution in different built environment conditions as well as in broader climatic conditions. As these are incorporated into building envelopes the indoor air quality should be examined carefully.

4.3 Photocatalytic coatings

The strengths and the limitation for photocatalytic coatings emerge from the nature of the process of the photocatalysis. Different materials are having different potentials for the absorption of light of the appropriate wavelength in creating holes in the electronic structure of the coating surface. Particular attention should be paid to the case of adsorbed water and oxygen molecules. These molecules can react with the holes and excited electrons of the photocatalyst and are transformed into highly reactive compounds (such as hydroxyl radicals and superoxide anions). Despite the extensive research that has been devoted in the laboratory on photocatalytic oxidation technology for the removal of organic and inorganic compounds limited field work have been carried out. The problems of catalyst deactivation, moderate removal efficiency, and by-products prediction are not sufficiently covered. For the purposes of this project, we have to make sure that the photocatalytic process continues during long periods with minimum maintenance or through very simple washing interventions. In the following sections, we describe the approach on how photocatalysis will be utilised as a passive control system by iSCAPE, we describe how to assess the effectiveness in the lab and in real atmosphere and estimate the costs and potentials of similar uses in an urban environment.

4.3.1 Measuring methodology

For the technology of air-cleaning building materials or concrete pavement, various gaseous contaminants, including NO, NO_2, SO_2, CO, toluene, formaldehyde, as well as particulate matter, such as carbon soot Smits et al, 2013 have been tested for challenge contaminants to examine the photocatalytic degradation performance. Most of the studies have been implemented on controlled test benches at small scales in order to obtain a theoretical potential of gains in air-quality though several combinations of photocatalytic processes. The research on such tests was devoted to the photoreaction systems and operational conditions, to assess the air-purification performance for a variety of photocatalytic materials. The diversity of these proposed methods makes it difficult to properly compare the results from different experimental conditions such as the airflow rate, light exposure time, relative humidity and etc. These tests were targeting the purification process of five specialised gases and the following methodologies have standardised so far as per the following table. Such standards will certainly increase in the coming years, however, from this table, it is noticeable the differences on the conditions of the exposure time as well as flow rates required.

GAS	Photo Exposure Time (h)	Flow Rate (L/min)	ISO REFERENCE METHOD
Acetaldehyde	3	1	ISO22197-2 - Fine ceramics (advanced ceramics, advanced technical ceramics) – test method for air purification performance of semiconducting photocatalytic materials – part 2: removal of acetaldehyde. Geneva (2011)
Formaldehyde	3	3	ISO22197-4 - Fine ceramics (advanced ceramics, advanced technical ceramics) – test method for air purification performance of semiconducting photocatalytic materials – part 4: removal of formaldehyde. Geneva (2013)
Methyl Mercaptan	3	1	ISO22197-5 - Fine ceramics (advanced ceramics, advanced technical ceramics) – test method for air purification performance of semiconducting photocatalytic materials – part

			5: removal of methyl mercaptan. Geneva (2013)
NO	5	3	ISO22197-1- Fine ceramics (advanced ceramics, advanced technical ceramics) – test method for air purification performance of semiconducting photocatalytic materials – part 1: removal of nitric oxide. Geneva (2007)
Toluene	3	0.5	ISO22197-3 - Fine ceramics (advanced ceramics, advanced technical ceramics) – test method for air purification performance of semiconducting photocatalytic materials – part 3: removal of toluene. Geneva (2011)

Table 28: Analytical measuring methods

From this table, it's difficult to establish harmonised test conditions and it is impossible to speculate on the test conditions for other gases found in the real atmosphere. It is worth mentioning that analytical measuring methods are based on chemiluminescence and gas/ion chromatography hence it is essential before these the performance of our coating in the real atmosphere to confirm that the sensors developed in iSCAPE will be able to pick such effects under controlled laboratory experiments. For this reason, prior to spraying the PURETi coatings in exterior surfaces, roads and pavements, we test these results under the following experimental bench.

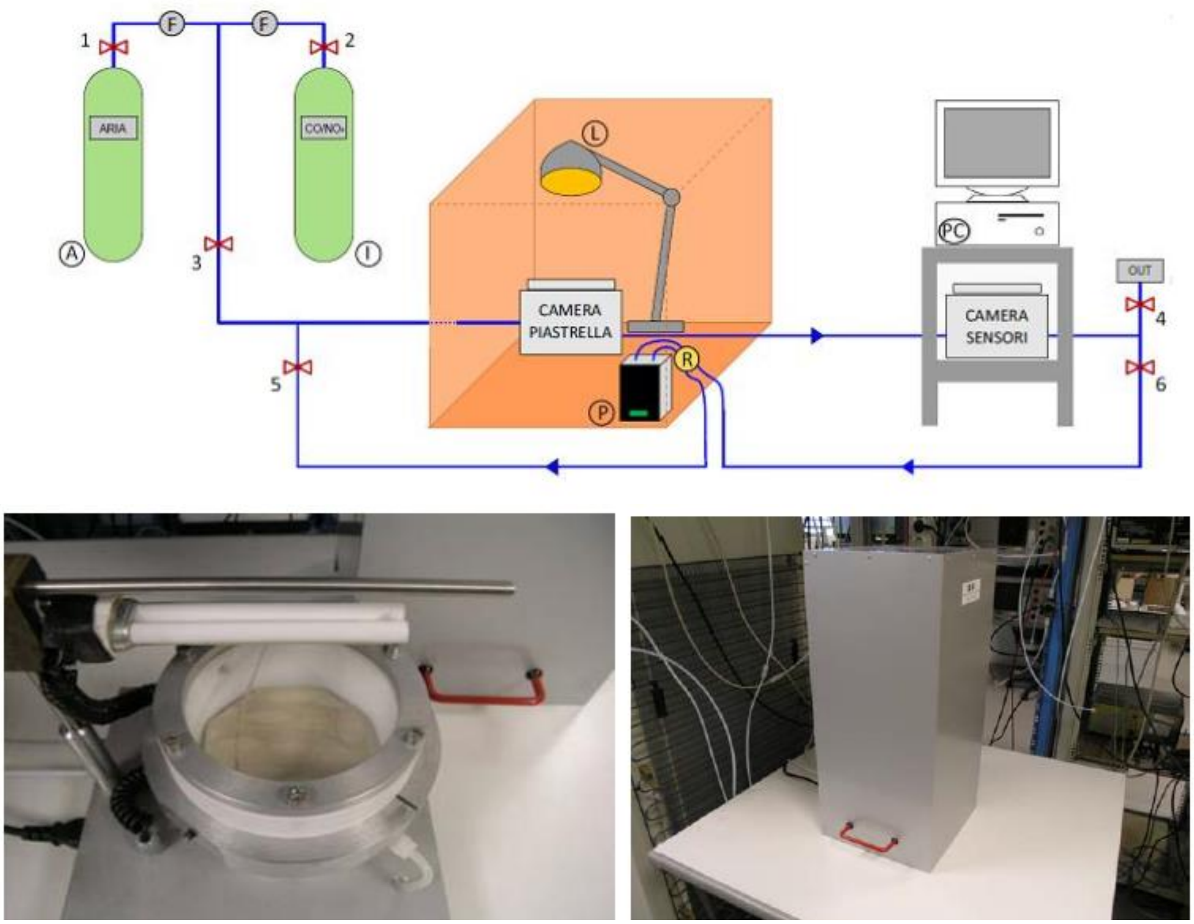


Figure 7: Laboratory test bench, with below the chamber tiles exposure (below left) and the chamber of the measuring sensors (below right).

With the same laboratory facility, we will test how direct solar photons could be utilised better. Since the UV light accounts only 3–5% of the sunlight we should try to examine if the implantation techniques of metal ions such as Fe, Pt, Co, Ce, Cr, Mn, Mg, Ni and Ag, which introduce impurity atoms into pure TiO_2 so as to change electron–hole concentrations in TiO_2 as discussed by Sun et al, 2011. Such a doping method leads to the transformation of an intrinsic TiO_2 into a crystal phase of a P-type or N-type TiO_2 that reduces the absorption band of TiO_2 initiated from visible light regions. For example, the optical band gap energy of the Fe-doped anatase TiO_2 is 0.51 eV (Cui et al, 2010), which is significantly lower than that of pure anatase TiO_2 of 3.2 eV. Hence, also examine how direct sunlight behaves for this new-generation of TiO_2 photocatalysts. It is expected that in the coming year's more favourable combination of impurities will become available permitting the migration of electrons and/or holes between transition metal oxide and TiO_2. Other approaches could also become available based on materials other than TiO_2 (e.g: BiOBr, Zn_2SnO_4, α-Bi_2O_3 etc.) that might be more suitable for indoor air purification under visible light.

All these measurements will examine the theoretical potential of photocatalysis in the laboratory which will be then examined under a full-scale implementation in a realistic environment. The potential of such a deployment is described in the next section.

4.3.2 Effectiveness assessment in the iSCAPE city domains

Although the potential of photocatalytic coating in buildings and construction material has been evident for several years now, there are still unresolved problems when these materials are used in real-life applications. These technical problems are mostly related to the removal efficiencies for tested materials and how these behave in real environments. The coatings need to demonstrate a stable photocatalytic activity for a long period considering the long usage period of the construction materials. Pirola et al. 2012 examined photoactivity of two walls paint-based and two plaster-based TiO_2 materials in the NOx degradation for one year. They recorded the decrease of photoactivity with time for all products under different environmental conditions, such as dust, fouling, and mechanical abrasion, also has negative effect on the stable photocatalytic efficiency.

In the following table are summarised the conclusions from the few studies have been carried out on the full-scale implementation and realistic environmental conditions. It is worth noticing that recent applications are coupled with the very high frequency of temporal registrations and is perhaps the reason why poor air quality improvements could not be demonstrated easily with classical instrumentation.

AQ Improvement	Campaign Duration	Application	REFERENCE
- 20% NOx	2 months	Cement coating in Rome inside a Tunnel	Guerrini, 2012
Evident reduction of NOx, HC, CO		TiO_2 paint on cement anti-collision wall on middle ring in Pudong district at Shanghai	Xu et al, 2012

- 19% NOx (per day) and - 28% NOx (afternoons only) - 45% NOx under ideal conditions (high radiation and low relative humidity	26 days for a period exceeding a year	TiO_2 over a length of 150m road at Hengelo, The Netherlands	Ballart et all, 2013
Evident NOx reductions nitrates were collected from the coated and uncoated areas for evidence of photocatalysis	3 weeks in spring	concentrations were monitored for both the coated and uncoated sections simultaneously at quarter-mile concrete roadway was sprayed with a photocatalytic coating in Baton Rouge, Louisiana, US	Dylla et al, 2012 and Dylla et al, 2011
Field results showed no observable reduction of NOx in the tunnel. An upper limit of 2% was determined for the max possible NOx reduction, which is comparable to experimental uncertainties	Jun/Sep 2011 and 21 Jan 1 Feb 2013	Leopold II tunnel in Brussels, Belgium (70m and 160m), with cementitious coating materials and an artificial UV lighting system.	Gallus et al, 2015
At summer solstice for NO a monthly abatement of 22% and noon abatements higher than 45% were measured. NO	Test carried out between Apr 2012 and Aug 2013. Days with total precipitations higher than 6 mm and total daily sunlight hours lower than 4 h were excluded. Measurements of	Gasværksvej, street located in the Vesterbro district Copenhagen, The test area involved 200 m long x 2 (both side of the road) sidewalk pavers, 100m of ordinary concrete blocks on	Folli et al, 2015

(hence NOx). Efficiency was also found to decrease with increasing relative humidity. Over an entire year, the daily average NO concentration kept to very low values (below 40 ppb-v) in the area paved with coatings containing TiO2.	NO, NO_2, NOx concentrations, temperature and relative humidity were performed every minute throughout the entire duration of the testing (more than a year).	the northern end and 100 m of concrete blocks with TiO_2 as a photocatalyst on the southern end. The traffic loads were taken into account from adjacent bigger roads.	
Coatings had good purification ability, self-regeneration and repetition ability. Minimum Efficiency NOx ranges from 12% to 24%. Photodegradation of NOx as the light intensity increases the reaction rate increases, and conversely as temperature increases the reaction rate decreases	Measurements were taken in summer and winter, continuously from 06:00 to 18:00. The entire sampling was carried out under natural conditions and specimen exposure lasted 1 h. The entire test was carried out over 3 months at the same location.	Two sections of 50m at stretch of road at the Zhonghe Toll Station on federal highway G11 from Tsitsihar to the Nehe River section in China.	Chen et al, 2011

Table 29 Recent worldwide experiments with various technologies of photocatalytic coatings and the reported improvements with respect to conventional urban NOx pollution.

From the aforementioned table, it is rational to expect approximately a 20% reduction in NO_x. The outlier is the European Life+ project PhotoPAQ (Demonstration of Photocatalytic

Remediation Processes on Air Quality) that has been ill-conceived right from the beginning and with surface areas that had serious passivation of the surface reactivity under the heavily polluted tunnel conditions by one order of magnitude was identified in laboratory experiments subsequent to the tunnel study as the main reason for the observed low remediation. In addition, high relative humidity and wind speed inside the tunnel further limited the photocatalytic uptake of NO_x. NO_x was also measured by the chemiluminescence technique which is selective to NO. For the additional detection of NO_2, molybdenum converters were used in the NOx channel of the instruments. However, it is known that this conversion is non-selective leading to positive interferences from other NO_y species. It is the reason why reliable miniaturised sensor devices can become significantly important in demonstrating the results in real field experiments.

AQ Improvement	Campaign Duration	Application	REFERENCE
- 15% to - 25% NOx when UV-A irradiance varied from 10-40 W/m² **+25 NOx when Relative Humidity increased from 30% to 70%** **+40-55% NOx with flow rates from 1 to 5 L/min.**	40 min (5 min without UV-A, 25 min with UV-A and 10min after UV-A is switched-off)	TiO_2-modified cement mortars inside a photoreactor chamber simulating São Paulo/Brazil in the dry period, between May and September with a constant initial concentration of NO of 20 ppm-v.	De Melo et al, 2012

Table 30: Influence of air purification efficiency on local climatic conditions for NOx.

Most research results indicate moderate removal efficiencies for strongly varying experimental conditions. The most technical limitation being the low reachability of gaseous contaminants to the photocatalyst surface under the condition of low airflow rates. Ballari et al. in 2011 found similar trends about the effects of the airflow rate and relative humidity. In addition, common contaminants from the road such as dirt, de-icing salt, and motor oil had important negative impact with oil having the largest negative effect (H. Dylla et.al. 2011).

As for other outdoor pollutants, as for example toluene, the following works have examined the removal efficiency in building materials and in white cement paste. Demeestere et al. 2008, observed up to 63% toluene removal efficiencies using TiO_2-containing roofing tiles and corrugated sheets whereas Chen et al. in 2011 did not detect the conversion of toluene using

TiO_2 modified white cement paste. Perhaps the in Demeestere et al.'s the surface area, long exposure time and light intensity have been more effective.

4.3.3 Generalisation and costs

Assuming that we calculate the cost of deploying in 10000 m^2 of a main road with the PURETi coat of 0.7 €/m^2 with guaranteed duration for 2 years, with conservative efficiency of NOx reduction of 15% and by ignoring the urban background concentration and assuming that this is the distance of 1 km road with a typical fleet composition and mean urban driving conditions will result in an improvement of;

0.5 gr NOx/ km s , which annually is: 15768 kg NOx at a cost of 3500 € ignoring labor and maintenance.

Taking into account only the hospitalization costs for respiratory diseases from NOx emission range from 60 to 294 in United States (in €) per ton of NOx emitted annually it is reasonable to expect that these hospitalizations will cost between 948 to 4635€.

Hence, the costs are lower even when taking into account the only type of adverse health effects.

Commercialization is expected to accelerate the progress and reduce the costs further. There is ample need for conducting more basic research work to resolve these technological challenges. In our opinion, priority research in the near future should focus on the development of new photocatalysts which can demonstrate properties of (i) high adsorption performance in the presence of various VOCs, (ii) find compositions of products that are less influenced by moisture levels, (iii) less or no generation of by-products, and (iv) an ability of trapping photons from UV to sunlight spectrum.

One of the promising opportunities for efficiency improvement would be an increase of the surface area of photocatalysts by treating with some solutions during the catalyst coating preparation. An alternative way is an expansion of active sites from outer surfaces to inner surfaces by using the highly open porous supporting media. Effective utilisation of photons from sunlight is another key technological breakthrough if visible-light-responsive photocatalysts can be successfully developed and proven experimentally. For example, replacing conventional TiO_2-based catalyst with Cu-modified WO_3-based photocatalyst has ten times higher reactivity under visible light conditions, which is in the further verification stage (Kibanova et al, 2009).

As far as the indoor application is concerned, controversy surrounds the question of whether it is safe to apply the photocatalytic materials. The organic material of paints and coatings, such as binders and additives, can be decomposed due to photocatalysis. This self-degrading effect may result in relatively high quantities of organic compounds, like undesired by-products, such as formaldehyde, acetaldehyde, ethyl acrolein, pentanal, 1-hydroxy-butanone, and hexanal, which are related to the composition of paints Salthammer and Fuhrmann in 2007. These compounds are quite stable indoor air pollutants and may decrease the indoor quality of the air due to possible health effects of by-products formed in incomplete photo-oxidation (Auvinen and Wirtanen, 2008). In addition, the potential impacts of nanomaterials on human health should also be assessed. The particle size of nanoscopic photocatalysts is so small that it is possible it could enter into the human body triggering adverse health effects during the production, transportation, storage, and use (Wang et al, 2008).

4.3.4 Potential of future used in walls, tiles, pavements and roads

The process that will be used by the iSCAPE project advances a lot the area of application by simultaneously examining North and South European domains. We will deploy the PURETi coat at least in one south European urban domain over an area exposed to normal sunlight over an area of 10000 to 15000 m^2. This already a product with superior performance presents a significant technological and design challenge. The spraying process will be conducted as per the following photos provided to us courtesy of the PURETi.

Figure 8: The automated process of utilizing PURETi coatings in main roads and surrounding areas.

We will not utilise areas where tunnels or urban street canyons occur because want to avoid the drawback non-natural wind circulation across the streets and for maximising the exposure to natural sunlight. Although we will not use campaigns of long duration we will generalise the gains but extensively look into the cluster of pollution categories from all stationary monitoring stations. We will set a basis of the theoretical gains in a laboratory test facility where will also test the durability of photocatalysts and investigated the generation especially if they risk to cause adverse health consequences.

The immobilisation of TiO_2 by the construction materials can lead to significant loss of the photocatalytic activity. It is thought that the reduction of active surface and the presence of ionic species, which contributed to the charge recombination, are the reasons for the catalytic activity loss. The report published by the Hong Kong Environmental Protection Department claimed that the photocatalytic activity of TiO_2 coated paving blocks decreased significantly after 4-month exposure in a downtown area due to the accumulation of contaminants on the block surface (Yu, 2003). For reason, we will repeat the campaign at least at two location after periodic servicing (washing or replacement) of the TiO_2 materials may be necessary to maintain the pollution reduction effect.

It also should be noticed that the photocatalytic air purification function is usually restricted to pollutants which are absorbed on the surface of the construction materials. In widely open spaces, the pollutant removal efficiency may be low as only a small fraction of the pollutants can be trapped. It is believed that the pollution elimination effect is more easily quantified using continuous monitoring data for confined spaces when the dispersion and ventilation conditions are poor (Bygott et al, 2007).

We will assess the frequency when water could be continuously sprinkled onto to the surfaces of the roads which have been coated with TiO_2. With solar irradiation, the surface becomes highly hydrophilic due to the coated TiO_2, which minimises the amount of water consumption to form a water film. A very thin water layer of approximately 0.1 mm thickness can cover the whole building with small quantities of water supply hence avoid the washing of other toxic substances from car catalysts or other toxic particulates. Such a spraying can drop the temperature by 40–50 C on black roof-tile surfaces on a clear day in the middle of summer. Hence, TiO_2 based materials can act as promoters also energy-saving technology.

4.4 Spatial perspective

The approach of creating city profiles allowed a compact presentation of information on air quality parameters throughout the six Living Lab cities. A distinct strength of this approach is that information is displayed in a clear, easily understandable and consistent way that allows comparison between the different cases. However, as profiles only contain a certain amount and degree of information, indicators need to be chosen carefully (see chapter 2.4) in order to gain an adequate overview. Therefore, a reflection on indicator and data validity is necessary to identify strengths and limitations of the city profiles.

4.4.1 Validity of spatial data

Spatial analyses provide a decent overview of different land uses and their locations within cities. Therefore, spatial general maps provide a good first impression on a city's physique. However, the quality of spatial analyses and maps highly depends on the data's resolution and degree of information, e.g. the differentiation of land-use categories.

The datasets used in this Deliverable (Urban Atlas + CORINE) originate from the EEA, guaranteeing an EU-wide inherent methodology. However, the dataset with the higher resolution (Urban Atlas) is only available for cities above 100,000 inhabitants and therefore for just five of the six iSCAPE Living Lab cities. In comparison to the Urban Atlas data, CORINE data have a lesser resolution, affecting their overall preciseness. As an example, smaller areas of a certain land use cannot be differentiated from adjacent larger areas of another land-use category, leading to the dilemma that the smaller area is simply added to the larger area of the other land use[4].

Being aware of this limitation, the more precise Urban Atlas dataset was applied where possible (five out of six cities). However, in order to sustain comparability also for the City of Hasselt, CORINE data were additionally analysed and displayed for all six Living Lab cities (see chapter 3.4.2). Furthermore, the transparent description of the land-use category calculation

[4] An example for this dilemma can be seen in the case of Bologna, indicator 'Water bodies (%)': while Urban Atlas data identify that 0.25 % of the city's 76.88 km² total area consist of water bodies, CORINE data do not identify any areas of this land-use category.

(see chapter 3.4.1.2) allows comparison between the two datasets' results, despite their differing land-use categories.

4.4.2Indicator validity

4.4.2.1 Spatial indicators

The spatial indicators used in the city profiles designate area percentages of various land uses. At a glance, the prevailing land uses become obvious and can be compared both with other land uses of one city as well as with the land uses of other cities. The following table contrasts the area percentages of the six iSCAPE Living Lab Cities.

	Bologna	Bottrop	Dublin	Guildford	Hasselt	Vantaa
Total city area***	76.88 km²	100.27 km²	117.52 km²	270.80 km²	102.70 km²	240.33 km²
Sealed ground (%) ****	40.99* / 29.23**	24.23* / 11.06**	50.20* / 34.02**	13.70* / 5.32**	14.63**	17.71* / 18.52**
Industry and trade (%)	22.55* / 15.11**	9.08* / 6.69**	11.39* / 10.86**	8.98* / 1.02**	6.20**	7.10* / 8.66**
Traffic area (%)	14.96* / 5.32**	5.67* / 0.18**	9.32* / 0.20**	3.79* / 0.00*	0.94**	9.97* / 5.27**
Water bodies (%)	0.25* / 0.00**	1.01* / 0.46**	0.78* / 0.05**	0.58* / 0.00**	2.79**	0.62* / 0.23**
Forest (%)	1.46* / 0.59**	23.46* / 18.69**	0.13* / 0.00**	21.85* / 23.84**	7.81**	36.42* / 32.10**
Agriculture (%)	19.43* / 25.26**	30.60* / 43.92**	3.15* / 2.65**	40.84* / 56.91**	46.05**	22.76* / 20.59**
Urban green (%)	6.78* / 2.07**	2.97* / 0.64**	12.04* / 10.42**	2.47* / 0.56**	0.34**	2.74* / 2.18**
Sum Green/Blue	27.92* / 27.92**	58.04* / 63.71**	16.1* / 13.12**	65.74* / 81.03**	56.99**	62.54* / 55.1**

**) Based on Urban Atlas Data: http://www.eea.europa.eu/data-and-maps/data/urban-atlas*
***) Based on CORINE Data: http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2*
****) Based on specific municipal boundaries*
*****) The specific degree of soil sealing assumed for each land-use category is itemised in the Annexe*

Table 31: Percentages of land uses in the Living Lab cities

The spatial indicators chosen are meant to reflect the cities' urban characteristics and to help estimate whether local conditions are fostering air pollution and urban heat. Furthermore, the indicators help evaluate a city's situation in comparison to others. Dublin, for example, has the highest rate of sealed ground, indicating densely built structures. At the same time, the city has the lowest rate of green and blue areas. Guildford, on the other hand, has the lowest rate of sealed ground and more than 65% of the area covered by green and blue structures, indicating rather scattered spatial structures. This simple comparison of spatial indicators in two cities reveals the enormous differences between the cases and indicates a higher UHI potential in Dublin than in Guildford.

However, these indicators can of course only imply but never conclusively capture local conditions. Furthermore, the spatial indicators are only indicating quantities; statements on the quality of e.g. urban green spaces, their interconnection or local climatic function need to be investigated in separate analyses. As an example, urban green areas cover more than 12 % of the total area of Dublin, while in comparison with the other cities, Dublin's share of green and blue areas is quite low.

4.4.2.2 Statistical indicators

All statistical indicators are derived from the Eurostat database, a Directorate-General of the European Commission and are therefore reliable and available for all Europe. The largest limitation to most of the statistical data from Eurostat is its broad spatial resolution. An example is the indicator 'commuter outflows' within the air quality parameter 'private transport'. While, generally speaking, the commuter rate is a valid indicator for the approximation of work-related traffic, Eurostat data are solely available for NUTS[5]2 regions. In the case of Bologna, this e.g. means that commuter outflows are averaged for all of Emilia-Romagna region or in Dublin for all of Southern and Eastern Ireland.

Despite the broad resolution, the indicator is still a convenient choice for the parameter ‚private transport', as a great share of traffic takes place at a regional scale. And, however, the regions show great differences in their commuter outflow rates. While in the regions around Bologna and Dublin commuter outflows are very low (1.4 resp. 1.3), the regions around Bottrop (16), Guildford (18.2) and Hasselt (19.1) have a more than ten times higher rate. Accordingly, work-related traffic is more focused on the region or an urban centre in the regions around Bologna and Dublin than it is in the other Living Lab cities.

Concluding, the spatial and statistical indicators chosen represent a valid basis for estimating the local air pollution and urban heat parameters. Nonetheless, the indicators are coincidently subjected by limitations, which have to be kept in mind when drawing guidelines in the following chapter 5.

[5] NUTS stands for *Nomenclature of territorial units for statistics* and is a hierarchical system for spatial compartmentalization of the EU for statistical means. Therein NUTS1 reflects socio-economic greater regions (e.g. Federal States in Germany) NUTS2 reflects base regions for regional policy (e.g. Regioni in Italy) and NUTS3 smaller statisical regions like provincies or cities. (European Union, 2015)

4.5 Combinations of interventions

Solid passive methods such as noise barriers, low boundary walls and parked cars can improve local air quality and detailed strengths and limitations of these physical interventions are reported in a comprehensive review by Gallagher et al., (2015). Only a few studies have investigated the combined effect of solid passive methods and vegetation on neighbourhood air quality (Abhijith and Gokhale, 2015; Baldauf et al., 2008; Bowker et al., 2007; Tong et al., 2016). These combinations altered the pollutant dispersion characteristics at local scales when compared to that obtained with individual interventions.

Some arrangements of passive methods complimented each other in reducing pollutant exposure than individual reductions. Modelling study by Bowker et al., (2007) observed a combination of trees and noise barriers resulted in enhanced dispersion leading to reduced pollutant concentration in downwind locations. Similarly, trees with noise barrier caused additional mixing and turbulence, as well as filtering by trees led to consistent concentration reduction, was reported by Baldauf et al., (2008) who studied CO and PM concentration along the open road with and without noise barrier and vegetation in Raleigh, North Carolina. When the wind was flowing from the road, noise barrier and noise barrier with vegetation reduced concentration immediately behind a barrier and accumulated pollutants in front of barrier (windward side) and particle reduction was up to 50%. Noise barrier only case results showed a larger reduction for 20 nm particle than 75 nm and concentration of particle became equal to that of open terrain after a distance, such as 20 nm particles after 120 m and 75 nm particles after 50 m. However, PM number concentrations, behind a barrier with trees were lowest of all cases along entire distance from the road and it reduced both particles irrespective of size. The combination of trees with various spacing and size and different parking systems were analysed in a street canyon under various wind directions (Abhijith and Gokhale, 2015). Parked cars with trees improved air quality than vegetation only cases, and smaller trees with spacing and high porosity combined with parallel parking reduced pedestrian exposure in parallel and perpendicular winds. A special arrangement like windward side tree row with perpendicular car parking improved air quality in oblique wind direction. Vegetation- solid wall combination was examined near road conditions (Tong et al., 2016) which accounted for largest reduction than a solid wall or vegetation barrier alone in downwind of the barrier. The study observed combined effect of vegetation and solid wall reduced concentrations of all particle sizes. These studies indicate special arrangements of vegetation and solid passive methods could provide low pollutant exposure in both street canyon and open road conditions. Further real world studies are needed for validation and practical application of outcomes.

5 Conclusions and recommendations for the interventions

5.1 Physical PCS

The review process of each physical passive method for improving air quality shows some concluded preliminary guidelines and points that can be recommended, which are discussed in this section.

5.1.1 Conclusions for the use of noise barriers

The summarised important points, recommendations and some guidelines regarding the use of noise barriers as physical control systems are presented as following:

- Both modelling and measurement studies have reported consistent reductions in pollutant concentrations downwind of the barrier and an increase in upwind concentrations has been reported because of the recirculation of pollutants in the zone in front of the structure.

- The reattachment of a plume downwind of a noise barrier could lead to higher concentrations further downwind of the barrier compared to no barrier.

- The height and layout of the noise barrier present the greatest effect on the dispersion of pollutants along the highway.

- Wind conditions have a significant impact on pollutant transport and air quality along arterials and highways when the noise barrier exists.

- Noise barriers are a feasible passive method of pollution reduction and present less variable factors in their effectiveness than porous barriers as concluded by (Gallagher et al., 2013a).

- Guidelines require development that can respect the both functions of the barriers, so the studies should examine the impact of noise barrier design on both noise levels and air pollution.

5.1.2 Conclusions for the use of LBWs

The summarised important points, recommendations and some guidelines regarding the use of LBWs as physical control systems are presented as following:

- LBWs act as a baffle at street level and increase the distance between the pollutant source and human receptor.

- Both measurements and modelling studies show LBWs as an effective physical passive control method.

- Reductions in pollutant concentrations have been reported on the footpaths in most wind conditions when LBWs exist.

- Low wind speeds, wall and canyon geometry impact the effectiveness of the LBWs to promote dispersion and the development of vortices in street canyons, that moves pollutants to the roof level.

- Negative effects on air quality were measured on the leeward footpath from model simulations for perpendicular wind conditions, where the LBWs exist.

- More research is needed in order to develop guidelines to provide practical instructions for implementing LBWs in a street canyon environment.

- An increase in the pollutants concentrations in the road can be reported when the LBWs exist.

5.1.3 Conclusions for the use of parked cars

The summarised important points, recommendations and some guidelines regarding the use of parked cars as physical control systems are presented as following:

- Parked cars are presented as a higher and wider barrier than a LBW.

- The gaps between cars and the presence of empty spaces allow the direct moving of pollutants from the street to the footpaths.

- Modelling studies for different parking configurations reported that the parking bay layout and occupancy rate have impacts on the pollutant dispersion.

- As parallel parked cars provided improvements in air quality in all wind conditions.

- Due to the spacing between vehicles, parked cars impact air flow differently to the other barrier types.

- Car parking bay designs in street canyons present great potential to improve local air quality in the built environment.

5.2 Green infrastructure

As discussed in previous sections, formulation of guidelines for implementing green infrastructures is difficult to form current published works. Instead of generalised recommendations, site-specific design solutions are required for implementing vegetation in street canyons whereas generalised guidelines can be formulated for open street conditions as built environment features are similar in later. Prior to implementing vegetation in street canyons, pilot modelling investigations can give possible locations and vegetation parameters for least polluted conditions. As far as green wall and green roofs are considered further investigation is required to develop recommendations. Comprehensive intercomparison between vegetation types is essential for finalising most suitable vegetation for a specific urban location. Even though, some general observations on vegetation improvement of air quality can be made out of this study.

- Under *street canyon* conditions trees general had a negative impact on air quality and hedges had a positive impact. A majority of investigations reported 26 to 96% increase in concentrations of different pollutants due to the presence of trees in street canyon compared with those without the trees. Even though oblique wind direction was identified as critical wind direction; improvement or deterioration air quality in street canyon depends on a combination of aspect ratio, vegetation density and wind direction. Increasing space between trees and reducing cross-sectional area occupied by the canopy (through increased pruning, selecting smaller trees) can reduce the personal exposure. Available real world studies show surrounding built-up geometry can alter pollutant concentration profile in street canyon. Limited studies on hedges in street canyon showed improvement in air quality and able to propose optimum height of hedge in the shallow street canyon; detailed studies are required to provide favourable hedge dimensions and densities in different aspect ratios and meteorological conditions.
- Under open road conditions, vegetation barriers had a positive impact on air quality in general. The majority of the studies reported reductions in concentrations of between 15% and 60% for various pollutants with vegetation barriers along open roads. Studies observed considerable pollutant removal through designing vegetation barrier thickness and position with respect to the distance between source and plume’s maximum concentration. A reduction of different pollutants over 50% was observed with a green belt of 10m thickness. Optimum density of vegetation barrier was suggested by various studies. Relative humidity showed significant impact on pollutant removal by green belts. Evergreen trees were proposed for vegetation barrier in open road condition. Vegetation impact on air quality varied among warmer and cooler climatic regions which needed to be investigated further.
- Arrangements of hedges or smaller shrubs in front and trees behind the structure of green belts are observed to reduce pollutants downwind.
- Vegetation density has been accounted by dissimilar parameters in published investigations. Study observed standardisation in expressing vegetation density is important to facilitate comparison of study outputs and to create generalised recommendations
- The combination of vegetation and solid passive air pollution control measures displayed an improved reduction in personal exposure than the individual reduction in both street canyon and open road conditions.
- Only a few studies investigated air quality improvement of green roof and green walls. Reduction in air pollutants about 20% or greater was reported with green walls and in the case of the green roof, the same was 9% or above. However, their ability to remove pollutants were lesser compared to trees and vegetation barrier. Among green wall and green roof, pollution reduction of green roof was inferior to the green wall. Even though these intervention needs less special requirements than trees and green belts and can be attached to a various structure such as bridges, flyovers, retaining walls, and noise barriers, further investigation required to produce generic recommendations.

5.3 Photocatalytic coatings

In iSCAPE, the interventions that will be applied is based on the assessment of the area where PURETi material will be employed before and after a testing period of two weeks. We will assess two urban sites with strong photochemical activity in South Europe and one site in North Europe. This will consistently report the gains in air quality from photocatalysis and will help in promoting the utilised coatings in large urban areas. For measurements, we will use several devices based on sensor technologies with the most accurate technologies. For reference purposes, we will also analyse the concentrations obtained from all surrounding conventional air-quality stations for identifying the cluster of occurring conditions during similar meteorological periods. The local effectiveness will be based on gains from the local measurements with photocatalytic coatings against the values measured during corresponding periods when the coatings were not deployed.

Since we use consistent coating we will be able to generalise for several types of urban pollutants as per the following paragraphs.

- Nitrogen dioxide

The degradation of nitrogen dioxide in the form essentially soluble nitrates in water and, where appropriate nitrates. The amount formed of these species is very limited so that they do not constitute a problem for cleaning with water which afterwards is disposed within the normal pluvial system. If the coatings are not exposed, the calcium nitrate molecules, resulting from the reaction of photooxidation, remain in the photocatalytic surface as inert substances.

- Carbon monoxide

The oxidation of carbon monoxide leads to the formation of carbon dioxide that is virtually inert substance. The carbon monoxide could also be oxidised by the OH radicals leading to the formation of hydrogen radicals (H). These radicals react rapidly with atmospheric oxygen to form hydroperoxide radicals: $H + O_2 \Rightarrow HO_2$
The latter possesses much more strong oxidising properties of the OH radical, for which the carbon monoxide could thus amplify the oxidising properties of the photocatalytic surface with an obvious increase in its purification capacity.

- Benzene

The benzene degradation of photocatalytic surfaces proceeds at very low speed because of the poor reactivity of the benzene towards the OH radical. The oxidised molecules can still turn into simpler compounds such as aldehydes or bivalency acids that do not have any environmental effect. Alternatively, it can be assumed that the Benzene can add OH radicals and then transformed into phenol, which is soluble in water substance, hence with little environmental interest because of the low reported concentrations.

- Sulphur dioxide

The sulphur dioxide is oxidised to sulphuric acid and afterwards immediately adsorbed by the substrate of the alkaline photocatalytic surface. The result is the formation of calcium sulphate, weakly soluble in water. The calcium sulphate, commonly known as gypsum, is not a problem for the environment.

- Formaldehyde

The formaldehyde is degraded to carbon monoxide or carbon dioxide. Because the concentration of formaldehyde is relatively small, also the concentrations of the formed products will be very low and in any case lower than about 100 times those normally present in the atmosphere. The eventual oxidation of formaldehyde would lead to the formation of carbon dioxide and in formic acid traces that would still be absorbed by the alkaline substrate of the photocatalytic surface.

- Aero-disperse Particulate Matter

The evolution of the particulates on the photocatalytic surfaces is still the subject of scientific evaluation. The particles constituting the particulate matter in atmospheric pollution are also probably attracted on the surface of the coatings due to the presence of the free charges. Once on the surface, the particles may react with free radicals or with water molecules and oxygen, degrading to soluble.

5.4 Spatial perspective

This section aims at developing transferable guidelines and recommendations on how to approach air quality and urban heat from a spatial perspective. In order to achieve transferability to other cities besides the iSCAPE Living Lab cities, guidelines will be derived along with the three most common urban development models (see subchapter 5.4.1). Subsequent, the models are assessed in the light of air quality and local climate (see subchapter 5.4.2) and guidelines are drawn (see subchapters 5.4.3-5).

5.4.1Urban development models

5.4.1.1 The compact city

The urban development model of the compact city is an internationally discussed and broadly accepted spatial guiding principle in urban planning in Europe (Burton et al., 2003; van Stigt et al., 2013; Tian et al., 2014). The model describes the counteraction of urban sprawl by refocusing on the quality of inner-city districts.

Figure 9: The model of compact city (LEP B-B, 2006, p. 27)

The model of the compact city is characterised by a concentrated and resource-efficient settlement development. Accordingly, the different land uses within a city (residential areas, business districts, industry and trade, urban green etc.) are in direct proximity, promoting a functional mix. Public transport is attractive to overcome the in general short distances. This model is also known as "new urbanism" and "smart growth". Summarising, the urban development model of the compact city is characterised by the following aspects (Greiving and Fleischhauer, 2009; Mitchell et al., 2011):

High-density settlement development within existing urban areas (reduction of land usage)
Functional mix of land uses instead of mono-functional areas
Attractive and efficient public transport systems, strengthening of local connections

5.4.1.2 The decentralised city

The urban development model of a decentralised city evolved in the 1980s as a reaction to the continuous urban sprawl, resulting from suburbanization processes. Suburbanisation describes the outward migration of population and compact cities' function to the suburbs and beyond.

Figure 10: The model of decentralised city (LEP B-B, 2006, p. 27)

The urban development model draws on the diffusion of the compact city and promotes a revaluation of disperse settlement structures by focusing on a spatial development outside the core city (Knieling et al., 2012). Characteristics of decentralisation can also be found in other models such as „Edge City" or „Postsuburbia" (LEP B-B, 2006).

The urban development model of a decentralised city is characterised by the following aspects:

- Population and core city functions are spread across a complex network of central and less central places instead of being concentrated in a dominant core city
- Nodal points have less concentration and are not bound by hierarchical centralization patterns. However, these networks of nodal points are significantly more finely woven
- No clear distinction between open spaces and densely populated settlement areas is possible. In contrast, open spaces and loosely built-up areas form a mosaic similar structure (LEP B-B, 2006).

5.4.1.3 Decentralized concentration

The spatial model of „decentralised concentration" has evolved in reaction to the two spatial models described above and may be described as a combination of both. It combines large-scale decentralisation and small-scale compact settlement structures with high density and high amounts of open spaces. Therefore, spatial decentralisation and concentration are being applied on different scale levels (Greiving and Fleischhauer, 2009).

Figure 11: The model of decentralised concentration (LEP B-B, 2006, p. 27)

The model of decentralised concentration focuses at counteracting disperse settlement development in order to develop and maintain a balanced spatial development. The model roots from various other urban development models. In the view of Knieling et al. (2012) "decentralised concentration" originates from Ebenezer Howard's "Garden City" model. The German Academy for Spatial Research and Planning (ARL) states the model's evolution from the "Central Place Theory" by Walther Christaller (ARL, 2016).

Summarising, the urban development model of decentralised concentration is characterised by the following aspects:

- Development of decentralised centres and small-scale networks by concentration of settlement development and infrastructures in centres along the main transportation axes (Greiving and Fleischhauer, 2009)
- The small decentralised centres are being developed following the principles of the compact city (Greiving and Fleischhauer, 2009; Knieling et al., 2012)
- Prevention of spatial disparities and overburdening in growth regions; instead strengthening of the "endogenous regional potential" (ARL, 2016)

5.4.1.4 Classification of Living Lab cities

Based on the description of the characteristics of the urban development models, each of the six Living Lab cities can be predominantly assigned to one of the models. The classification including the decisive characteristics is shown in the following table.

	Compact City	**Decentralised City**	**Decentralised Concentration**
Bologna	High population density (2,720 inhabitants per km^2)		

	Large area of sealed ground (40, 99%) Attractive and efficient public transport		
Bottrop			Two settlement centres, instead of one core city Settlement development along transport axes
Dublin	High population density (4,526 inhabitants per km^2) Large area of sealed ground (50, 20%) Attractive and efficient public transport		
Guildford			Core city can be identified. However, there are several smaller centres around the core city. These smaller centres are interconnected by axes
Hasselt			Core city can be identified. However, there are several smaller centres around the core city. These smaller centres are interconnected along axes on which new development can be seen.
Vantaa		No dominant core city No clear distinction between open spaces and built-up areas Dispersed and mosaic similar settlement structure	

Table 32: Classification of Living Lab cities according to urban development models

5.4.2 Assessment of urban development models

In the following, the characteristics of the three urban development models are assessed regarding their significance towards air quality and local climate.

5.4.2.1 Assessment of the compact city

In a compact city, vehicle kilometres travelled per inhabitant are generally lower than in the other urban models due to rather short distances and well-developed public transport. Concomitant, carbon emissions from private transport are reduced. Additionally, compact cities have a favourable environmental balance due to their concentrated surface sealing (protection of the countryside, low urban sprawl) and a good modal split (Mitchell et al., 2011; Greiving and Fleischhauer, 2009).

These advantages of a compact city can be exemplified with the cities, Bologna and Dublin. According to the European Commission, more than 20% of the respondents to the 'survey on the perception of quality of life' in both cities use public transport on a daily basis (EC, 2010).

Further advantages of compact cities are the maintenance of city-centre vitality (Mitchell et al., 2011) and a low-cost balance as infrastructure systems are also compact and no long, energy-consumptive transmission needed (Greiving and Fleischhauer, 2009).

However, there also are disadvantages to the urban development model of compact cities. Usually, compact cities are at risk of being too compact, meaning if urban green spaces are giving way to further settlement development, local recreation gets more and more restricted and people might even commute to the periphery for recreational purposes, creating transport emissions (Greiving and Fleischhauer, 2009).

Furthermore, not only settlement structures but also emissions appear concentrated in a compact city, having a high impact on the densely living and working population. Also, ventilation is often restricted in a compact city, increasing, in combination with a considerable degree of sealed surface and building structure, the UHI potential (Greiving and Fleischhauer, 2009).

5.4.2.2 Assessment of the decentralised city

Decentralised cities have the advantage that ventilation is usually decent as they have a high share of green spaces and no highly condensed core centre. The city of Vantaa is a suitable example for a decentralised city with over 60% of its area being green and blue spaces contrasting only 18% sealed surface. A decentralised settlement structure generally offers the opportunity for high-quality design of settlement and green structures (LEP B-B, 2006).

However, the urban development model of a decentralised city is highly criticised due to the urban sprawl, the fragmentation of landscape and the accompanying impairment of eco functions such as loss of biodiversity and arable land (LEP B-B, 2006). Moreover, disperse settlement structures hold the risk of encouraging private transport and consequently trigger traffic-induced CO_2 emissions, as often public transport is underdeveloped due to high maintenance costs and the dominance of many-to-many travel directions that makes any public transport quite inefficient.

5.4.2.3 Assessment of decentralised concentration

In the model of decentralised concentration, the stress on the core centre is lightened as the settlement structure consists of various smaller centres. Furthermore, spatial disparities are reduced and agglomerated regions are strengthened (ARL, 2016). At the same time, suburbanization processes are prevented due to a point-axial development. In the ideal realisation of the urban development model, there is less settlement pressure than in the compact city, green spaces can be preserved and even connected so that eco functions remain high and the UHI potential is lowered (Greiving and Fleischhauer, 2009; Knieling et al., 2012) .

However, the sophisticated supply infrastructure that exists within cities belonging to the model of decentralised concentration may as well be understood as its greatest threat. If the infrastructure is well developed until wide in the periphery, further land consumption may become an option (Greiving and Fleischhauer, 2009).

5.4.3 Guidelines for compact cities

From a spatial perspective, the following guidelines can be summarised for cities applying to the urban development model of a compact city:

- Positive characteristics as e.g. a sophisticated public transport network and operation should be preserved.
- Further settlement development should take place with respect to the preservation of urban green spaces.
- Possibilities for settlement compression need to be weighed carefully against the opportunity for green space development and should consider ventilation and UHI potential.
- Existing green and blue spaces should interlink best possible, in order to enable fresh air transport.
- Existing green and blue spaces should be qualitatively developed and re-evaluated in order to explicitly foster climatic and air quality functions (Cohen and Potchter, 2010).
- Especially in dense structures, space-saving solutions of urban green need to be found, as e.g. façade greening and green roofs. Both types of urban green are able to reduce urban heat, especially in core cities (Filho, 2016). Furthermore, extensive green roof systems are able to filter fine dust particles (Steyn and Castell, 2010)
- Roadside greenery can help filter transport emissions if planted and maintained with respect to ventilation and fresh air corridors (MKULNV NRW, 2011).
- Measures aiming at a reduction of private transport can actively be implemented e.g. through a reduction of parking spaces in the core city centre, the introduction of vehicle tolls, closure of roads for motorised vehicles or an increase of parking fees (Onursal and Gautam, 1997).

A good practice example can be taken from the city of Bologna. In Bologna, the threats of a compact city have been recognised and measures have been set up: „Bologna, like many Southern European cities, is facing drought, extreme temperatures and water scarcity as a result of climate change. With no national or regional adaptation action plan still in place, the city of

Bologna took it upon them to draft an Adaptation Plan to Climate Change. The plan, which was approved by the City Council on October 2015, focuses on the development of innovative, concrete measures that could be tested locally. These measures were developed as part of the LIFE+ project BLUE AP (Bologna Local Urban Environment Adaptation Plan for a Resilient City). One of the successful initiatives that contribute to reaching the local target is the "green areas inner-city agreement" (developed within Life+ project GAIA). This initiative shows how the financing and realisation of additional green areas in the city to provide relief under heat waves were successfully undertaken." (EEA, 2016)

Remark: Maintaining a compact city model requires a so-called conforming land-use planning system (Rivolin, 2008). Building permissions must only be granted if an investment is in line with the graphical designation laid down in a legally binding land-use plan (that demarks settlement zones and preserves open spaces).

5.4.4 Guidelines for decentralised cities

From a spatial perspective, the following guidelines can be summarised for cities applying to the urban development model of a decentralised city:

- On-going decentralisation tendencies need to accepted but picked up in development concepts, which focus on a concentration of jobs and public functions (LEP B-B, 2006).
- Further settlement development should be conducted in line with the urban development model of decentralised concentration, i.e. along existing axes and with a local focus on concentration.
- A good functional mix should be aimed at in order to reduce distances.
- Public transport should be enlarged, especially between cities, so that it becomes an alternative to private transportation.
- Other private transport reduction measures, like car sharing, could be fostered.
- Environmental functions like the production of ground water, cool air or valuable habitats need to be protected either by land-use planning or environmental planning in order to mitigate the negative effects of the further expansion of settlements and infrastructure.

A good practice example can be taken from the city of Vantaa. Vantaa is actively working on a reduction of private transport emissions and a shift to public transport. The local public transport provider Helsingin seudun liikenne (HSL) is promoting sustainable mobility: „The aim is to encourage people to reduce driving alone in their cars and increase walking, cycling, use of public transport, car sharing, ride sharing and economic driving. Good public transport services, town planning and locating services and jobs close to housing reduce the need to use a car on a daily basis. " (HSL, 2017).

5.4.5 Guidelines for cities with decentralised concentration

From a spatial perspective, the following guidelines can be summarised for cities applying to the urban development model of a decentralised concentration:

- Positive characteristics as e.g. an adequate mix of functions and sophisticated public transport should be preserved.

- Further settlement development should take place with respect to the preservation of urban green spaces and especially the maintenance of ventilation channels and other ecologic functions such as groundwater production, habitats, etc.
- Existing green and blue spaces should be qualitatively developed and re-valuated in order to explicitly foster climatic and air quality functions (Cohen and Potchter, 2010).
- In denser settlement structures, space-saving solutions of urban green can be enhanced, as e.g. façade greening and green roofs. Additionally, roadside greenery can help filter transport emissions if planted and maintained with respect to ventilation and fresh air corridors (MKULNV NRW, 2011).
- Measures aiming at a further reduction of private transport can actively be implemented e.g. through a reduction of parking spaces in the core city centre, the introduction of vehicle tolls, closure of roads for motorised vehicles or an increase of parking fees (Onursal and Gautam, 1997).

Remark: Maintaining a model of decentralised concentration requires a so-called conforming land-use planning system (Rivolin, 2008). Building permissions must only be granted if an investment is in line with the graphical designation laid down in a legally binding land-use plan (that demarks settlement zones and preserves open spaces).

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Annex

Land use class	Key for calculation of basic information for each town							Map
For further information on which land use is contained in which land use class look at: http://www.eea.europa.eu/data-and-maps/data/urban-atlas/ **for Urban Atlas data and** http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2/ **for CORINE data**	**Degree of soil sealing assumed for each land use**	**industrial and commercial area**	**traffic area**	**water area**	**forest area**	**agricultural area**	**green urban area**	**legend**
Urban Atlas								
Agricultural + Semi-natural areas + Wetlands	0%	No	No	No	No	Yes	No	
Airports	100%	No	Yes	No	No	No	No	
Construction sites	50%	No	No	No	No	No	No	
Continuous Urban Fabric (S.L. > 80%)	90%	No	No	No	No	No	No	
Discontinuous Dense Urban Fabric (S.L. : 50% - 80%)	65%	No	No	No	No	No	No	
Discontinuous Low Density Urban Fabric (S.L. : 10% - 30%)	20%	No	No	No	No	No	No	
Discontinuous Medium Density Urban Fabric (S.L. : 30% - 50%)	40%	No	No	No	No	No	No	

Discontinuous Very Low-Density Urban Fabric (S.L. < 10%)	**5%**	**No**	**No**	**No**	**No**	**No**	**No**	
Fast transit roads and associated land	**100%**	**No**	**Yes**	**No**	**No**	**No**	**No**	
Forests	**0%**	**No**	**No**	**No**	**Yes**	**No**	**No**	
Green urban areas	**0%**	**No**	**No**	**No**	**No**	**No**	**Yes**	
Industrial, commercial, public, military and private units	**50%**	**Yes**	**No**	**No**	**No**	**No**	**No**	
Isolated Structures	**15%**	**No**	**No**	**No**	**No**	**No**	**No**	
Land without current use	**0%**	**No**	**No**	**No**	**No**	**No**	**No**	
Mineral extraction and dump sites	**10%**	**No**	**No**	**No**	**No**	**No**	**No**	
Other roads and associated land	**100%**	**No**	**Yes**	**No**	**No**	**No**	**No**	
Port areas	**100%**	**Yes**	**No**	**No**	**No**	**No**	**No**	
Railways and associated land	**50%**	**No**	**Yes**	**No**	**No**	**No**	**No**	
Sports and leisure facilities	**10%**	**No**	**No**	**No**	**No**	**No**	**No**	
Water bodies	**0%**	**no**	**No**	**Yes**	**No**	**No**	**No**	

Land use class	Key for calculation of basic information for each town							Map
For further information on which land use is contained in which land use class look at: http://www.eea.europa.eu/data-and-maps/data/urban-atlas/ **for Urban Atlas data and** http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2/ **for CORINE data**	**Degree of soil sealing assumed for each land use**	**industrial and commercial area**	**traffic area**	**water area**	**forest area**	**agricultural area**	**green urban area**	**legend**
CORINE								
Continuous urban fabric	90%	No	No	No	No	No	No	
Continuous urban fabric	30%	No	No	No	No	No	No	
Industrial or commercial units	50%	Yes	No	No	No	No	No	
Road and rail networks and associated land	75%	No	Yes	No	No	No	No	
Port areas	100%	Yes	No	No	No	No	No	
Airports	100%	No	Yes	No	No	No	No	
Mineral extraction sites	10%	No	No	No	No	No	No	

Dump sites	**10%**	**No**	**No**	**No**	**No**	**No**	**No**	
Construction sites	**50%**	**No**	**No**	**No**	**No**	**No**	**No**	
Green urban areas	**0%**	**No**	**No**	**No**	**No**	**No**	**Yes**	
Sport and leisure facilities	**10%**	**No**	**No**	**No**	**No**	**No**	**No**	
Non-irrigated arable land	**0%**	**No**	**No**	**No**	**No**	**Yes**	**No**	
Fruit trees and berry plantations	**0%**	**No**	**No**	**No**	**No**	**Yes**	**No**	
Pastures	**0%**	**No**	**No**	**No**	**No**	**Yes**	**No**	
Complex cultivation patterns	**0%**	**No**	**No**	**No**	**No**	**Yes**	**No**	
Land principally occupied by agriculture, with significant areas of natural vegetation	**0%**	**No**	**No**	**No**	**No**	**Yes**	**No**	
Broad-leaved forest	**0%**	**No**	**No**	**No**	**Yes**	**No**	**No**	
Coniferous forest	**0%**	**No**	**No**	**No**	**Yes**	**No**	**No**	
Mixed forest	**0%**	**No**	**No**	**No**	**Yes**	**No**	**No**	
Natural grasslands	**0%**	**No**	**No**	**No**	**No**	**Yes**	**No**	
Moors and heathland	**0%**	**No**	**No**	**No**	**No**	**Yes**	**No**	

Transitional woodland-shrub	**0%**	**No**	**No**	**No**	**Yes**	**No**	**No**	
Beaches, dunes, sands	**0%**	**No**	**No**	**No**	**No**	**Yes**	**No**	
Salt marshes	**0%**	**No**	**No**	**No**	**No**	**No**	**No**	
Intertidal flats	**0%**	**No**	**No**	**No**	**No**	**No**	**No**	
Water courses	**0%**	**No**	**No**	**Yes**	**No**	**No**	**No**	
Water bodies	**0%**	**No**	**No**	**Yes**	**No**	**No**	**No**	
Estuaries	**0%**	**No**	**No**	**Yes**	**No**	**No**	**No**	
Sea and ocean	**0%**	**No**	**No**	**Yes**	**No**	**No**	**No**	