Strategic portfolio choice
Deliverable 5.4 iSCAPE project

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Strategic portfolio choice

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Short Description	*This deliverable presents a summary of the intervention characteristics, impacts on air pollution and limitations of the interventions. These summaries are partly based on the work presented in the previous deliverables and partly on new material presented for the first time. The deliverable shows that the iSCAPE interventions have many desirable properties, although more research is required before an accurate quantification of the advantages and disadvantages of the interventions can be performed. This report, together with D5.3 – Report on Interventions, concludes Task 5.3 of the iSCAPE project.*

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List of abbreviations

BC	–	Black Carbon
CC	–	Climate Change
CFD	–	Computational Fluid Dynamics
DALY	–	Disability Adjusted Life Years
GI	–	Green Infrastructure
LAD	–	Leaf Area Density
LBW	–	Low-Boundary Wall
PEATB	–	Pro-environmental activity Travel Behaviour
PM	–	Particulate Matter
PNC	–	Particle Number Concentration
PT	–	Public Transport
VKT	–	Vehicle Kilometres Travelled
WP	–	Work Package

1 Executive Summary

Air pollution is one of the main environmental health problems in Europe (Annesi-Maesano, 2017) with more than 400,000 premature deaths caused per year (Guerreiro et al., 2018). To alleviate this problem different approaches can be taken, where focus in the present report is on physical/technological rather than legislative approaches. The focus of the iSCAPE project is on a range of interventions designed for reducing air pollution exposure. These interventions are characterised by having a shorter implementation time compared to other approaches. The present report summarises the intervention characteristics and optimal use covering both exposure and socio-economic impacts and is targeted towards a general audience. The following characteristics, advantages and disadvantages have been shown for the individual interventions:

- Hedges are characterised by being elongated vegetation of low average height and low width compared to height. Several studies have reported air pollution reductions behind hedges due to deposition on the vegetation and enhanced dilution (see Abhijith et al. (2017) for a review). In the iSCAPE project, a field campaign was carried out on two hedges in Guildford, UK which measured changes in particulate species as a result of the hedge. The field methodology and the results of the field campaign are summarised in section 4.1. Air pollution reductions up to 43% were measured for geometries consisting of hedges only, and reductions up to 52% were measured for geometries consisting of both hedges and trees. The largest concentrations were measured for along-road wind directions. Further information on these results can be found in Abhijith and Kumar (2019). On the other hand, hedges also have limitations such as the effect decreasing with downwind distance, negligible effects of low-height hedges, and deciduous hedges losing their leaves during winter and thus providing smaller barrier effect.
- Trees interact with air pollution in a number of ways such as increasing dry deposition of air pollutants, increasing the roughness length thus leading to reduced wind speeds and increased turbulence, as well as direct emission of pollen, fungal spores and biogenic volatile organic compounds. The literature has reported air pollution reductions caused by trees in open road conditions and increased air pollution caused by trees in street canyons (see Abhijith et al. (2017) for a review). In the iSCAPE project, the effect of trees on air pollution was evaluated through one field campaign, targeting open-road conditions, carried out in Guildford, UK, (summarised in section 4.1); two modelling studies on the urban scale were carried out in Guildford, UK (summarised in section 5.1) and in Bologna, Italy (summarised in section 4.3). The effect of trees on air pollution and air temperature was moreover analysed in two intensive experimental field campaigns, carried out in two street canyons in Bologna, which enabled also the collection of observations used to validate the high resolution CFD (Computational Fluid Dynamics) numerical simulations (summarised in section 4.3). The field campaign in Guildford, UK showed no pollution reduction behind the trees at breathing height. The results of the experimental campaigns and of the modelling study for Bologna, Italy showed generally a reduction of pollutants considering the whole neighbourhood area of the street canyon, especially close to the intersections and local pollution hotspots. The reduction in pollutant concentration depends mostly on wind direction, reaching values up to 40%. In addition, the insertion of trees in a canyon also lead to a more uniform distribution of pollutants. The modelling study on the urban scale for Guildford, UK showed air pollution reductions of 18.6 %, 12.9 % and 8.6 % for respectively NO_x, PM_{10} and $PM_{2.5}$ as a result of the green infrastructure. This discrepancy between little effect or even negative effect on street and local scale and positive effect on urban scale is a hindrance to more widespread use of trees for air pollution abatement, and calls for further research. The same is true for selection criteria such as height, width and tree species, which are likewise under researched topics.

- A low-boundary wall is characterised as being a solid impenetrable structure placed parallel to the emission source with a height of 1 m – 2 m. The literature has reported from increases up to 25 % in pollution concentrations to reductions up to 75 % as a result of the LBW. In Dublin, Ireland, two experimental campaigns were carried out to measure the effect of a low-boundary wall (summarised in section 4.2). The results show air pollution reductions up to 43% for most species with the exception of NO_2 showing an increase in concentrations behind the wall. Depending on the exact position of the LBW, and the geometry and wind conditions of the street, the LBW can shift air pollution from one location to another. Depending on the circumstances, this may be desirable or not.
- Photocatalytic coating is a coating for building facades etc. which is designed for reducing NO_x pollution through oxidation. The effect of the photocatalytic coating intervention was studied through one intensive experimental field campaign in Lazzaretto site in the outskirts of Bologna, Italy, whose results served both to analyse thoroughly the effect of the coating in real street canyons and to verify the setup of a computational fluid dynamic modelling study (summarised in section 5.3). The results of the numerical simulations showed reduction of up to 40 % in the vicinity of the wall in the presence of photocatalytic coating. The results also showed strong dependency on temperature, solar radiation, wind speed and direction. A disadvantage of the use of photocatalytic coating is that the effect diminishes with distance to the wall.
- An action plan as a policy instrument for urban design and planning sets tailor-made objectives, coordinates measures and bundles them. Apart from organisational measures, it also includes technical measures to mitigate air pollution and the urban heat island effect. Through coordinated implementation within an action plan, urban planners are able to consider possible interactions between measures such as synergies or conflicts. The action plan on urban level has been developed for Bottrop and Hasselt on the basis of an iterative process and includes field trials with exemplary interventions (summarised in section 6.1). On this basis, a critical reflection of already implemented measures has been conducted and can be used as lessons learned for other target cities. Furthermore, the action plan presents general recommendations for developing successful action plans that can be adopted by other European cities.
- Behavioural interventions are characterised by providing information to the citizens that enables them to make environmentally friendly choices. The literature has shown that successful behavioural interventions depend on identifying a target group and subsequently analysing the barriers and benefits perceived by said target group to the desirable change in behaviour. In the iSCAPE project, individual travel behaviour was recorded using a smartphone application, and suggestions for more environmentally friendly modes of transport were subsequently fed back to the user (summarised in section 6.2). The intervention was tested in Hasselt, Belgium. The efficiency of the behavioural intervention was assessed by monitoring the pro-environmental activity travel behaviour indicator before and after the intervention. The results show that the informational strategy has some influence on the travel behaviour routine of the individuals. The limitations of the interventions relate to the study design, as only one season (summer) was analysed in the study, as well as the lack of availability of high-resolution air pollution concentration data.
- Based on the portfolio analysis, a mix of green infrastructure and behavioural interventions will bring the highest benefits (summarised in section 7). In case the NO_2 concentration level within the area is more than 20 $\mu g/m^3$, also photocatalytic coating and low-boundary walls would bring health benefits above their costs

In this way, the iSCAPE project has contributed with important methodological developments to the air pollution community and contributed to a better understanding of the advantages and disadvantages of the respective passive control systems. Part of the limitations of the passive control systems relate to topics not studied in the iSCAPE project, and these thus constitute potential research topics in the coming years.

2 Introduction

Air pollution is one of the main environmental health problems in Europe (Annesi-Maesano, 2017) with more than 400,000 premature deaths caused per year (Guerreiro et al., 2018). To alleviate this problem different approaches can be taken, where focus in the present report is on physical/technological rather than legislative approaches:

1. Emission of air pollutants can be reduced through the implementation of cleaner technology in e.g. vehicles and industry, thus leading to lower concentrations.
2. Nature-based or man-made barriers can be inserted between the source and the receptor leading to lower personal exposure locally.
3. Personal protective equipment such as face masks can be used to protect the citizens e.g. when walking or bicycling.
4. Changing the physical environment of the city (e.g. urban green space, development of housing areas, density, transport infrastructure, sealing) can lead to lower air pollution concentrations.
5. Changing behaviour of the citizens through provision of information (e.g. in the form of route advise) can lead to a lower personal exposure.

The iSCAPE-project's focus is on the second, fourth and fifth approaches in the form of a range of interventions designed for reducing air pollution exposure. These interventions are characterised by having a short implementation time compared to the first and third approach mentioned above. The present report summarizes the intervention characteristics and optimal use covering both exposure and socio-economic impacts and is targeted towards a general audience.

This report together with the "Report on interventions" (Deliverable 5.3) completes Task 5.3 of the fifth work package (WP) of the iSCAPE project. This WP covers air pollution and meteorological measurements, air pollution and climate modelling, as well as socio-economic impact assessment of both physical (e.g. low-boundary wall and urban green infrastructure), behavioural (e.g. informational interventions) and engagement (e.g. Living Lab activities) interventions. Task 5.3 is entitled "Evaluation of interventions" and consists of two parts:

1. Environmental impact assessment, where cases with and without the interventions will be assessed using scenario modelling.
2. Socio-economic impact assessment where the methodology developed in Task "Definition of the socio-economic impact assessment methodology" (Task 5.5) will be applied to evaluate the interventions.

An overview of the iSCAPE interventions along with the state of the knowledge before the iSCAPE project started is presented in Section 3. The following sections detail the methodology used in the evaluations of the interventions and the results from the evaluations.

3 Overview of iSCAPE interventions

This section provides an overview of the iSCAPE interventions. The working mechanisms of the interventions and the spatial and temporal scales of the interventions will likewise be described.

A categorisation of the iSCAPE interventions according to selected properties is given in Table 1. As can be seen, the iSCAPE interventions are a heterogeneous collection of interventions differing on aspects such as spatial scale and timescale for implementation. Some of the iSCAPE interventions operate on the street scale, some on the neighbourhood scale and some on the urban scale. In general, the larger the area affected by the intervention, the longer the timescale required for its implementation. The exception to this rule is the behavioural interventions, which works on the urban scale but can be implemented on a short timescale, since it does not require changing the physical infrastructure of the city for which it is implemented.

Intervention:	**Spatial Scale**	**Timescale**
Low boundary walls (section 4.2)	Street	Short
Hedges in open-road environments (section 4.1)	Street	Short
Trees in street canyons (section 4.3)	Street	Short
Trees (section 5.1)	Neighbourhood	Medium
Green walls and roofs (section 5.2)	Neighbourhood	Medium
Photocatalytic coating (section 5.3)	Neighbourhood	Medium
Action plan (Urban development planning) (section 6.1)	Urban	Medium to long
Behavioural intervention (section 6.2)	Urban	Short

Table 1 Overview of the properties of the air pollution interventions in the iSCAPE project. Following the classification from Barlow (2014), street scale can be defined as 10 m – 100 m, neighbourhood scale as 100 m – 1000 m, and city scale as 10 km – 20 km. The timescale is a relative timescale.

The *street scale interventions* are characterised by taking up little space in the urban environment. This is an advantage, since space is often a scarce resource in many cities of Western Europe. Moreover, these interventions are characterised by creating large air pollution reductions compared to their price and operate in the interface between the source and the receptor of air pollution. For hedges and trees, these interventions have the advantage of being visually appealing and of contributing to a more comfortable urban microclimate in the form of increased air humidity (even though this can also be a drawback in warm climates), increased shadow, and increased infiltration for rainwater. These interventions also have the advantage that they can be applied precisely and target-oriented in heavily affected areas.

For the *neighbourhood interventions*, trees need a substantial amount of space, whereas green walls and roofs require only a little space. These are however interventions that need to be applied over a wider area compared to the street scale interventions before a measurable effect can be detected. This adds to the complexity and the timescale for implementation of these interventions. Like the green infrastructure on the street scale, these interventions also contribute to improved urban microclimate and improved rainwater infiltration.

For the *urban scale interventions*, action plans to mitigate air pollution and urban heat islands (instrument of urban development planning) have the longest timescale for implementation among all the iSCAPE interventions. This is the case, since this intervention is a bundle of many different measures, which requires organisational and coordinating effort and whose measures can take different scales. Contrary to this, behavioural intervention, being an informational intervention, can be implemented on a short timescale.

In the following paragraphs, the properties of the different interventions and how these were evaluated in the iSCAPE project are detailed.

An overview of the effects of *green infrastructure in street canyons and open road conditions, as* resulting from a literature review carried out before the realization of the iSCAPE interventions in the iSCAPE cities, is shown in Figure 1. The figure shows that hedges and green walls lead to improved air pollution when implemented in both environments, and green roofs lead to improved air quality when implemented in street canyons. Planting of trees will lead to improved air quality when applied in open road conditions but will lead to a deterioration of the air quality in street canyons. The reason is that trees reduce the (already low) wind speed in street canyons and thus hampers dilution of pollutants. Conversely, in open road conditions, where trees serve as a barrier between the source and the receptor and thus enhances dilution and deposition of pollutants. More details along with quantifications of reductions can be found in Abhijith et al. (2017). However, as we will see in the following, the detailed analysis of the results of the campaigns and simulations carried out in the iSCAPE project provided new evidence, and in some cases additional contrasting outcomes, for some of the interventions.

Figure 1 Effect of green infrastructure in street canyons and open road conditions; figure taken from Abhijith et al. (2017).

A photo of the *low boundary wall* from the boardwalk in Dublin, Ireland is shown in Figure 2. As can be seen, a low boundary wall is a solid, impenetrable structure placed parallel to the emission source. A low boundary wall will typically have a height of 1 m - 2 m and is often located next to low-speed roadways as opposed to noise barriers that are often 4 m – 5 m tall and located next to high-speed highways. The wall is characterised by being narrow, meaning that the height to width ratio is substantially larger than 1. The wall can be made of bricks, concrete or other impenetrable material. Previous studies have reported that the low boundary wall acts as a baffle to the flow from source to receptor and leads to increased dispersion and therefore reduced concentrations downstream of the wall. Depending on the location of the wall, changes in concentrations have been reported from increases up to 25% to reductions up to 75%. For more information see Deliverable 1.2 - Guidelines to Promote Passive Methods for Improving Urban Air Quality in Climate Change Scenarios.

Figure 2 Photo of a low boundary wall in Dublin, Ireland. Figure from Gallagher et al. (2015).

Photocatalytic coating is a special kind of coating that can be applied to e.g. building facades, road tunnels etc. The coating forms Hydroxide (OH) radicals in the presence of Ultraviolet (UV) light, which serves to break down air pollution. The basic principle of photocatalytic coating is shown in Figure 3. The concept is that Nitrogen Oxides (NO_x) is transformed in the presence of Titanium Dioxide (TiO_2) and ultraviolet radiation into Nitrate (NO_3^-), which is adsorbed to the surface of the concrete due to the alkalinity of the concrete. The nitrate can subsequently be removed by rain or artificial washing. The mechanism is created by adsorbed OH radicals being formed at the surface of the concrete, which subsequently oxidizes NO_x. Contradictory results have been reported in the about the NO_x reductions following the application of photocatalytic coating in laboratory and field experiments, showing low and negligible reductions (Gallus et al., 2015) but also consistent reductions (Maggos et al., 2008, Guerrini, 2012, Ballari and Brouwers, 2013). However, only few experiments were conducted regarding the application of photocatalytic coatings in real world conditions, and very few works evaluated the modelling of photocatalytic coatings at the street scale.

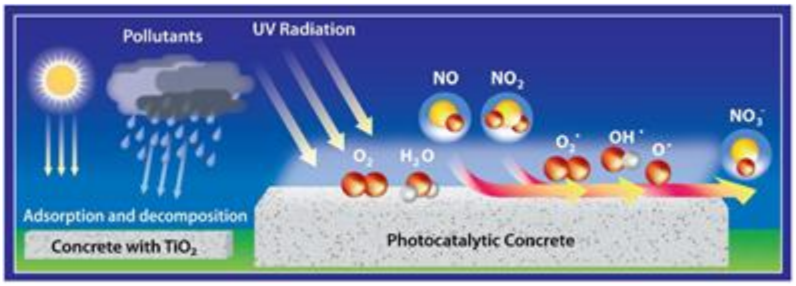


Figure 3 Principle of photocatalytic coating. Figure from Boonen and Beeldens (2014).

Whereas many of the previous research topics are in their infancy with large uncertainties related to the efficiency of the interventions, *urban design and planning* has a long research history. The settlement development as well as transport structure of a city in the form of roads and public transport naturally plays a dominating role in the air pollution. This is important for both transport of freight and people. Likewise, the size of the city and the commuting patterns will be the dominating parameters. The amount of urban green and blue space in the city will on the other hand contribute to reduce air pollution concentrations due to urban ventilation and interactions between the vegetation and the air pollution. Urban green and blue infrastructure also contributes to reduce the urban heat island effect. The density and alignment of settlement structure can promote or impede ventilation. Urban design and planning therefore focus on the interplay of urban structures at different scale levels. Various policy instruments are available to urban planning aiming at mitigating air pollution and urban heat islands, such as an action plan that addresses all these relevant fields of action. The environmental and socio-economic impact depends on the measures defined in the action plan and their interactions and side effects.

Behavioural interventions are, like some of the other interventions previously described, novel approaches that have not received much attention in the scientific literature previously. However, the literature has reported that successful behavioural interventions depend on identifying a target group and subsequently analysing the barriers and benefits perceived by said target group to the desirable change in behaviour.

The rest of this report is structured around the methodology used for testing the impact of the interventions and the results of these tests. The results for the street level interventions are described in Section 4, the neighbourhood level interventions in Section 5, the urban level interventions in Section 6, the portfolio analysis for the iSCAPE interventions is detailed in Section 7 and the conclusions are presented in section 8.

4 Street level interventions

4.1 Hedges and trees in open-road environments

4.1.1Intervention characteristics

In the study by Abhijith et al. 2017, the intervention of hedges and trees on street level air pollution was reviewed based on different urban morphologies, such as open roads and street canyons (Figure 4). An open road is an urban built environment feature in which both sides of the traffic corridor are open with generally detached, single or multi-story buildings and other manmade structures. In open road conditions, vegetation barriers have a positive impact on air pollution with thick, dense and tall vegetation having the largest impact (Abhijith et al., 2017).

Street canyons are a commonly found urban feature and typically consists of buildings along both sides of the road. In a street canyon environment, high-level green infrastructure (GI) such as trees generally have a negative impact on air quality while low-level dense vegetation with complete coverage from the ground to the top of the canopy (i.e. hedges) hinder the air flow underneath and hence generally show a positive air quality impact. Further details on the impacts of vegetation placed in both open roads and street canyons can be found in Abhijith et al. (2017).

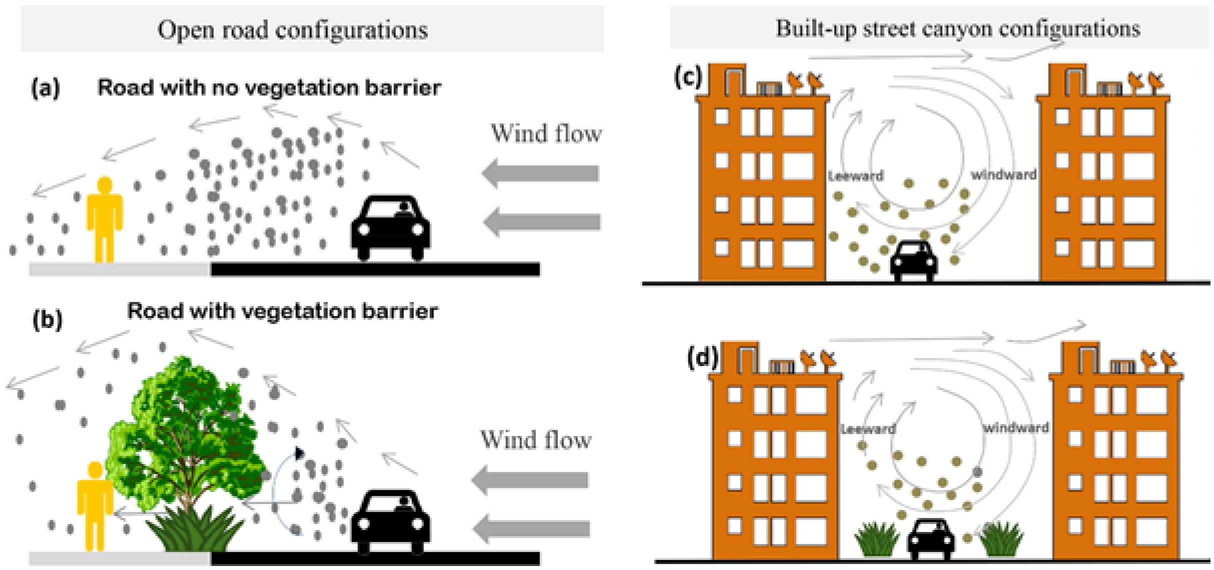


Figure 4 Dispersion patterns of road pollutants under open road configurations, (a) without vegetation barrier, and (b) with vegetation. Description of flow and pollutant dispersion patterns in a street canyon, (c) without vegetation barrier, and with vegetation (hedges) (d). Figures are not to scale. Figures from Abhijith et al. (2017).

Many terms have been used in the literature to describe urban vegetation such as "hedge", "hedgerow", "shelterbelt" and "vegetation barrier". Here, we focus on hedges since these are one of the common vegetation types found in urban areas. In general, hedges are defined as an elongated vegetation type with length to width ratio (L/W) greater than 2, low average height (less than 4 m), low width compared to the height (H/W>1) and foliage from the ground to the top of the canopy. A hedge is generally used as a barrier to mark the boundary of neighbouring properties in many parts of the UK.

Several studies have reported air pollution reductions for different species between measurements upstream and downstream of a hedge (see Abhijith et al. (2017) for a review). This reduction is caused by deposition to leaves, stems and branches of the hedge and increased dispersion when the wind is forced over the hedge (Al-Dabbous and Kumar, 2014). However, the vegetation and environmental parameters influencing the effects of vegetation on air pollution are not well known (Janhäll, 2015, Tiwari et al., 2019).

4.1.1.1 Experimental Details of Interventions

Two busy roadside locations in Guildford (Aldershot Road and Stoke Road), falling under typical open-road environments, were selected for the study (Figure 5).

Figure 5 Two monitoring locations along Aldershot Road and Stoke Road.

The hedge types in Aldershot Road are Hawthorn (Crataegus monogyna) and common Ivy (Hedera helix), while Beech (Fagus sylvatica) is the hedge type in Stoke Road. Table 2 lists the hedges and their leaf types in Guildford Borough, UK, as studied in iSCAPE project by Abhijith and Kumar (2019).

Type	**Hawthorn**	**Common Ivy**	**Beech (Fagus sylvatica)**
Leaf type			
Type	**Yew**	**Holly**	**Laurel**
Leaf type			
Note: The images were taken from https://www.hedgesdirect.co.uk			

Table 2 Hedge types and their leaves as studied by Abhijith and Kumar (2019).

Figure 6 shows a schematic representation of monitoring locations along with the dimensions of hedges, distance from the edge of the road to the monitoring point, and width of the traffic lanes.

The pollutant concentrations were simultaneously monitored behind and in front of or adjacent to the hedges. Two GRIMM aerosol monitors measured PM_1, $PM_{2.5}$ and PM_{10} concentration levels at a temporal resolution of 6 s (80–100 h of sampling). The mass of bulk particles was collected on Teflon filters, which were analysed for their chemical and morphological characteristics. Particle number concentrations (PNCs) (in the range of 0.02–1 μm) were measured with a temporal resolution of 6 s. Black carbon (BC) concentrations, sooty black material emitted from gas and diesel engines, were obtained from the analysis of filters. The campaign collected 5 days of monitoring data per site, which generated 8–10 h of high-resolution data per day. A detailed summary of the implemented methodology can be found in Abhijith and Kumar (2019).

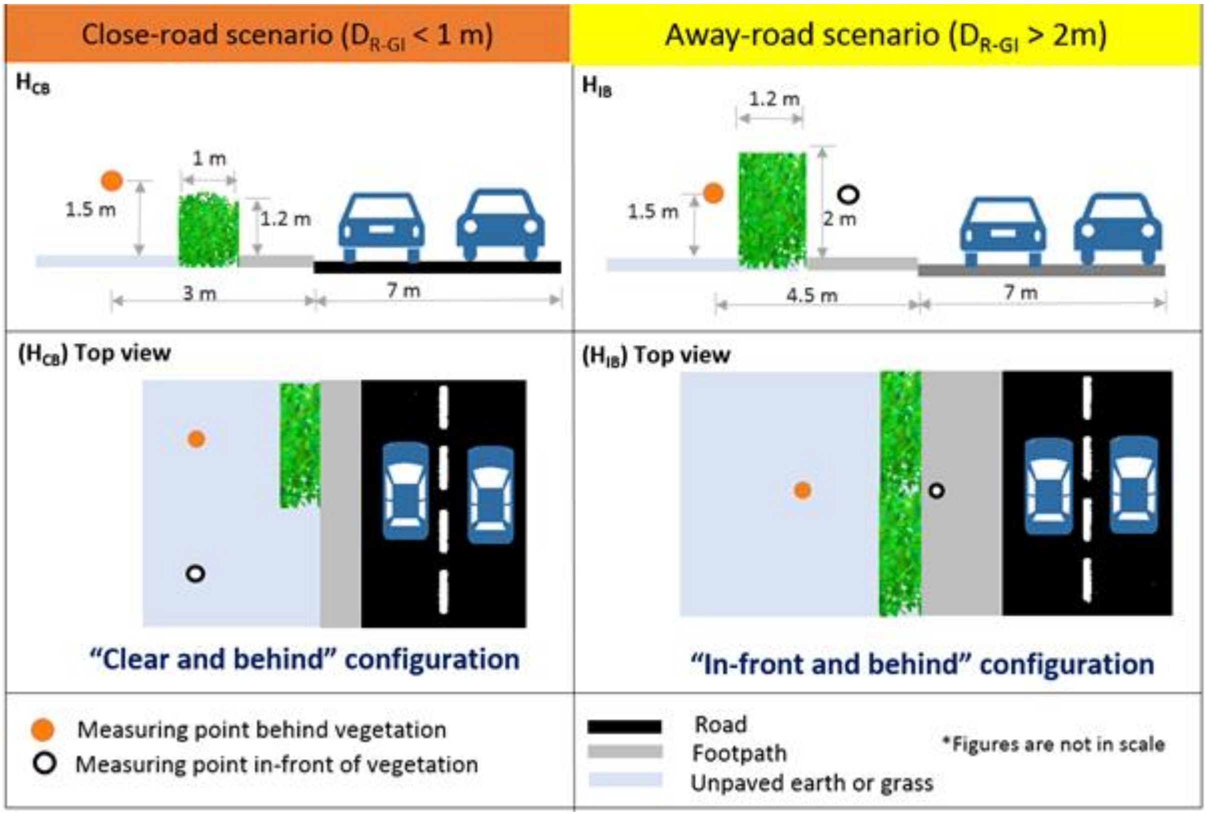


Figure 6 Schematic representation of monitoring locations (in two views) with the type of GI (hedges) and road details. HCB and HIB represent hedges in Aldershot Road and Stoke Road, respectively. The orange circle and black ring denote measurement points behind and in front of hedges, respectively. DR-GI refers to the distance between the road and the hedge types. The elements in the figures are not to scale. Figures adapted from Abhijith and Kumar (2019).

As showed in Figure 6, in one of the sites the second measurement point was at a clear area next to hedges, equidistant from the road as that of the sampling point behind the barrier (HCB), while in the other site the second measurement point was located in front of the hedge (HIB). The HCB site had a distance of less than 1 m between hedges and the road, leaving no space for placing instruments; these sites are referred to as ‘close-road’. The HIB site was more than 2 m distant from the edge of the road to the hedges, leaving enough space to place the instrument in front of the hedge; these sites are referred to as ‘away-road’. Henceforth, the terms ‘close-road’ and ‘away-road’ are used to define the ‘clear area and behind (CB)’ measurement configuration and ‘in front and behind (IB)’ measurement configuration, respectively.

4.1.1.2 Air Pollution Reductions

The study at two different sites in Guildford found that the use of hedges under open road configurations (close-road and away-road scenarios) could be an encouraging option for the reduction of pollutant concentrations behind vegetation. When comparing concentration changes among pollutants, hedges could reduce the levels of pollutants in both close-road and away-road sites by different percentages due to deposition and dispersion effects (see Figure 7 – top). As described in section 5.1, trees only did not show any positive influences on the measured concentrations behind GI. Without segregating by ambient wind directions, the study by Abhijith and Kumar (2019) suggested that the use of hedges (Figure 7 – top) or a combination of hedges and trees (see Figure 7 – bottom) emerged as favourable options for the reduction of pollutant concentrations behind vegetation.

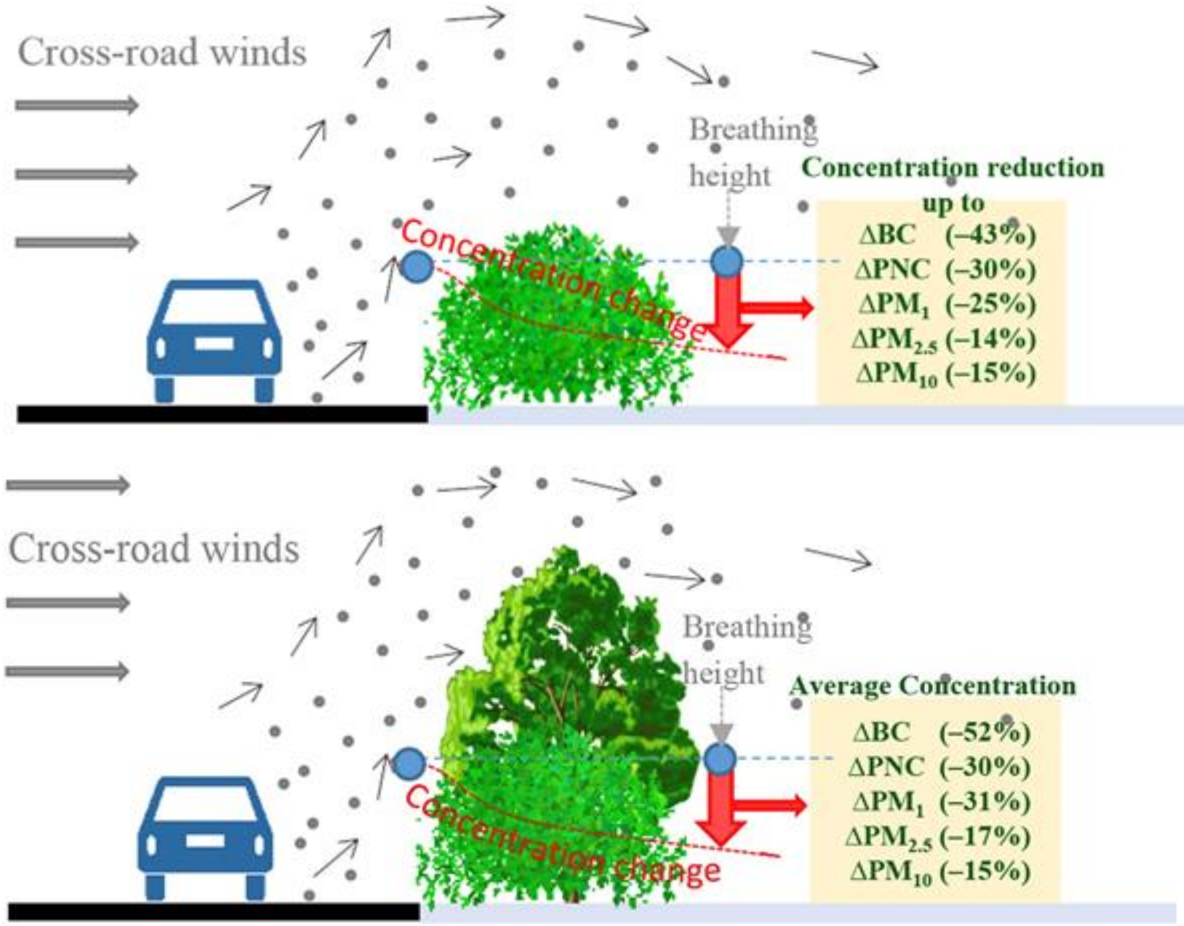


Figure 7 Top: schematic representation of the impact of the hedge on pollution reduction at breathing height. Figure adopted from Abhijith and Kumar (2019). Bottom: combination of hedges and trees as favourable options.

The analysis of vegetation density indicated higher relative pollutant reductions with an increase in leaf area density (LAD[1]). LAD describes vertical and horizontal structures of tree canopies. Further, hedge dimensions such as thickness and height had an important role in lowering pollutant concentrations. However, a relatively low height hedge (less than breathing height) could deteriorate air quality behind the hedges due to insufficient barrier effect.

In terms of wind direction, a maximum reduction in the concentration of all measured pollutants during along-road (parallel to the road) wind conditions was observed followed by cross-road (perpendicular to the road, from the road to GI) wind conditions. This was expected due to the sweeping of emissions by the wind and the wake of road vehicles whilst the barrier effect of GI enhanced this cleansing, limiting lateral diffusion of the pollutants. However, cross-road winds that forced vehicular emissions to pass through the GI also showed a significant reduction in pollutant concentration levels. Further, the chemical analysis of the particles collected on the filters demonstrated a reduction of harmful traffic-related particles and heavy metals by hedges via deposition and enhanced dispersion. Further details and elaborations on PM fractions and their compositions can be found in Abhijith and Kumar (2019) and in the iSCAPE report D5.2 “Air pollution and meteorology monitoring report (Update)”.

[1] Measured one sided green leaf area per unit volume of tree canopy.

4.1.1.3 Limitations of interventions

A range of limitations related to the use of hedges for urban air pollution mitigation have been identified in the literature:

- The effect of the individual hedge decreases with the downstream distance from the hedge as the concentrations approach the urban background concentration. One could however speculate that urban scale deposition of particles could increase in cities with many hedges compared to cities without hedges, although this effect remains to be shown.
- Deciduous hedges will lose the leaves during the winter season thus leading to increased porosity of the hedge. In general, dense hedges show larger air pollution reductions and deciduous hedges should therefore have smaller air pollution reductions during the winter although this remains to be shown.
- The optimal height, width and hedge species is an open question, which is a contributing factor that hampers the widespread application of hedges for air pollution mitigation.
- Urban space is a scarce resource in many cities in the UK, as well as in other EU cities. This limits the applicability of hedges for air pollution mitigation, although the scale of the problem remains to be quantified.

In the experimental campaign in the iSCAPE project, the following limitations have been the most important:

- Negligible effect of low-height hedges for air pollution mitigation at breathing height.
- The air pollution mitigation effect of hedges are strongly wind direction dependent with a maximum reduction in pollutant concentration during along-road wind conditions, followed by cross-road wind conditions. These observations clearly indicate that considering local wind directions during the urban planning of new built-up areas could help to reduce exposure of roadside users.

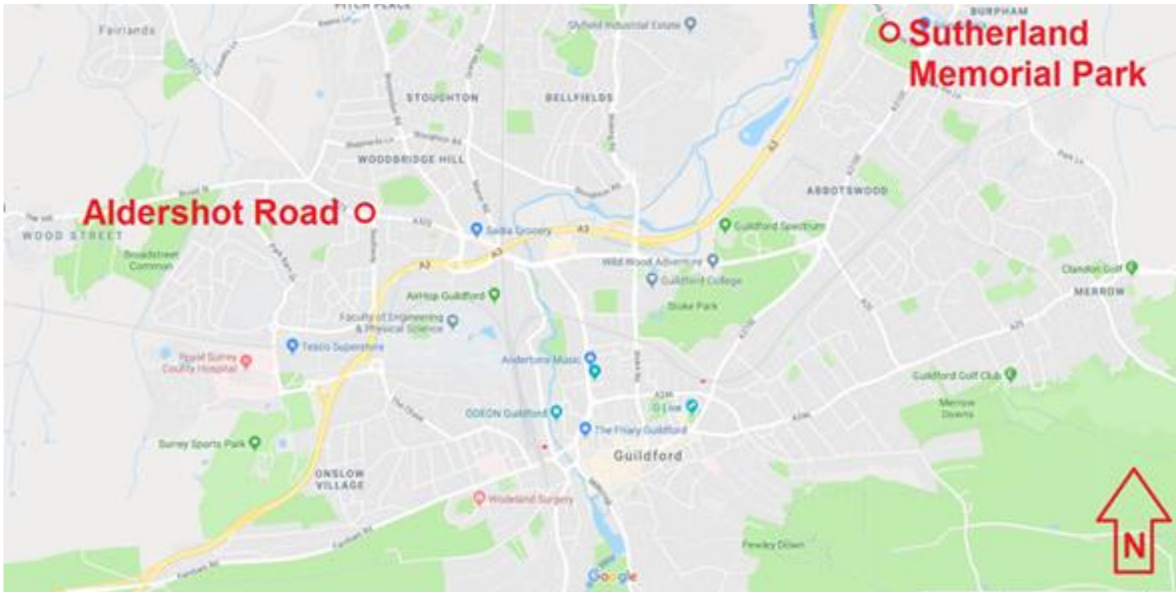
4.1.1.4 Summary

The study showed that the use of hedges and hedges combined with trees could be favourable options for the reduction of pollutant concentrations behind vegetation under open road configurations. The impact of hedges on the reduction of sub-micron particles and harmful traffic-related particles via deposition and enhanced dispersion was presented

4.1.2Trees in open road environments

4.1.2.1 Experimental Details of Interventions

Two roadside locations in Guildford (Aldershot Road and Sutherland Memorial Park), characterised as typical open-road environments, were selected for this study. The tree type in Aldershot Road is Common lime (Tilia x europaea), while Common lime (Tilia x europaea), Field maple (Acer campestre), Poplar (Populus nigra), and Bird cherry (Prunus padus) are the tree species in Sutherland Memorial Park (Figure 2). Table 1 shows the leaf structures of the trees in the roads. The description of instrumentation is similar to the previous section (hedges) (Section 4.1.1).



Aldershot Road	Sutherland Memorial Park

Figure 8 Map and pictures of the monitoring locations in Guildford, UK. Aldershot Road and Sutherland Memorial Park road. Simplified planting formations (single row and zig-zag) are shown schematically. Note: Planting formations are not to scale.

The tree arrangements are as follows:

- Aldershot Road: single tree row, the vertical distance between the bottom of the tree crown and the ground surface ranged from 1.7 to 2.5 m.
- Sutherland Memorial Park: multiple rows (up to 4) of trees in zig-zag planting formation, the vertical distance between the bottom of tree crown and the ground surface ranged from 1.0 to 2.5 m.

Tree type	**Common lime**	**Field maple**	**Poplar**	**Bird cherry**
Tree leaf				
Note: The images were taken from https://www.mailordertrees.co.uk				

Table 3 Typical trees observed in Aldershot and Sutherland Memorial Park Roads.

Sites were selected based on the availability of stretches of road with different GI configurations, as well as space for placing instruments behind GI and at an adjacent clear area or in front of GI. Figure 9 shows a schematic representation of monitoring locations along with the dimensions of trees, distance from the edge of the road to the monitor location, and width of the road. Each site had one sampling point behind the trees (T_{CB}), but only one site had a second measurement location in front of the trees (T_{IB}). The terms 'close-road' and 'away-road' are used to define the 'clear area and behind (CB)' configuration and 'in front and behind (IB)' configuration, respectively. $D_{R\text{-}GI}$ refers to the distance between the road and the GI types. Further details concerning the sampling location and procedure can be found in D5.2 and Abhijith and Kumar (2019).

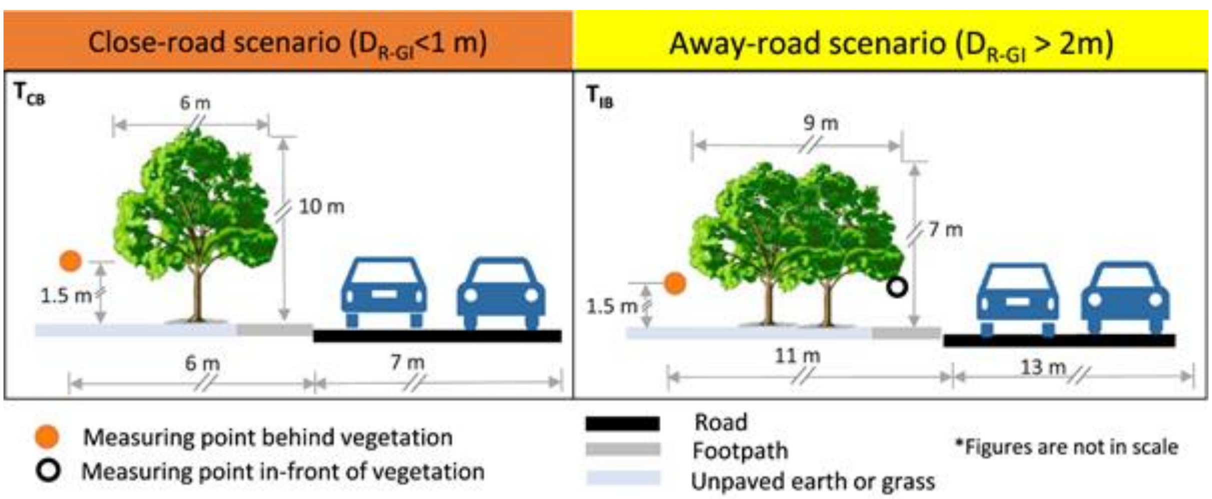


Figure 9 Schematic representation of monitoring locations with the type of GI (trees) and road details. The orange circle and black ring denote measurement points behind and in front of the GI, respectively. The tree heights were obtained approximately from Google Earth. Note: Dimensions are not to scale. Figures from Abhijith and Kumar (2019).

4.1.2.2 Air Pollution Changes

The studies on hedges and a combination of hedges and trees clearly showed their importance in the reduction of harmful emissions behind vegetation (see section 4.1.1). The street level interventions of trees only showed changes in the pollutant concentrations behind and in-front/clear of trees as shown in Figure 10. Under the open-road condition, roadsides with only trees showed no positive influence on pollution reduction at breathing height (between 1.5 and 1.7 m), as the tree canopy was too high to provide a barrier/filtering effect of road-level tailpipe emissions.

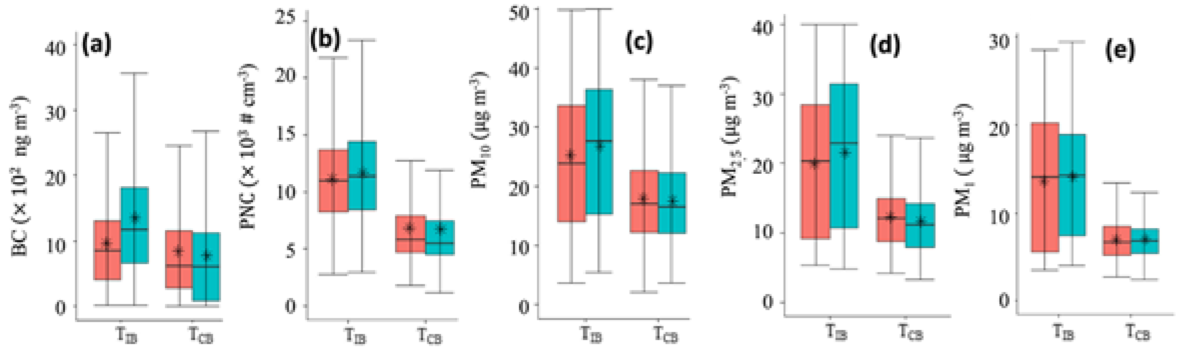


Figure 10 Boxplots of pollutant concentration behind (red) and in-front/clear (green) measurement points for (a) BC, (b) PNC, (c) PM10, (d) PM2.5, and (e) PM1 concentrations; mean values are shown as star notation. Figures from Abhijith and Kumar (2019).

4.1.2.3 Limitations of interventions

Although the literature has shown air pollution mitigation resulting from trees in open road conditions, the present study failed to replicate these results. The details of the differences remain to be entangled but could include differences in measurement setup or differences in vegetation parameters between the studies. The limitations identified in the literature for hedges in open-road conditions are likewise limitations for trees.

4.2 Low-boundary walls

4.2.1 Intervention characteristics

The pilot in Dublin is aimed at investigating the effect of low boundary walls on ventilation. The aim is to reduce the personal exposure of air pollution in the built environment. Moreover, the benefit of decreasing environmental pollution has many economic benefits which should not be underestimated. The solutions that iSCAPE proposes have a relatively low cost. Based on the evaluation obtained after the preliminary experimental phase, guidelines can be designed to implement intelligent choices in urban planning using a "win-win" approach to climate change and the reduction of atmospheric pollution. iSCAPE promotes a transformation of society into a green and low-carbon economy by engaging Dubliners in community activities as part of the Living Labs.

Low-boundary walls (LBW) have been chosen as the intervention to improve localized dispersion and reduce pollution in the various road canyon environments. This kind of interventions is a passive control system and has been shown to provide positive results on the dispersion of pollutants. Several experiments were conducted in Dublin to find out how the presence of LBWs changes the amount of pollution to which pedestrians are exposed. Experiments were carried out along Pearse Street, where LBWs were placed, and pollutants linked to nitrogen oxides and particulate matter in the front and behind walls were analysed. High-end and low-cost sensing technologies have been used and installed which allowed monitoring the pollutants on both sides of the walls.

Two experimental phases can be distinguished. In the first phase, the pollutants of nitrogen oxides were analysed; in the second, those related to particulate matter were analysed. Before experimenting, a risk assessment analysis was carried out, and the necessary authorisations were obtained to place the LBW. The instrumentation necessary for the experimental phase was obtained from the Dublin City Council, university College Dublin and Trinity College Dublin.

The results of the experiment were positive. The data was collected in March and July of 2018. The wall was useful for creating a barrier and reducing the exposure of the pedestrians to air pollution in the street canyon.

Wind speed and direction were measured from a high position to prevent the data from being disturbed by the street canyon. The traffic count was obtained with a multiple click counter. The choice of the time of the sampling is very important because it affects the results. For this reason, three random hours in the morning, afternoon and evening were chosen, so that the final data could be analysed and compared. The detection interval was five minutes. In addition, each sampling time provides twelve data points. The selection of sampling hours can be related to the different parameters that come into play during the experimental phase, such as wind speed or traffic volume.

4.2.2 Results of the impacts on air pollution

As mentioned in the previous section, two experimental phases have been implemented in Dublin to test how LBW affects the citizens' personal exposure of air pollution in the built environment. During the first testing phase, the LBW was placed at the edge of the footpath in Pearse Street in Dublin City Centre. The road that has been chosen is 16 meters wide with North-South alignment; it has four traffic lanes and a very high traffic volume. The circulation is one-way. There are no other components that could affect the pollution data detected, such as the presence of parking lots or public green areas. An 18 meter long and one meter high LBW was installed along the roadside on bollards already present onsite. Pollution data were detected through monitoring points on both sides of the walls, through sensors placed behind and in front of the wall, so that the difference in concentration due to the presence of the LBW could be captured.

The first phase of the experiment was conducted starting from 27 March 2018 until 6 April 2018, and NO_x was taken as the reference pollutant.

Two sets of LBWs were placed using plastic canvas sheets. The only openings in the installed LBWs are due to the entrances in the buildings. The LBWs were assembled at 8:00 am, to be removed only at 5:00 pm. These operations were carried out every working day. Two Chemiluminescent NO / NO_2 / NO_x analysers (Model 200E and 200EU), used for the evaluation of nitrogen compounds, were placed on both sides of the LBW. They were installed in the basement of the Security Office, Trinity College Dublin. A wind vane (Cabled Vantage Pro2™ with standard radiation protection) was placed on the roof of the neighbouring structure for observation of wind-related variables.

In this first phase, it was necessary to calibrate the analysers to check how precise they are aligned with the necessary standards. This calibration was carried out by a representative of the Dublin City Council one week before the experiment was performed. In the second stage, the PM measurements were carried out with and without LBW. It began on July 9, 2018 and ended on July 27, 2018. This phase was conducted at the same location of the first phase. The first two weeks were used to monitor $PM_{2.5}$ and the last week for PM_{10}. Also, in this case, the LBWs were placed on the existing bollards, but, unlike the first phase, the LBWs were made more continuous and more prolonged. For this second part of the experiment, two portable aerosol analysers TSI, model SIDE PAK AM520 and DUST TRAK DRX 8534, were used for the quantitative evaluation of $PM_{2.5}$ and PM_{10}. Data related to meteorology in the experimental phase, such as wind speed and direction, together with the volume of vehicular traffic, were also taken into consideration.

As required in the manufacturer's guide, before each sampling, both instruments have undergone a zero calibration, so that the recording of pollutant data was accurate even if it was deficient. The reported results demonstrate a significant reduction in air pollution attributable to LBW in Pearse Street, the details of the reduction percentage are illustrated in the following Figure 11, Figure 12, Figure 13 and Table 4.

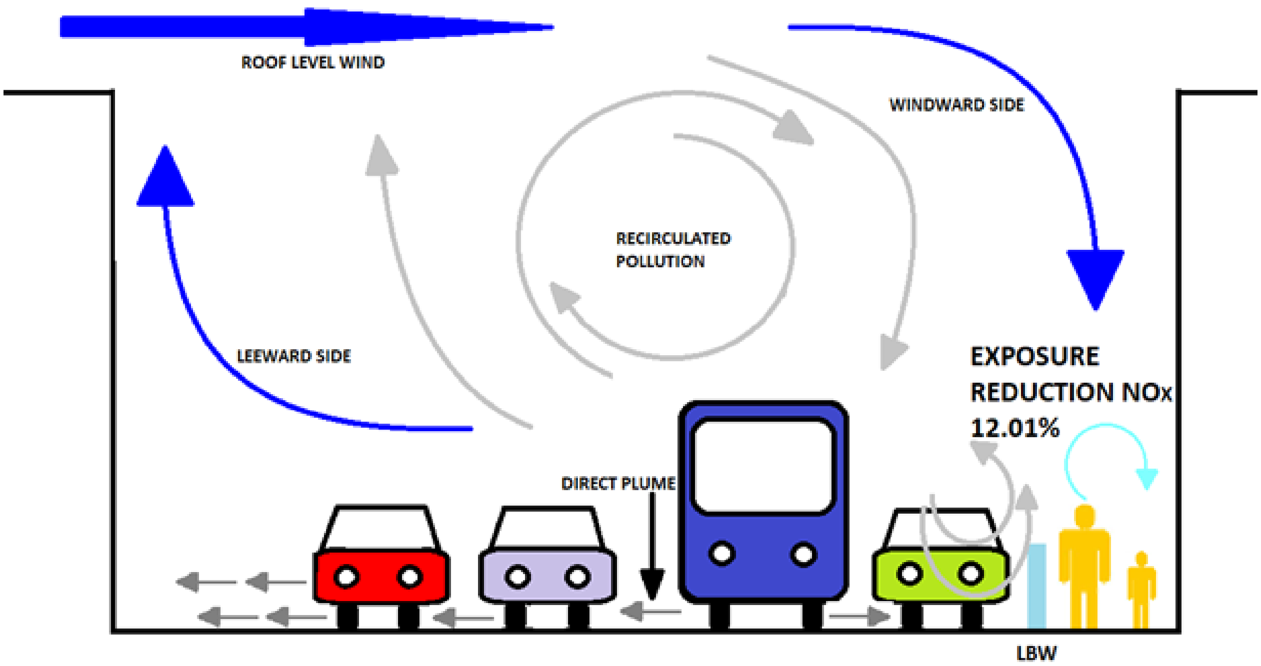


Figure 11 Schematic representation of the decrease of the concentration of NOx.

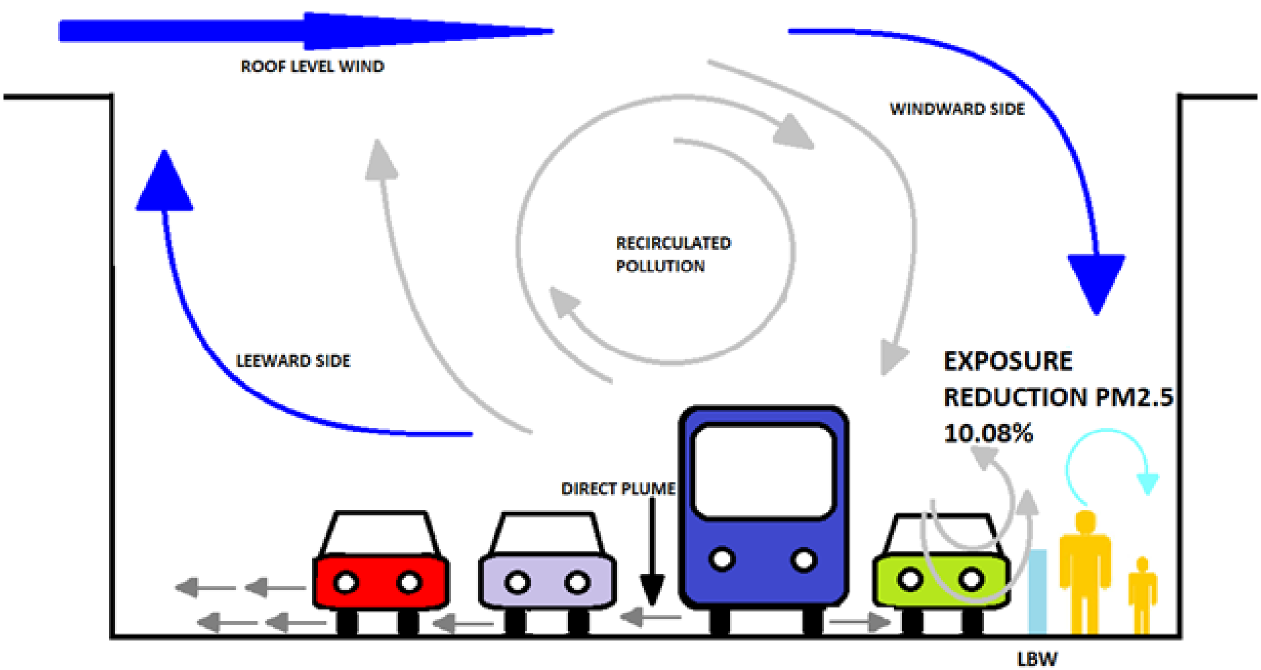


Figure 12 Schematic representation of the decrease of the concentration of PM2.5.

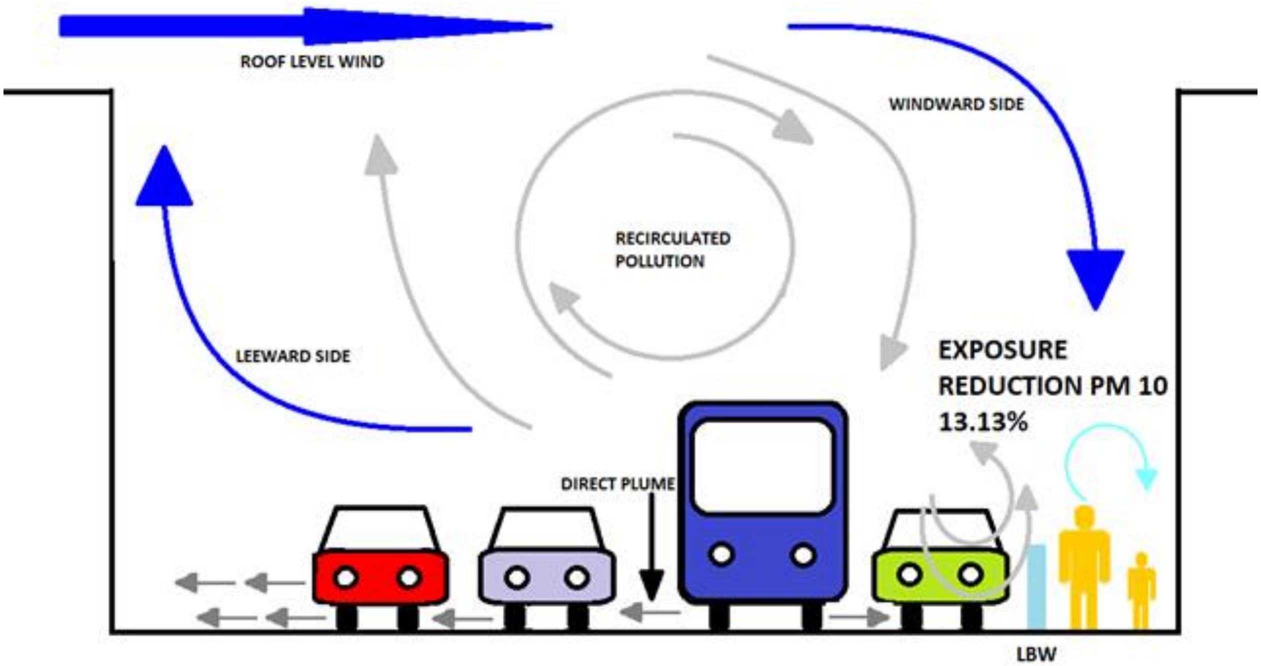


Figure 13 Schematic representation of the decrease of the concentration of PM10.

Since LBW setup and sampling times were randomised and data were averaged, see Table 4, the following results are only relevant on a large and extended framework (Deliverable 5.3).

Concentration	Without LBW	With LBW	Exposure reduction
NO	24.5646 µg/m3	13.9378 µg/m3	43.26 %
NO_2	12.7315 µg/m3	18.8775 µg/m3	-48.27 %
$N0_x$	37.2961 µg/m3	32.8153 µg/m3	12.01 %
$PM_{2.5}$	0.0387 mg/m3	0.0348 mg/m3	10.08 %
PM_{10}	0.0099 mg/m3	0.0086 mg/m3	13.13 %

Table 4 Randomised and averaged LBW experiment results.

The results show that the effectiveness of LBW significantly depends on wind direction and wind speed over the street canyon. The result obtained for NO_2 turns out to be unexpected; in fact, an increase by a factor of 1.5 is observed for this pollutant. On the other hand, the other nitrogen compounds behave like particulate matter, and decrease successfully in the presence of low boundary walls.

4.2.3 Environmental and socio-economic effects

It is possible to generalize the results obtained on an urban scale. Since the experimentation took place in the absence of other passive systems possibly affecting the data, such as car parks, it is possible to extend the results obtained to roads with the same characteristics as Pearse Street. It is clear that it must be taken into account that each street canyon has different conditions, for example, a different volume of road traffic, different wind energy and various sizes, but a generalization can be carried out over the entire Dublin area with the necessary corrective coefficients, in such a way as to simplify the process and create a measurement campaign that sets out the positive aspects of this choice of passive control systems on the environment and the economy. With this argument, the total emission reduction coefficient for the entire Dublin area is assimilated to the coefficient of reduction of the local exposure. As for the construction of future scenarios, it was conducted based on the prohibition of Diesel cars in the Dublin area. Using DALY (Disability Adjusted Life Years), it is possible to calculate the sum of years of the potential loss of life due to premature mortality and years of productive life lost due to disability. Therefore, when the future scenarios for Dublin were built about the LBW, an alternative scenario to that of 2015 and one that calls for the elimination of diesel vehicles in 2030 was taken into consideration. To these two existing scenarios, the improvements of the emissions with the presence of LBW in the streets must be added, in order to build a socio-economic conclusion.

The following Table 5 shows the projection of annual reduction of pollution in Dublin. This projection is obtained by assuming that LBWs are placed in all streets where it is possible and that diesel cars are prohibited. The data related to PM_{10} were not available, so that it was not possible to construct a scenario for this pollutant.

Pollutant	NO_x	$PM_{2.5}$	PM_{10}
Car emissions (t)	2987.46	185.26	268.39
LCV emissions (t)	1332.69	61.67	81.44
Bus emissions (t)	571.84	10.14	12.23
Total emissions (t)	4891.99	257.07	362.06
Unit damage cost (€/t)	5861	200.24	19.143
Damage cost (x1000€)	28671.95	51.48	6.93
Unit health damage (DALYs/kt)	90	700	
Health damage (DALYs)	440	180	

Table 5 Projection of annual reduction of air pollution in Dublin.

Considering the implementation of LBWs without the elimination of diesel vehicles in the Dublin scenario in 2015, a cost saving of 3.45 million euros and a health damage savings of 71 DALY could have been obtained. In the scenario for 2030, if diesel cars were also eliminated, they could provide total savings of 1.62 million euros and 35 DALYs on health. These savings must be reduced taking into account the financial and technical expenditure for the distribution of LBWs in the entire territory of Dublin.

4.2.4 Limitations of interventions

LBWs can provide a solution to enhance localized dispersion and improve air pollution in distinct street canyons settings. However, depending on the wind direction, street geometry and position of the LBW, they may also cause crease in air pollutant concentrations behind the LBW, having therefore the opposite effect of increasing pollutant concentrations instead of decreasing them. It is necessary to understand that it is not possible to rely only on this type of intervention to mitigate air pollution. The LBWs, in fact, only serve to reduce the concentration on the footbath behind themselves, to ensure that they are not inhaled by pedestrians directly. This means that cyclists and motorists in their cars cannot take advantage of the improvements provided by LBWs. For this reason, it is essential to associate the adoption of LBWs with a policy of reducing emissions, eliminating, for example, diesel vehicles. Only such a complete intervention will result in a significant decrease in pollutant concentrations.

4.3 Green infrastructure (trees) in street canyons

4.3.1Intervention characteristics

In this section, we summarize the description of the pilot carried out in Bologna, which is described thoroughly elsewhere (especially in D3.3 ‘Report on Footprint of Passive Control Systems’, and in D5.2 ‘Air pollution and meteorology monitoring report’). Two intensive experimental field campaigns, one in summer (10 August 2017-24 September 2017) and one in winter (16 January 2018-14 February 2018) were performed with the purpose to monitor air pollution and meteorological and turbulence variables in two adequately identified urban street canyons in the city of Bologna. The primary aim of the two experimental campaigns was to evaluate the impact of GI, and in particular of trees, on air flow, air pollution and thermal comfort in urban street canyons, but also to gather experimental data to verify the outputs of high resolution numerical simulations used to further evaluate those effects.

Figure 14 Measurement sites for air pollution and meteorological variables within the two intensive experimental field campaigns in Bologna.

To this aim, two urban street canyons (Figure 14), Marconi and Laura Bassi Sts., were selected to have a similar N-S configuration and similar traffic volumes, but as being characterized by a different presence of vegetation: in fact, while Marconi St. is a main business road located in the historical city center, almost free of vegetation and with highly packed buildings encompassing a four-lines street, Laura Bassi St. is located in a residential area in the outskirts of Bologna, characterized by small houses and apartments, wide frontal distances and by the presence of a tree line of deciduous trees on both sides of the street (Figure 15).

Figure 15 Street views and details (W = width, H = height, α = orientation angle of the street canyon) of the two street canyons in Bologna (source: Google Earth).

Both street canyons were instrumented for the measurements of air pollution and meteorological variables at high time resolution at three different height levels.

In particular, one ARPAE (Emilia-Romagna Environmental Protection Agency, new name for ARPA-ER) mobile laboratory was deployed along each street canyon. The mobile laboratory was equipped for continuous 1-minute measurements of gaseous (NO_x, NO_2, NO, SO_2, CO, O_3) and daily averages of particulate matter (PM_{10} and $PM_{2.5}$) pollutants. During the winter campaign, further measurements of Black Carbon and particle size distributions with high time resolution (sub-daily) were also carried out in both street canyons.

Accurate and fast measurements of the 3-d wind field and for estimating a range of turbulence parameters and fluxes by means of eddy correlation techniques were carried out with a sonic anemometer sampling at 50ms time resolution deployed at three different height levels, i.e. at ground level, at mid-level inside the canyons and above the two canyons. In addition, sonic anemometers were coupled with thermohygrometers for the measurements of air temperature and air relative humidity at high time resolution (1s). One net radiometer was also deployed at the highest instrumented level to characterize the energy balance between incoming short-wave and long-wave Far Infrared Radiation (FIR) versus surface-reflected shortwave and outgoing long-wave radiation.

This allowed to characterize flow and turbulence dynamics within and above the two canyons.

Additionally, 5-minutes traffic counts in the two street canyons and their vicinity were available by means of inductive loop counters from the Bologna Municipality.

Finally, a Lidar Ceilometer was installed on the rooftop of the Department of Physics and Astronomy of the University of Bologna (Irnerio St. 46, Figure 14) for measuring and analysing the boundary-layer height at a location adequate to characterize the atmospheric structure of the whole city and as such of both the investigated sites. Additional measurements of meteorological and air pollution variables were performed by ARPAE meteorological and fixed air pollution stations (Figure 14): this allowed to obtain background air pollution concentrations and wind conditions.

During both the winter and summer experimental field campaigns, two intensive thermographic campaigns with the two thermal cameras were performed in the two street canyon areas (Figure 16). The aim of these campaigns was to analyse temperature distribution of building façades and ground surfaces in the two streets, in order to collect and analyse data for the UHI effect at neighbourhood and city scale levels. Images were simultaneously collected by an operator on foot at the two sites during a 24-hour acquisition with regular intervals of 2 hours (total of 12 acquisitions in 24 hours at each site). During both campaigns, the days for the so-called UHI experiment (intensive thermographic campaigns) were selected according to the weather forecast to have a clear sky, calm wind, day (22-23 August 2017 during the summer campaign, and 08-09 February 2018 during the winter campaign).This choice allowed to collect images at 12:00 PM (close to the maximum surface temperature), 2:00 PM, 4:00 PM (close to the maximum air temperature), 6:00 PM, 8:00 PM, 10:00 PM (close to maximum UHI intensity). Analysed buildings were selected on the basis of the homogeneity of construction material and the absence of obstacles (balconies, eave, etc.), metal or glass. Several shots or portions of the same building façade at several different heights were taken in order to maintain a similar resolution for all images. Finally, measurements of ground surfaces were also collected.

Figure 16 Positions of the building chosen for the temperature measurements within the two intensive thermographic campaigns in Bologna (source: OpenStreet Map).

Air pollution and meteorological data collected from fixed and mobile monitoring stations within the field campaigns and within the two intensive thermographic campaigns were used to validate the setup of CFD (Computational Fluid Dynamics) and dispersion simulations aimed to extend the results of the impact of trees on air pollution and thermal comfort at neighbourhood and urban scale (see D6.2 'Microscale CFD evaluation of PCS impacts on air quality' and D6.3 'Detailed report based on numerical simulations of the effect of PCSs at the urban scale'). The validated setup was used to conduct simulations aimed to evaluate the impact of planting different tree species in the current scenario at local and urban scales (see D6.2, D6.3 and D5.3 'Evaluation of interventions'); in addition, D6.5 'Detailed report of the effect of PCSs on air quality in the future CC (2050) in the target cities' extends the evaluation of the impact of trees on air pollution in a climate change scenario.

4.3.2 Impact on air pollution and thermal comfort

The analyses conducted about the effectiveness of trees in improving urban thermal comfort clearly showed a positive impact at local scale, with reductions up to 2°C (Figure 8).

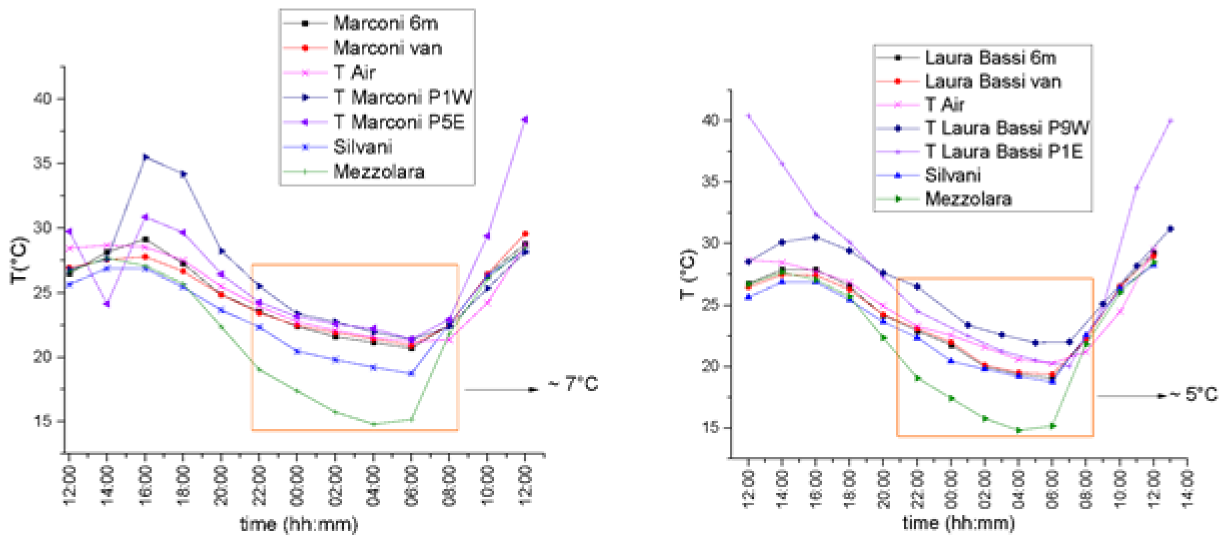


Figure 17 Temperature evolution within the day of the summer intensive thermographic campaign in Bologna (22-23/08/2017), measured by the thermo-hygrometers, the ARPA-ER instrumentation in one urban (Silvani St.) and one rural meteorological station (Mezzolara) and of building façades of buildings located on the West and East side of the two street canyons (Marconi St. upper and Laura Bassi St. lower) as retrieved from the thermal images (source: D5.2).

In addition, simulations at urban scale conducted in a scenario where trees are planted in Marconi St. indicate that the improvement in thermal comfort is not limited to the area of the intervention but extend over larger spatial scales (Figure 18).

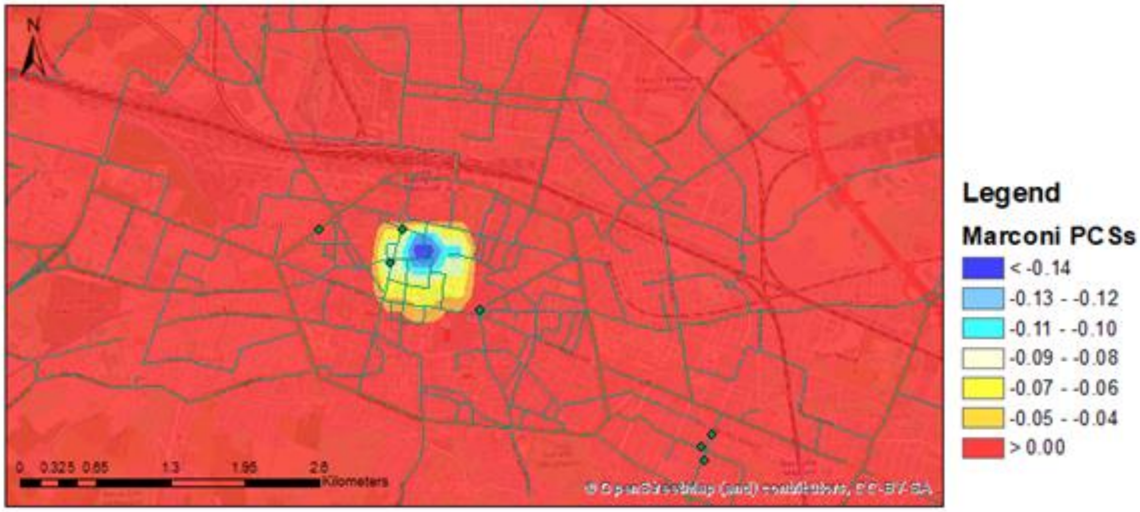


Figure 18 The difference of temperature (°C) between the current scenario and a scenario where trees are planted in Marconi street canyon. The difference is expressed in °C (source: D6.3).

The impact of trees on air pollution at local scale has been thoroughly described in D5.2 and D6.2. In particular, in D6.2 two different scenarios, one where trees are planted in Marconi street canyon and one where trees are removed from Laura Bassi St., were evaluated. The results (Figure 19 for Marconi street canyon) indicate that although concentrations generally tend to increase in the presence of trees, the pollutant distribution is more uniform and there are lower levels of pollutant concentration especially near the intersections.

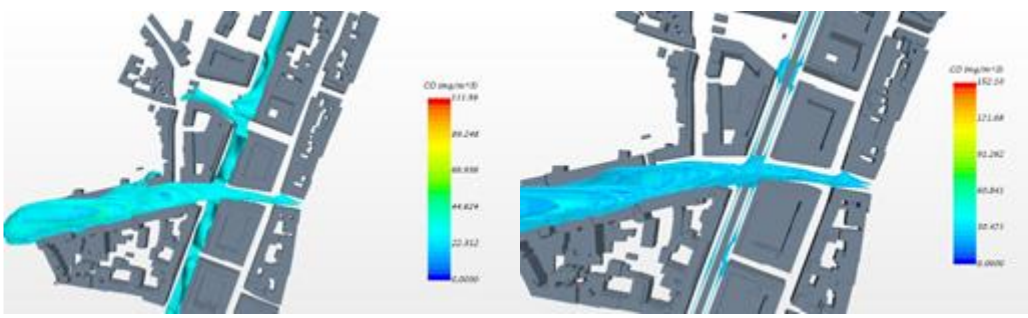


Figure 19 Streamlines of CO concentration obtained from CFD simulations for Marconi street canyon, case 22/08/2017 UTC 12:00 PM, in the real case (left) and in the scenario where trees are planted along the canyon (right) (source: D6.2).

Those results were further extended and better explored in D5.3, where the impact of different tree types characterized by different foliage densities and crown distances was evaluated, considering five simulation scenarios. In general, the simulation outputs showed that the pollutant concentrations increase when considering smaller crown distances with bigger foliage densities. However, the analysis of the pollutant concentrations obtained over the whole street canyon volume and not restricted only on a single location cannot be considered representative of the whole canyon. It showed an actual reduction in scenarios with trees, especially in the hotspots (Figure 20), and a more homogeneous distribution of pollutant concentrations along street canyons in the presence of trees. An improvement in air quality resulting from planting trees was further confirmed by analysing the outputs of a dispersion model setup for the neighbourhood of Marconi St. (see D6.5).

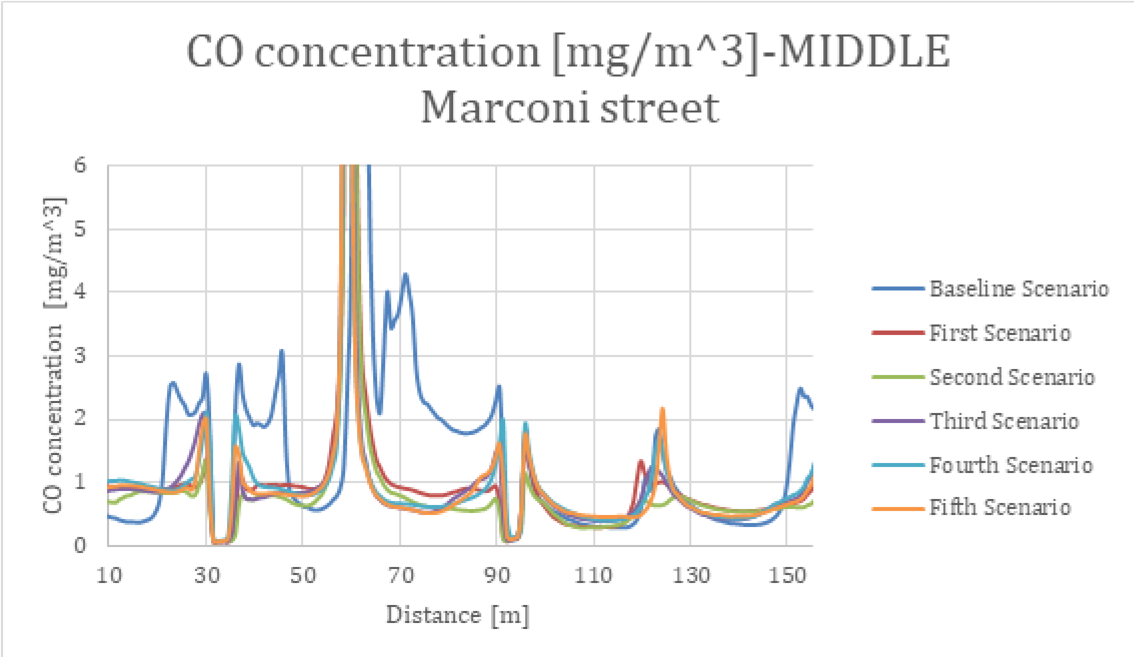


Figure 20 Middle probe line along the Marconi street reporting the CO concentration at 1.5 m from the ground for all scenarios (without the main intersection peak) (source: D5.3).

Finally, the detailed analyses conducted on the data collected within the two campaigns have shown that the impact on concentrations depend strongly on wind direction, showing larger reductions under katabatic and downwind conditions; in addition, events of reductions are more frequent in the warm period when deciduous trees are covered with leaves (see D5.2 update for further details), while for particulate matter which is greatly influenced by the effect of deposition, reductions in concentrations are also observed during the cold season.

Summarizing, the analyses conducted in the campaigns and in the simulations conducted in Bologna showed that:

- Trees may help in improving thermal comfort providing reductions of air temperature of about 1-2°C in the summer season.
- The impact of trees on urban thermal comfort is not only limited over the street canyon but extends to larger neighbourhood areas.
- Even though the concentrations of air quality pollutants can be enhanced in local single points, the introduction of trees in a street canyon may lead to strong decrease of concentrations in proximity of local hotspots and to more uniform pollutant distributions in the street canyon.
- Trees with larger crown distances and smaller foliage densities are to be preferred.

Figure 21 shows a schematic sketch of the important parameters to be considered for implementing an intervention consisting of planting trees in urban street canyons.

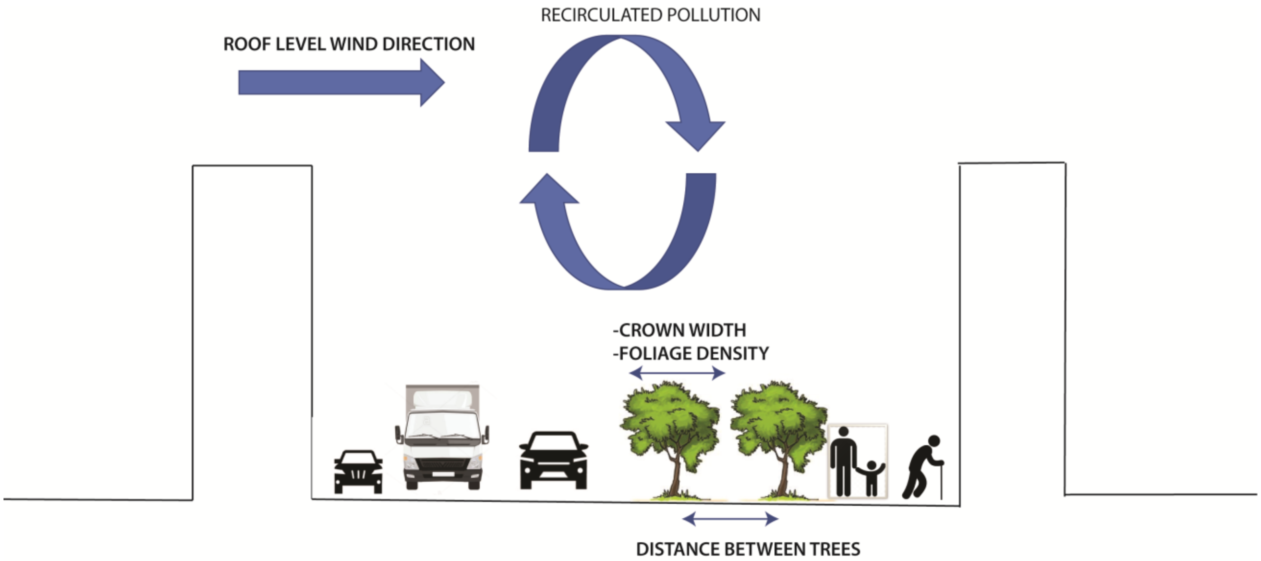


Figure 21 Schematic representation of the main characteristics that need to be considered before implementing an intervention consisting of planting trees in urban street canyons.

4.3.3 Limitation of interventions

A range of limitations related as to the use of trees for the improvement of air pollution and thermal comfort in urban street canyons have been identified in the literature and in the iSCAPE project:

- Since during winter no foliage is present on deciduous trees, the impact of trees on air pollution during the cold season is mostly limited to the deposition effect, which is not effective for gaseous pollutants.
- In general, because of the absence of foliage on deciduous trees in the cold season, there is a limited impact of trees on thermal comfort within the cold season.
- The optimal height, width and tree species remains an open question, possibly related also to the different allergenic potential of the various tree species, which was not investigated in the iSCAPE project
- The effect of trees on air flow and therefore on air pollution is strongly dependent on wind direction
- In general, dedicated campaigns and simulations are needed to adequately plan intervention in terms of effectiveness on air pollution and thermal comfort

5 Neighbourhood level interventions

5.1 Trees

5.1.1 Intervention characteristics

The presence of trees conveys a range of environmental, economic and social benefits to the urban/rural landscape of any countries. In terms of residential places, trees promote healthy communities, support biodiversity, improve local air quality, reduce noise pollution, and many more (FAO, 2015). Trees influence the urban air pollution levels in the following ways:

- Trees can increase the dry deposition of gaseous and particulate matter pollution. This is done through interception of the airflow by leaves, stems, barks, fruits and heads of trees (Tiwari et al., 2019).
- Trees increase the roughness length (measure of the friction experienced by the wind) of the city, thus leading to reduced wind speeds (Kent et al., 2017). This can both lead to increased concentrations due to reduced mixing (Yli-Pelkonen et al., 2017) and reduced concentrations due to increased deposition.
- Trees emit pollen (Pauling et al., 2012), fungal spores (Sadys et al., 2014), biogenic volatile organic compounds (Kesselmeier and Staudt, 1999), and contributes to the formation of ozone through emission of biogenic volatile organic compounds (Eisenman et al., 2019) to the atmosphere.

The magnitude of these effects and the parameters influencing these is an under-researched area. Figure 22 illustrates the impacts of GIs (hedges and trees) on the dispersion and deposition of emissions in both microscale and macroscale environments. In the following sections, the methodology and the results of the iSCAPE studies related to trees on street scale and urban scale are detailed, and the limitations of the intervention are explained as well.

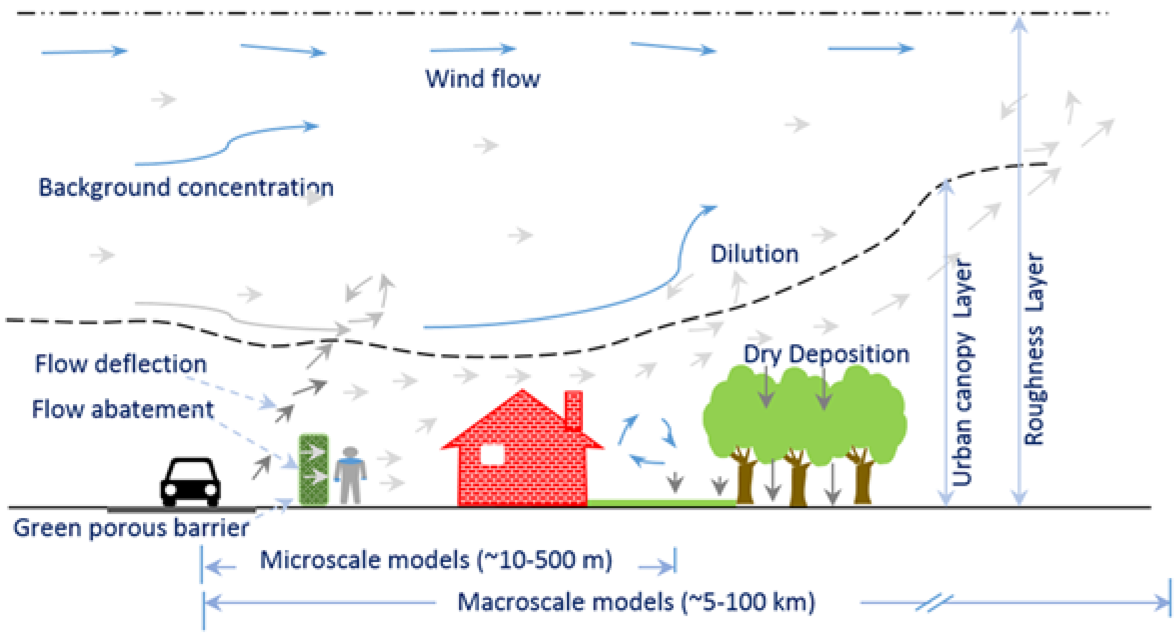


Figure 22 Schematic representation of GIs on dispersion and deposition of emissions in both microscale and macroscale models; figure from Tiwari et al. (2019).

5.1.2 Modelling Details of the Intervention

In the present study, the effect of trees on the urban air pollution was analysed through a modelling study. For this, two different scenarios were developed to assess the effect of GI on air pollution in Guildford through a model that considers both dispersion and deposition effects. Two scenarios, with and without urban vegetation, have been investigated for the year 2015 in order to evaluate the benefits of the existing vegetation in Guildford vis-à-vis, reducing the traffic-related air pollutants NO_x, PM_{10} and $PM_{2.5}$ concentration as described below.

- **2015-BASEAQ:** This is the baseline case for the year 2015 with the currently estimated vegetation cover around Guildford city. The air pollution is estimated by a combination of dispersion and deposition of air pollution by using Atmospheric Dispersion Modelling System (ADMS) developed for urban areas (D5.3 and D6.3).

- **2015-BASE-NoGIAQ:** This is a hypothetical scenario for the year 2015, which assumes that no urban vegetation exists and the land is covered only with urban area.

The year 2015 has been chosen to represent the current situation in Guildford since data for the model inputs were freely available for this year. An area covering Guildford borough along with the major roads and buildings was studied in the modelling approach as shown in Figure 5. Detailed descriptions of the modelling domain can be found in D5.3 and D6.3.

5.1.3Air Pollution Changes

The deposition amount offered by vegetation is dependent on the percentage cover of GI and pollutant concentration level. As shown in Figure 24 (left), GI has the potential to reduce concentration levels compared with the situation without GI. The results indicate that maximum air pollutants concentration reduction is near the traffic source (A3 – a major highway) because the deposition amount is proportional to pollutant concentration. The preliminary results show that the annual average pollution concentration reduction over the whole domain varied between 1.37 µg m^{-3} - 34.14 µg m^{-3}, 0.14 µg m^{-3} - 4.61 µg m^{-3}, and 0.03 µg m^{-3} - 1.05 µg m^{-3} for NO_x, PM_{10} and $PM_{2.5}$, respectively (Figure 24 – left). Compared to the baseline scenario, the vegetation reduced the pollutant concentration levels of NO_x, PM_{10} and $PM_{2.5}$ by 18.6, 12.9, and 8.6%, respectively. The vegetation has removed 1.16, 0.18, 0.06 ton yr^{-1} km^2 of NO_x, PM_{10} and $PM_{2.5}$ from the atmosphere near the traffic source due to deposition (Figure 24 – right), which is comparable with previous studies. The complete analysis of this modelling study has been submitted as a part of 'Report on interventions' (D5.3) and 'Detailed report based on numerical simulations of the effect of PCSs at the urban level' (D6.3). It was shown in D5.3 that these reductions result into annual benefits of 58 million euros in terms of avoided negative health impacts. The most important component in terms of economic benefits is the reduction of NO_2 concentration and resulting reduction of NO_2 related mortality.

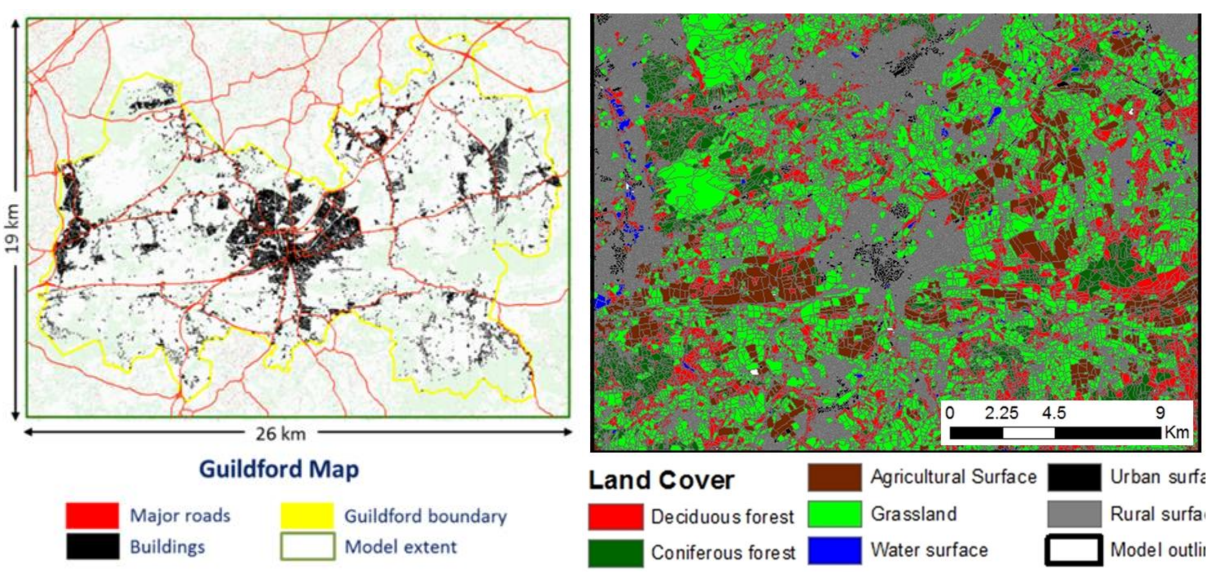


Figure 23 Left: modelled domain of Guildford borough along with the major roads and buildings (source: https://www.ordnancesurvey.co.uk/opendatadownload/products.html). Right: a map showing the spatial distribution of different land covers at 25 m resolution in the modelled domain over Guildford city (source: Digimap, UK).

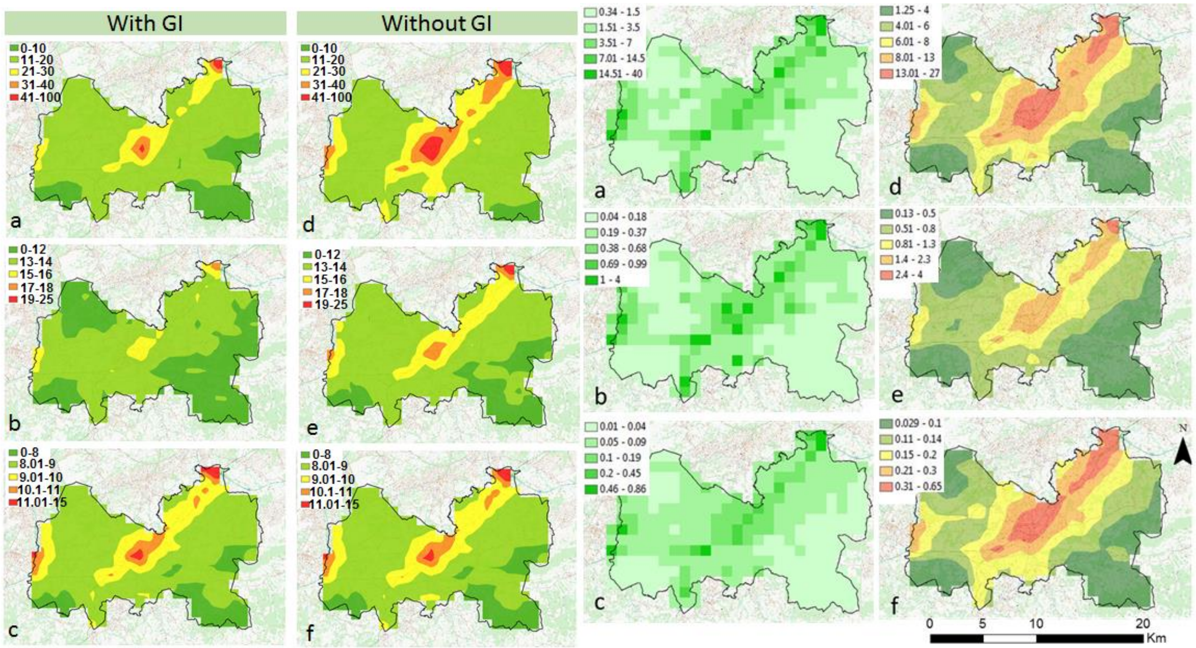


Figure 24 Left: Annual average modelled concentration (µg m-3) in modelled domain for 2015-BASEAQ (a) NOx (b) PM10 (c) PM2.5 and 2015-Base-NoGIAQ; (d) NOx; (e) PM10 and (f) PM2.5; Right: Spatial distribution of deposition (ton yr-1 km-2) in modelled domain over GI (a) NOx (b) PM10 (c) PM2.5 and annually averaged concentration reduction (µg m-3) in modelled domain for 2015 (d) NOx; (e) PM10 and (f) PM2.5 (source D6.3).

5.1.4Limitations of interventions

On the urban scale, the effect of trees for air pollution mitigation is limited by the fact that many trees are required before substantial effects are observed. As seen in Figure 24, a substantial part of the concentration reduction happens outside Guildford city, which is partly caused by the effect of the large A3 highway running there, but also because the large forest areas in the domain are located outside the city. From an exposure point of view this is not desirable, since the largest population density is located in Guildford city. This spatial discrepancy between sources, trees and population can in some cases be a limitation to using trees for air pollution mitigation at the urban scale.

The effects of emission of pollen, fungal spores and biogenic volatile organic compounds mentioned in section 5.1.1 are not included in the present analysis due to the lack of operational models for these effects. This uncertainty in the modelling approaches generally hampers the applicability of trees for air pollution mitigation at the urban scale.

5.2 Green Walls and roofs

5.2.1 Intervention characteristics

As described already in previous iSCAPE reports (see especially D1.2 and D6.4), Vantaa differs from the rest of the iSCAPE cities not only in its high-latitude position but also in its urban classification: Vantaa is highly *decentralized* while Bologna and Dublin are *compact*, Hasselt, Bottrop and Guildford are *decentralized and concentrated*; Vantaa has no specific main core but is constituted of several smaller town areas that are scattered within the surface area of the city. More than 60% of Vantaa is classified as green or blue.

The experimental pilot in Vantaa examines the role and impact of GI on the climate change and air pollution related citizen exposures. The intervention impacts for air pollution and meteorological conditions in high-detail/neighbourhood scale were made with high-resolution urban model ENVI-met as follows (see a more detailed description in D5.3):

1. City blocks of sizes about 100 m x 100 m selected by the city of Vantaa representatives. These blocks were considered interesting either because of their present challenging nature (e.g., due to air pollution) or by future construction plans. One (i.e., most interesting) block was then selected for the modelling of the intervention impacts.
2. The selected city block was constructed into the ENVI-met simulation software in 5 m horizontal and 2 m vertical resolution (Fig. 5.2.1). This is the status quo GI-scenario representing the area and its GI as it is at present.
3. Two additional GI-scenarios were constructed by removing (no-GI) and maximizing (full-GI) the GI in the simulated area.
4. The meteorological and air pollution background data from the area was collected from a period of several years, analysed and inputted into ENVI-met.
5. ENVI-met simulations were performed indicating the GI impacts in the area with respect to climatic conditions and air pollution.
6. For the socio-economic impact assessment, the results from point (5) were upscaled for the whole Vantaa.

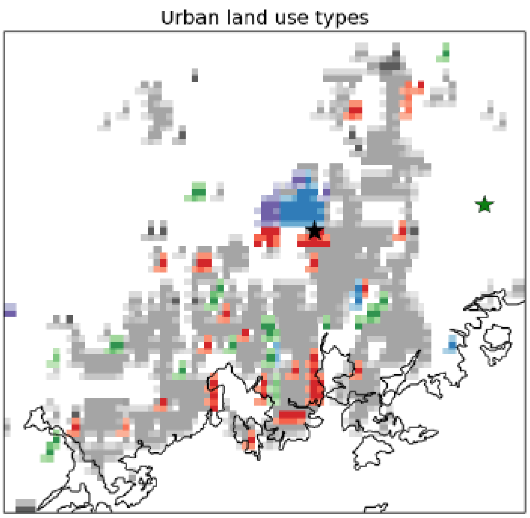
Figure 25 A 3-dimensional picture from the ENVI-met tool 'SPACE' of the Myyrmäki Vaskivuorentie area; gray: buildings, light green: trees with different heights and shading areas, orange: unsealed loamy area, not vegetated; white: sealed areas, stone slabs, black: main sealed roads with tarmac. Adapted from D5.3.

The climate change impacts and GI effects for climate change mitigation were modelled with regional scale surface interaction module SURFEX. The Town Energy Balance (TEB) model in SURFEX separates buildings, air within urban canyons, roads, as well as GI (trees, parks, etc). The approach was as follows (for specific details, see D6.4):

1. SURFEX was initialized for area covering South-Finland area (38 x 42 km) so that Vantaa is positioned approximately in the center (Fig. 5.2.2 left). Grid spacing was 500 m by 500 m.
2. GI intervention was implemented into SURFEX by substituting the urban areas (red colours in Fig. X left) suburban properties (different type of buildings and larger fraction of GI; Fig.

5.2.2 right). The assumption is that the intervention was not too dramatic so that the same atmospheric forcing can be used (i.e., the changes in the urban boundary layer were not too significant and the intervention effects are mainly in the street canyons).

3. Present (or recent) and future (2050s) climate data were constructed and digested into SURFEX. The SURFEX output indicates the impact of the intervention in present and future climate. The highest greenhouse gas concentration scenario for the future was used (RCP8.5). [Regarding the details of the construction of the recent climate data set, see D6.4].



	Building fraction	Building height (m)	Vegetated fraction	wall surface ratio
baseline	0.45	20	0.1	0.45
intervened	0.28	10	0.44	0.28

Figure 26 Left: Urban land use types over the domain of SURFEX. Suburban types are shown in grey, commercial and industrial areas in red, parks and sports facilities in green, and airports and ports in blue color. The commercial area of Vantaa Tikkurila and the forest of the Sipoonkorpi National Park are shown by black and green stars, respectively. Right: Urban characteristics at Vantaa Tikkurila before and after the intervention of lower and less dense buildings and more widespread green space. Adapted from D6.4

5.2.2 Impacts on air pollution and meteorological conditions

Overall, the impact of GI for the air pollution in Vantaa simulated by ENVI-met can be considered relatively small if compared to the results obtained in other iSCAPE cities: for example, the increase of NO concentration during the day time is few ug/m^3 in the no-GI -scenario (Fig. 5.2.3 upper). However, as can be seen from Fig. 5.2.3, locally and during specific rush hours the GI-impacts on the concentrations can be larger.

Regarding the impact of the intervention on meteorological conditions, the following can be concluded:

- The GI-induced impacts for the PET (physiologically equivalent temperatures) can be locally several degrees Celsius (Fig. 5.2.3 lower).
- Monthly temperatures in the present climate in summer (July) and winter (January) are affected modestly but systematically by the intervention; on average, the air temperature drops by less than half a degree in January and by more than half a degree in July, and in summer and winter the change is nearly independent of temperature.
- Wind speeds almost double in the SURFEX intervention due to the alteration in the urban environment.
- Simulated temperatures in the present and 2050s summer and winter climates with and without intervention (Figure 5.2.4) are clearly governed by the changes in the atmospheric forcing while the impact of the intervention is most noticeable for wind speeds.

- When comparing climate change and intervention impacts over urban and forested areas, it can be clearly seen that the climate change impact on the diurnal meteorological conditions is less important for the differences between the town and the forest, i.e., the differences are governed more by the urban vs. non-urban morphology.

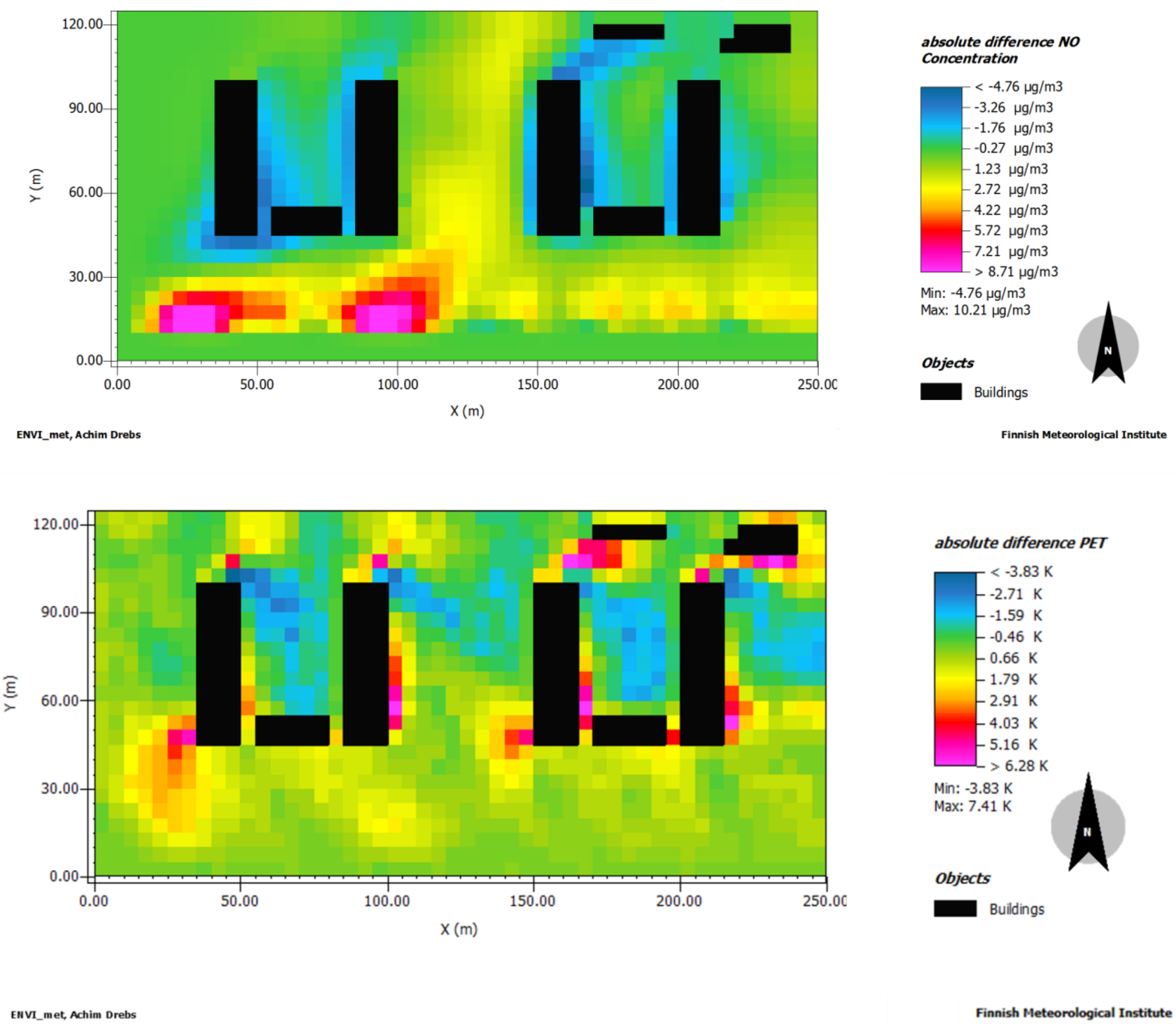


Figure 27 Above: Comparison of traffic emissions, NO, unvegetated vs. status quo (vegetated area), Vantaa Myyrmäki Vaskivuorentie, time: 16.00, date: 15.9.2018, x/y cut at k = 3 (z=1.4000m). Below: Comparison of PET (physiologically equivalent temperature) for the no-GI vs. status quo situation Vantaa, 12:00 local time on 15 July 2018. Adapted from D5.3.

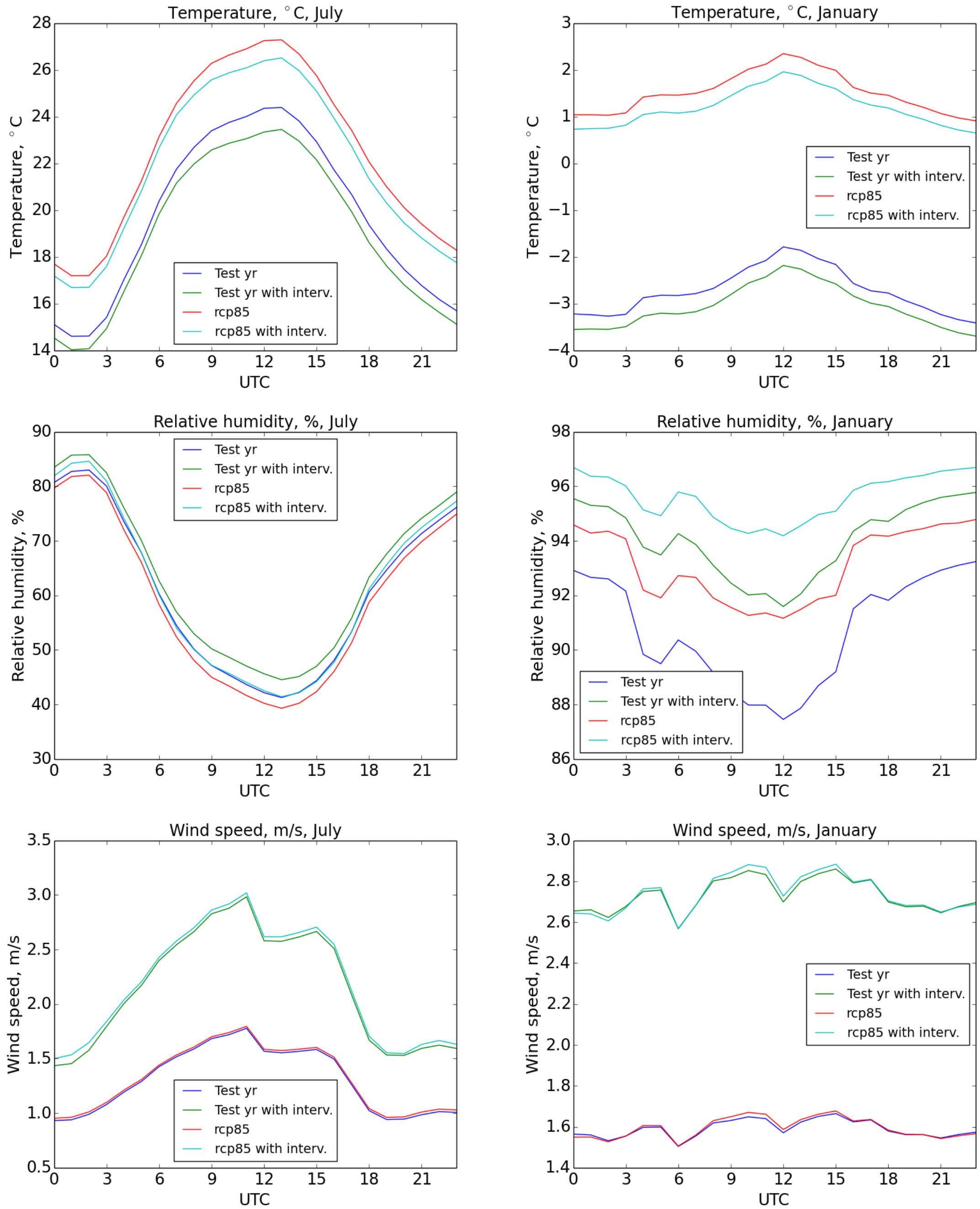


Figure 28 Monthly mean diurnal cycles of air temperature (top panels), relative humidity (middle panels) and wind speed (bottom panels), showing the response to changing climate and urban layout in SURFEX for Tikkurila in Vantaa in the months of July (left hand column) and January (right hand column). Adapted from D6.4.

The projected future changes in the climate of Vantaa deviate from those for the other iSCAPE cities. While the season with the largest projected warming, increases in diurnal temperature range and incident solar radiation and decreases in precipitation is generally summer in the other cities, for Vantaa the season with the most pronounced changes is winter. In other words, the warming trend (Figure 3) and also the projected changes in precipitation and solar radiation are stronger in winter than in summer (Figure 4). A similarity with the rest cities is that the multi-model mean changes in the mean wind speed are small compared to the uncertainty ranges.

5.2.3 Limitations of the intervention

As we have demonstrated, simulations regarding the impact of GI for air pollution and climate change mitigation are possible to do. However, when examining the simulation results for Vantaa the following limitations can be seen:

- High-resolution simulations regarding urban meteorology need large computing resources. This means that only specific examples can be simulated. Therefore, special attention should be paid on the selection of the region of interest because it is difficult to change it later.
- Coarser resolution makes possible to analyse longer time periods and larger domains. However, in this case urban areas are treated as “averaged” grid squares, each square having average values of the actual morphological factors (i.e., fraction of roads, buildings, water, etc). This may hide actual and even significant effects of any intervention.

5.3 Photocatalytic coating

5.3.1 Intervention characteristics

An intensive experimental field campaign was carried out in the Lazzaretto site in the outskirts of Bologna (Figure 29) during summer 2018 (04 August 2018 – 29 August 2018) with the aim to evaluate the impact of photocatalytic coatings on air pollution, and in particular NO_x, concentrations. Here we present a brief synthesis of the instrumental setup of this campaign, while a thorough description is available in ‘Report on deployment of neighbourhood level interventions’ (D3.8).

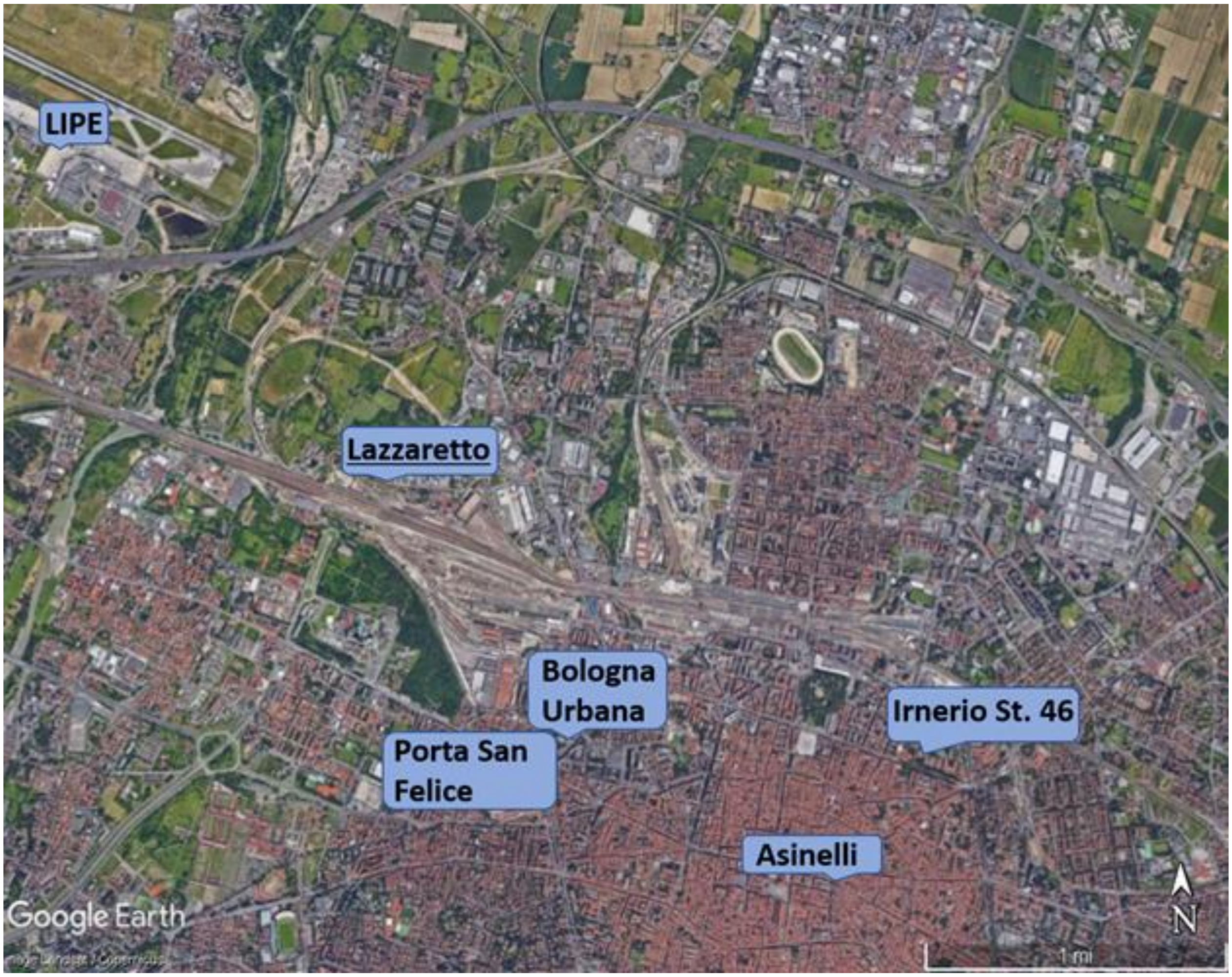


Figure 29 Location of the Lazzaretto area and other measurement sites for air pollution and meteorological variables within the intensive experimental field campaign of summer 2018 (source: Google Maps).

To this aim, similar to the experimental field campaigns conducted in Bologna, two parallel street canyons with the same NW orientation and affected by the same pollution sources were identified (Figure 30). In addition, the Lazzaretto site is much alike an open-air laboratory inside a real city, with all the buildings having similar dimensions, shape and materials.

Figure 30 Map of the two street canyons (A: painted canyon; B: reference canyon) in the Lazzaretto area (Bologna, Italy) with indication of the N-S orientation (source: Google Maps).

In this context, like the Bologna experimental campaigns, both street canyons were similarly equipped with air pollution and meteorological instrumentation at two different height levels, one at ground level and one above the canyons. In particular, ARPAE mobile laboratories for the monitoring of NO_x, NO, NO_2, CO, O_3, and SO_2 concentrations with 1-min time resolution were deployed along both street canyons at ground level. At ground level, one sonic anemometer, one barometer and one temperature and relative humidity probe were placed for the measurements of the 3-d wind field, air temperature and air relative humidity with high frequency and accurate resolution. At the top of each street canyon, one sonic anemometer, one temperature and relative humidity probe and one net radiometer to evaluate the energy balance Far Infrared Radiation (FIR) versus surface-reflected shortwave and outgoing long-wave radiation, were also deployed. Besides providing rapid response 3D wind field data, sonic anemometers allow estimating a range of turbulence parameters and fluxes using eddy covariance techniques. Additionally, on the rooftop of the A canyon, a LI-COR LI-7500 DS was installed to determine CO_2 and water vapour fluxes, when coupled with sonic anemometers air turbulence data and using eddy correlation techniques.

Similar to the experimental campaigns in Bologna, further measurements of air pollution and meteorological variables useful to evaluate the background conditions were also obtained by other fixed air pollution and meteorological stations spread over the Bologna territory. In addition, the Lidar Ceilometer installed on the rooftop of the Department of Physics and Astronomy of the University of Bologna (Irnerio St. 46, in Figure 29) was used to evaluate the boundary layer height during the Lazzaretto field campaign.

With the purpose to evaluate the effectiveness of photocatalytic coatings on NO_x reduction, canyon A in Figure 30 was painted with photocatalytic coating while canyon B was left untouched. A preliminary comparison between the two canyons prior to the painting was also performed in order to evaluate for the presence of differences between the two canyons other than the photocatalytic coatings.

Considering the reduction of traffic during the month of August in Bologna, and in order to have strong control on the pollutant emission sources in the two canyons, eight controlled pollutant releases (two fortnight and six daytime) with a known pollution source (one EURO-2 diesel car) were setup in each of the two street canyons.

Data collected within the experimental campaign served also to validate the setup of CFD simulations performed in the canyons used to extend the results of the intervention in other seasons characterized by different solar radiation and temperature conditions. Those simulations are extensively presented in D3.6 ‘Report on photocatalytic coatings’.

5.3.2 Impact on air pollution and health benefits

Detailed data analysis were needed in order to extract indications on the effectiveness of the coatings on NO_x concentrations: in fact, a simple comparison between the concentrations observed in the two canyons showed that they are affected by factors other than the coatings. As such, thorough data analyses were necessary to derive indications on the effectiveness of the coatings. In particular, analyses were conducted separately on adequately identified days, characterized by similar clear-sky conditions, before the painting and after the painting. In this way, reductions of 10-20% in NOx concentrations were derived from the experimental data.

The reduction of NOx concentrations provided by the coatings, however, was confirmed by validated CFD simulations (Figure 31), detailed and thoroughly described in D3.6, indicating reductions up to 40% near the wall in the presence of photocatalytic coatings.

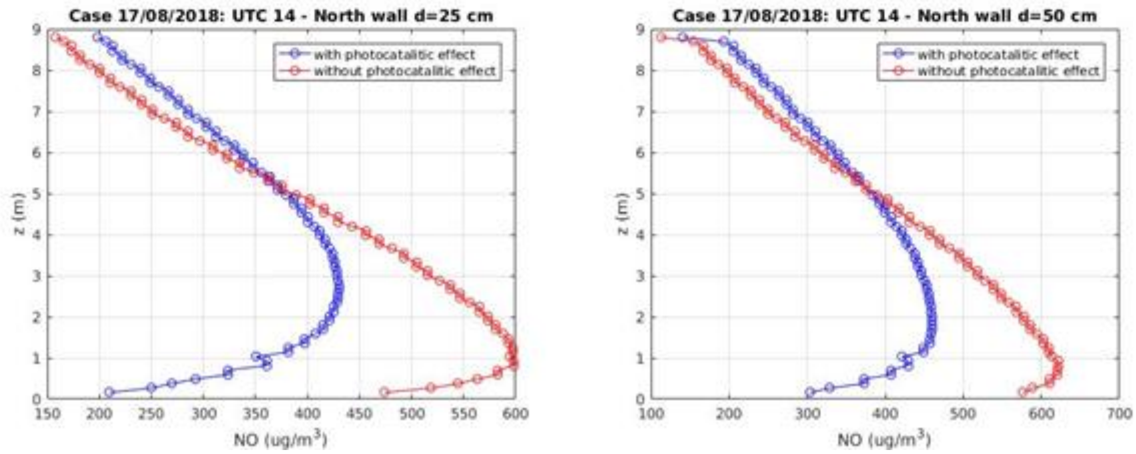


Figure 31 Canyon A: profiles of NO mass concentration (µg m-3) obtained for case 3: 17/08/2018, 14:00 UTC. Left: profiles of NO mass concentration (µg m-3) at a distance of 25 cm from the North wall; right: NO concentration profile at 50cm distance from the North wall (source: D3.6).

The outputs of CFD simulations conducted during the other seasons (Figure 32) showed that obviously the reduction in NOx concentrations is strongly dependent on atmospheric conditions, not only temperature and solar radiation, but also wind direction and intensity; less obviously, in winter, during sunny days, the reduction at noon can be higher than that observed in a summer afternoon, when some of the walls are in the shadows.

It was shown in D5.3 that the resulting annual benefits were 330 million euros, while the costs were only 36 million euros. The highly positive net benefits are explained by reduction of NO_2 related mortality, and high NO_2 concentration levels in Bologna.

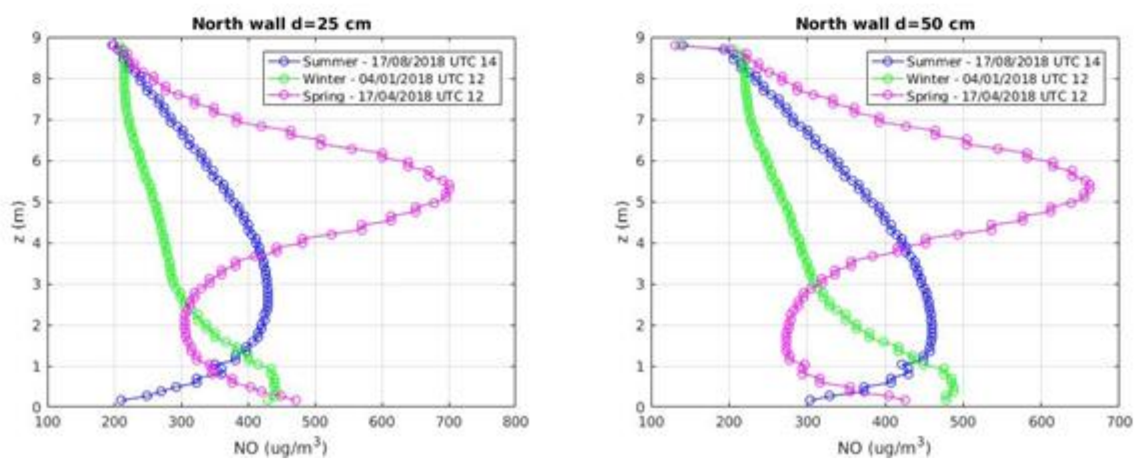


Figure 32 Canyon A: profiles of NO mass concentration (µg m-3) obtained for cases: summer (17/08/2018, 14:00 UTC), winter (04/01/2018) and spring (17/04/2018). Left: profiles of NO mass concentration (µg m-3) at 25cm distance from the North wall: right: NO concentration profile at 50cm distance from the North wall. (source: D3.6)

5.3.3 Limitations of interventions

A range of limitations related to the use of photocatalytic coatings for the improvement of air pollution in urban street canyons have been identified in the literature and in the iSCAPE project:

- The effect of the photocatalytic coatings is maximum in the proximity of the wall, while it can be reduced with increasing distance from the surface where it is applied.
- The effect of the coatings on NO_x reduction is strongly dependent on wind direction and intensity and other atmospheric conditions such as temperature and solar radiation.

- The impact of interventions conducted over more extended areas (e.g., over the whole Lazzaretto area) was not analysed in detail.
- In general, dedicated campaigns and simulations are needed to adequately plan interventions in terms of effectiveness on NO_x reductions.

6 Urban level interventions

6.1 Action plan to mitigate air pollution and urban heat islands

The city as complex system is composed of a variety of interconnected items (Cowan, 2005). It inheres dynamic processes of urban social life and built urban environment and is continuously developing (Dockter, 2010). These dynamic processes mean that neighbourhoods should not be viewed in isolation, but be managed on a city-wide or even regional basis. To steer the future spatial development in a sustainable manner, urban planners rely on integrated urban development planning as connecting element (Yigitcanlar and Teriman, 2015, Walsh et al., 2011), which can be defined as: all activities aiming at creating, sustainably securing and continuously improving the material and immaterial conditions for the well-being of the population and the functioning of urban community (Lenort, 1960). For this purpose, urban planners need to develop, weigh up, manage and take appropriate interventions at urban level. In order to coordinate these interventions, multi-faceted action plans or programmes have to be drawn-up and established that are addressing the respective city's needs.

Knowing the diversity of planning systems and legal frameworks in Europe, the following section presents a commonly applicable approach for developing informal action plans instead of tailor-made legally binding plans for around 50 different planning systems.

Many steps of the methodological approach for developing an action plan have been tested in the iSCAPE cities Bottrop and Hasselt. The entire approach is described in the 'Report on potentialities of urban interventions and action plans' (D3.9).

6.1.1 What is an action plan?

Action plans can be adapted to the needs and goals of the respective city. In principle, an action plan lists the individual steps that are required to achieve predefined objectives (Tang et al., 2010). As a policy instrument, it provides a clear and systematic framework and offers planners but also other local decision-makers an orientation for the complex and demanding task of developing, implementing and reviewing strategies for dealing with the consequences of climatic and environmental impacts. The single elements of an action plan are orientated on the urban development control cycle (see Figure 33). With the adoption of an action plan, the stakeholders publicly express their political will to implement the adopted interventions within a certain period of time.

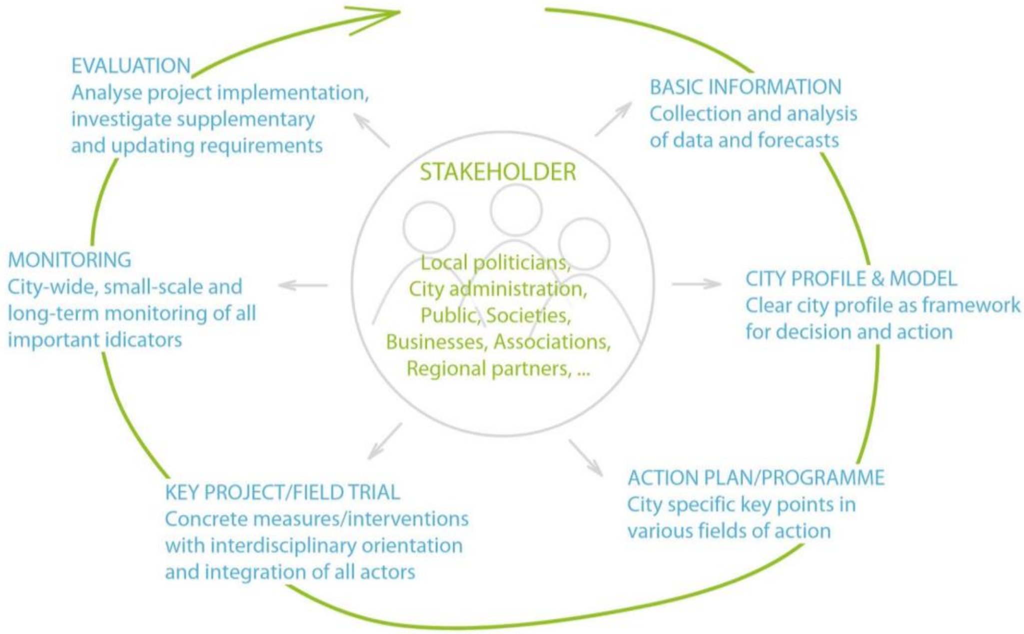


Figure 33 Urban development control cycle (own figure based on German Association of Cities (2013))

Strong action plans result from planning processes involving a wide range of administrative and non-state stakeholders. The latter is necessary to promote a significant impact on the actions of local governments (Burby, 2003). Stakeholder involvement ensures that specialist and local knowledge is integrated into plans and therefore contributes to learning and better plans (ibid.). At the same time, public participation promotes acceptance of the contents of the respective action plan and enhances its' acceptability and consequently implementability as several measures are up to private households. Public participation helps planners and politicians to broaden their problem understanding, minimise controversy and develop stronger guidelines for handling them (ibid.). All in all, irrespectively of any public participation that may be prescribed by law, the population and public bodies must be involved as early as possible in all relevant development steps of an action plan.

6.1.2 How to develop an action plan?

In order to develop action plans effectively, a number of conditions need to be met. A coherent stakeholder involvement and networking activities as well as public participation are some of them (see section 6.1.1). To create such conditions, several methodological approaches are considered as suitable in the procedure of developing an action plan. Illustrated by the example of the City of Bottrop and Hasselt a commonly applicable course of action is presented based on the development control cycle (see Figure 34).

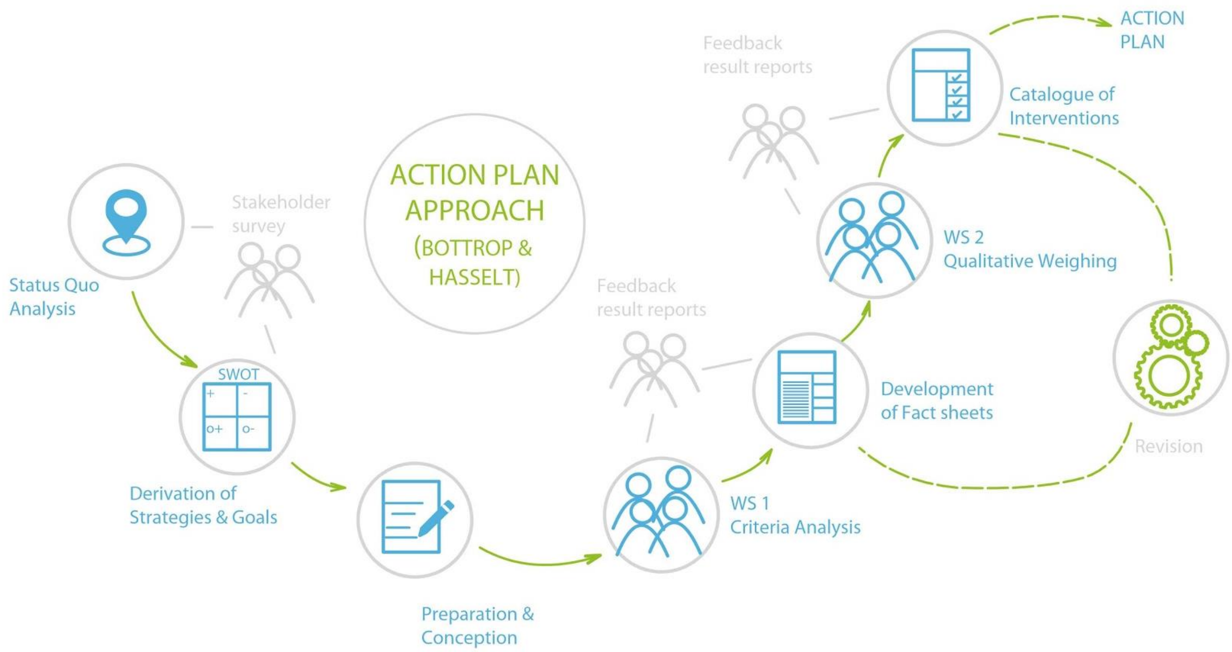


Figure 34 Action plan approach for the case studies of Bottrop and Hasselt (own figure)

As shown in Figure 34, one of the first steps of developing an action plan is to get familiar with the city profile and to analyse the current situation. Afterwards, relevant fields of action can be derived and involved stakeholders need to agree on future-compliant project objectives to develop integrated and locally suitable strategies. Having identified air pollution as one of the major environmental burdens of many cardiovascular diseases (World Health Organization, 2011), which also correlates with the urban heat island effect, the action plan aims to mitigate, reduce, and/or compensate air pollution and the urban heat island effect. By conducting a SWOT analysis (strengths, weaknesses, opportunities, threats) presented in the 'Report on solutions at urban level' (D3.4), strategies in three relevant fields have been crafted (see Figure 35). These are supplemented by cross-thematic strategies addressing the cooperation and coordination of stakeholders and governmental bodies. After setting the 'frame' for the action plan and connecting it to city specific key issues, the strategic orientation has to be underpinned with tailor-made urban level interventions that are determined in consultation with relevant stakeholders.

Workshops or other participatory methods at strategic points guarantee feedback loops and a coordinated and consensus-oriented outcome. In Bottrop and Hasselt, we have qualitatively supplemented the status quo analysis with a stakeholder survey. This has enabled us to identify a commonly accepted baseline. After deriving the need for action, we have conducted workshops to discuss effective measures to tackle urban heat islands and air pollution. A quantitative criteria analysis has identified the most suitable interventions. Within a further stakeholder workshop, these interventions have been qualitatively weighed based on well-founded fact sheets presenting necessary information for their implementation. Weighing criteria were synergies and conflicts with other measures, and potential side effects. This procedure has allowed us to extensively consider interrelations between the interventions and thus avoid undesirable developments due to complexity issues. The fact sheets are integrated into the action plan, while the weighing supports the prioritisation of measures. At the same time, the fact sheets serve as an evidence basis for decision-makers.

For the Cities of Bottrop and Hasselt two exemplary interventions, namely 'Wandering Trees/mobile Green Elements' (Bottrop) and 'Customised Coaching' have been put into practice.

Experiences from the field trials can be recalled from the ‘Report on potentialities of urban interventions and action plans’ (D3.9). This report also provides all fact sheets of urban level interventions and further methodological guidance for drafting an action plan.

6.1.3 What kind of interventions are essential for/effective in mitigating air pollution and urban heat islands?

For mitigating local air pollution and urban heat islands, it is neither efficient nor necessary to apply as many urban level interventions as possible, but tailor-made actions are required. For this purpose, it is essential to carry out an extensively analysis of the status quo (see Chapter 6.1.2) as well as to be aware of synergies, conflicts and side effects of planned interventions. To be aware of synergies and conflicts helps to control the impact of a bundle of interventions that serve one specific goal. Considering side effects is of great importance because it ensures that all dynamic processes of a city are taken into account while developing an action plan. This underlines the added value of a comprehensive action plan instead of an incrementalistic implementation of non-coordinated single interventions.

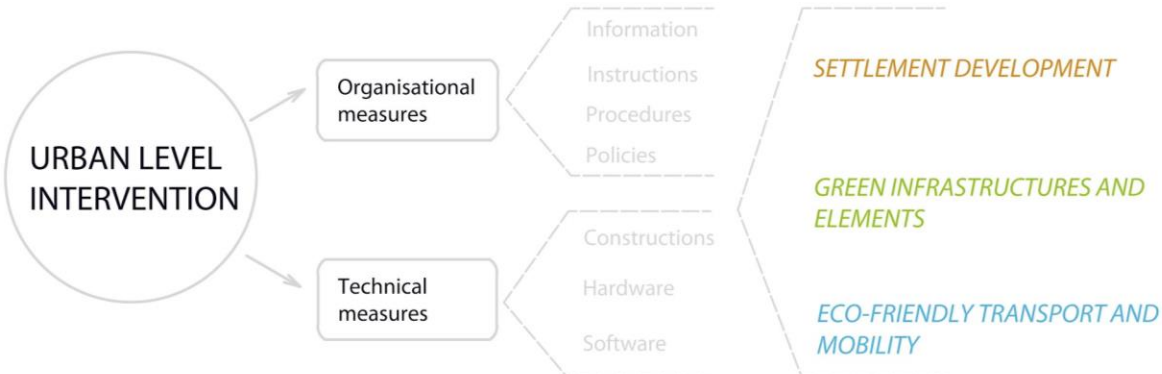


Figure 35 Categories of urban level interventions

Urban level interventions, integrated in an action plan, can differ significantly in their nature and impact. Thus, both organisational and technical measures are useful, which can be further assigned to content-related fields of action. To mitigate air pollution and urban heat islands, the fields ‘settlement development’, ‘green infrastructures and green elements’, and ‘eco-friendly transport and mobility’ are of great importance (see Figure 35). Common interventions and those that were assessed by relevant local stakeholder as being most effective, cost-effective and promptly implementable (see D3.9) are shown in Figure 36:

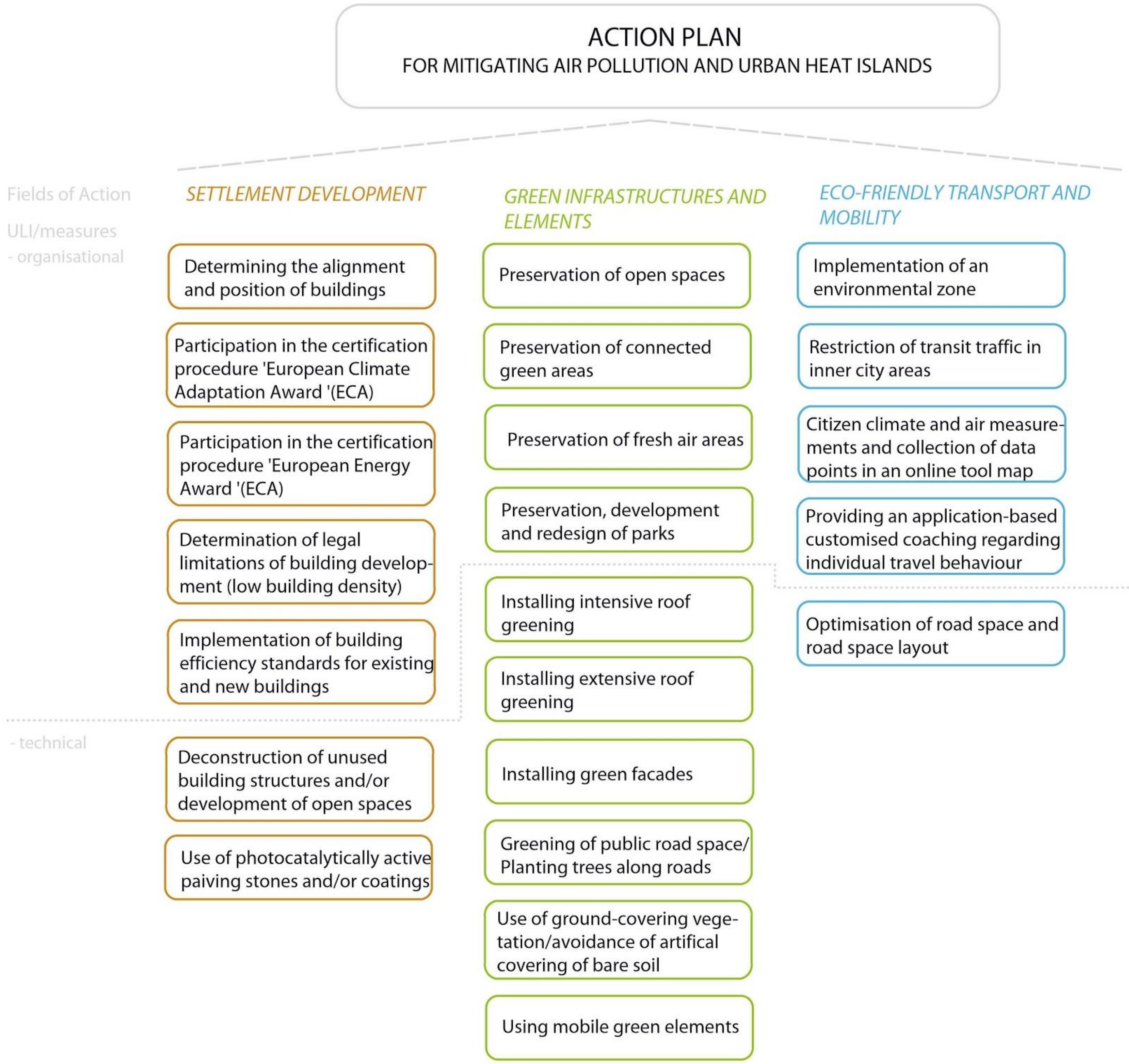


Figure 36 Common organisational and technical interventions the fields 'settlement development', 'green infrastructures and green elements', and 'eco-friendly transport and mobility'

The socio-economic effects of individual interventions can be qualitatively derived from experts' knowledge (ex-ante) or with the help of a social impact assessment (ex-post). Some socio-economic effects are listed in the fact sheets (see D3.9). The environmental effects of individual interventions can be assessed ex-ante by modelling and ex-post by monitoring their real effects. In the course of developing an action plan, the socio-economic and environmental assessments of every measure have to be interwoven and transferred into a holistic and city-wide picture. For this purpose, some results of the iSCAPE analyses described in the 'Report on environmental effects of behavioural actions' (D4.1), the 'Detailed report based on CFD simulations performed at neighbourhood scale' (D6.2), and the 'Detailed report based on numerical simulations of the effect of PCSs at the urban level' (D6.3) can also be used. The latter presents, for example, modelled changes in the PET values (bioclimatic situation) after planting additional trees in the street space in Bottrop (see Figure 37).

Figure 37 Model Bottrop 1 (Heideneck): Scenario A – Difference of PET values, scenario A minus baseline scenario (source: own account, data: City of Bottrop)

6.1.4 How to tackle barriers while developing and implementing action plans? Lessons learned and recommendations for other EU cities.

While developing an action plan, various obstacles often arise:

- Prioritisation of the action plan's objectives against other concerns of the current urban policy: in some cases, other urban problems are seen as more urgent by local politicians. Consequently, lower priority is given to environmental problems.
- Lack of resources in financial, temporal or personnel terms in city administrations: many local administrations do not invest in those fields of actions that are not legally required and action plans as informal concepts are not defined by law.
- Consideration of everyday conditions: it is somehow impossible to factor in everyday conditions and reactions of individual citizens.

However, some barriers may also occur during implementation. For example, the self-binding nature of the action plan is seen as one key success factor by many city administrations. Without political support, which leads to strong self-commitment, an implementation is difficult under some organisational conditions:

- Small municipal budget for implementation.
- Understaffed administrations while responsibilities must be named.

- Absence of an effective coordination, lack of existing organisational structures, and lack of cooperation between different responsible departments within an administration.
- Lack of incentive structures for interventions primarily addressed to private households.

For a successful development and implementation of an action plan and its embedded urban level interventions, some essential requirements have to be considered: Development of suitable implementation strategies, integration of urban level interventions into implementation instruments, financing as well as cooperation with/and acceptance by the population and other relevant stakeholders. In this regard, we provide the following various information and recommendations:

A good action plan is oriented along developing implementation strategies, …

There are different strategies for implementing action plans, e.g. mainstreaming or dedicated implementation. A mainstreaming strategy enables a competition with other objectives which can be inspiring and leads to interlacing and intertwining with other ambitions within the political realm in the best case scenario (Uittenbroek et al., 2013). However, in the worst case, other social or economic concerns become dominant, which makes the intended urban level interventions invisible. A dedicated implementation implies a stand-alone action plan which guarantees for the visibility of the intended interventions, but not for their implementation. Interventions need to be incorporated into legally-binding plans or programs first.

Whether in a mainstreaming strategy or in a dedicated stand-alone strategy, the estimation and availability of necessary resources in terms of labour force, know-how and costs as well as the integration in governmental and municipal budgeting, and a timetable to facilitate progress monitoring are essential (Marletto et al., 2012, Mickwitz et al., 2009, Ribeiro et al., 2009, Swart et al., 2009, Representatives of the City of Bottrop, 2019). Successful implementation of an action plan requires the incorporation in politics and public administration. Existing institutional structures should be used for observing, accompanying and advancing the process.

… merged with existing implementation instruments and tools, …

To efficiently implement urban level interventions of an action plan, they must be transferred to context-specific existing implementation instruments that vary from member state to member state and partly even between cities within in the same country. Both formal and informal instruments are available. Formal instruments are binding and usually laid-down in the respective planning laws of a member state (Hübler, 2005). Informal planning instruments that are mainly based on self-commitment are less formalised and are primarily used to influence the behaviour of spatial users (property owners, producers, road users, house builders, leisure users, nature conservationists, etc.) through information, incentives, etc. in accordance with predetermined principles and objectives (ibid.). The choice of implementation instruments depends on the stakeholder group to whom the measure is addressed.

Formal instruments are often preferred as they facilitate implementation due to their binding character which leads to legal and planning security. They tend to have a long-term character, whereas new environmental and societal challenges such as air pollution and climatic impacts require an up-to-date and sometimes flexible urban planning response (Priebs, 1999). Here, informal instruments offer more flexibility. In addition, it is undisputed that in view of the complexity of the task, coordination and cooperation between all relevant stakeholders are becoming increasingly important (Knieling and Roßnagel, 2014). Therefore, both binding instruments and flexible, non-formalised instruments should be combined for implementation.

… requires cooperation with and acceptance by the citizens and other relevant stakeholders, …

Planning objectives, contents and their acceptance and legitimacy are interwoven by the cooperation of different stakeholders in the planning process (Ritter, 1998). Information, conviction, acceptance and willingness to cooperate are becoming increasingly important planning resources (ibid.; Representatives of the City of Bottrop (2019)). There are different possibilities of participation, cooperation, co-creation, and bringing stakeholders together depending on the specific target groups:

- **City administration and other sector-specific stakeholders.** The interdisciplinary cooperation of experts while creating an action plan makes it possible to bring together conflicting interests. Moreover, it promotes the ability to reach a consensus Representatives of the City of Bottrop (2019). At the same time, resulting newly established networks represent an essential added value in the sense of integrated planning and can be maintained for future planning initiatives (ibid.).
- **Citizens.** The involvement of citizens ensures that everyday conditions are considered, local knowledge is integrated into plans and generates consensus-oriented plans (see Chapter 6.1.1). Moreover, a broad participation of citizens in the process of developing action plans can increase the legitimacy of the respective plan (Representatives of the City of Bottrop, 2019).
- **Decision-makers.** The support of political stakeholder is crucial for implementation (ibid.). There must be powerful political actors who have committed themselves to the mission of reducing air pollution and mitigating UHI.

… and is completed by an evaluation before revised in the next cycle.

Based on the urban development control cycle (see Figure 33), an action plan is neither fixed nor static, but dynamic and flexible in terms of adjustments to changing framework conditions (Faludi, 1989). In this sense, strategic spatial planning is based on collective learning, building consensus, and changing or adjusting existing routines according to new evidence (Wiechmann, 2008). While air pollution and urban heat islands pose great challenges for cities in many ways, it is possible and even likely that new fields of action emerge and need to be addressed or new priorities need to be set (Marletto et al., 2012). This makes continuous monitoring and subsequently an evaluation of the impacts of the action plan necessary in order to flexibly adjust it to new challenges or fields of action.

The evaluation should go beyond the mere assessment or measurement of impacts and should be used as a learning process for all stakeholders involved in the development and improvement of the urban action plan (German Association of Cities, 2013). In this way, process problems can be identified and, if necessary, external procedural support can be requested (Representatives of the City of Bottrop, 2019).

6.2 Behavioural change

6.2.1Intervention characteristics

Transportation Research Institute (IMOB) at Hasselt University conducted a behavioural change study together with city administration of Hasselt on urban level (see D4.1 ‘Report on environmental effects of behavioural actions’). The aim of this study was to encourage pro-environmental behaviour among citizens by designing informational-based behavioural interventions. In fact, this has been done by influencing travel behaviour by recording individual activity travel patterns using a smartphone application (see Figure 38). Based on the recorded activity travel diary customized feedback in the form of information package (Behavioural Intervention Tool) was provided to the individual. The Customized information package contains the ‘consequences’ (air pollution effect) of individual travel behaviour and suggestions to organise moves that are more environmentally friendly. This approach also helps citizens to be more active and healthier while improving the air pollution in the city by adopting active travel choices (walk/choices).

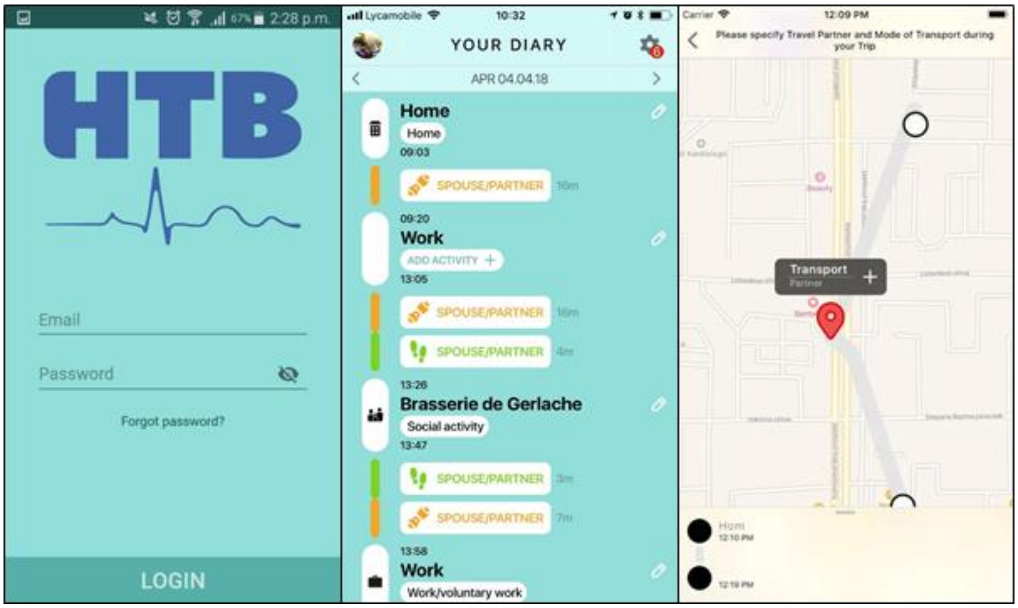


Figure 38 Screenshots of the smartphone application (own figure)

The design of this informational based behavioural intervention is following the four methods suggested in the literature, i.e. Feedback, Justification, Cognitive dissonance, and Commitments[2]. The customized information package is prepared for every individual, considered as a primary tool for information based behavioural intervention. Customized information is provided to each individual in four different aspects:

1. Exposure to air pollutant
2. Contribution to CO_2 emission (only if an individual uses a car)
3. Physical activity level
4. Hot and cold start of car (only in the event an individual uses a car)

The overall effectiveness of the informational based behavioural intervention depends considerably on how information is organized and presented. The information regarding each aspect is presented based on the following three fundamental elements:

- Brief information to increase the awareness of participant regarding a particular aspect, which is easy to understand and digest.
- Feedback regarding a quantitative measure of their behavior on each aspect and description of its effect.

[2] Explanation of these terms are as follows:
Feedback: It provides information about a specific behaviour which can be measured through some means, such as use of resources in some time frame (electricity, water etc.).
Justification: In this technique, reasons are provided for executing specific behaviour in the form of written material such as booklet, brochure etc.
Cognitive Dissonance: Interventions designed in a way that are consistent with existing beliefs and attitudes.
Commitment: Asking participants to make a verbal or written commitment about specific behaviours.

- Some recommended suggestions on how to change travel behaviour to decrease the effects along with its quantification. These suggestions are designed considering the ease in change for a particular participant based on certain rules, as mentioned in Ahmed et al. (2018).

The intervention study was conducted by following the AB[3] design as shown in the figure below:

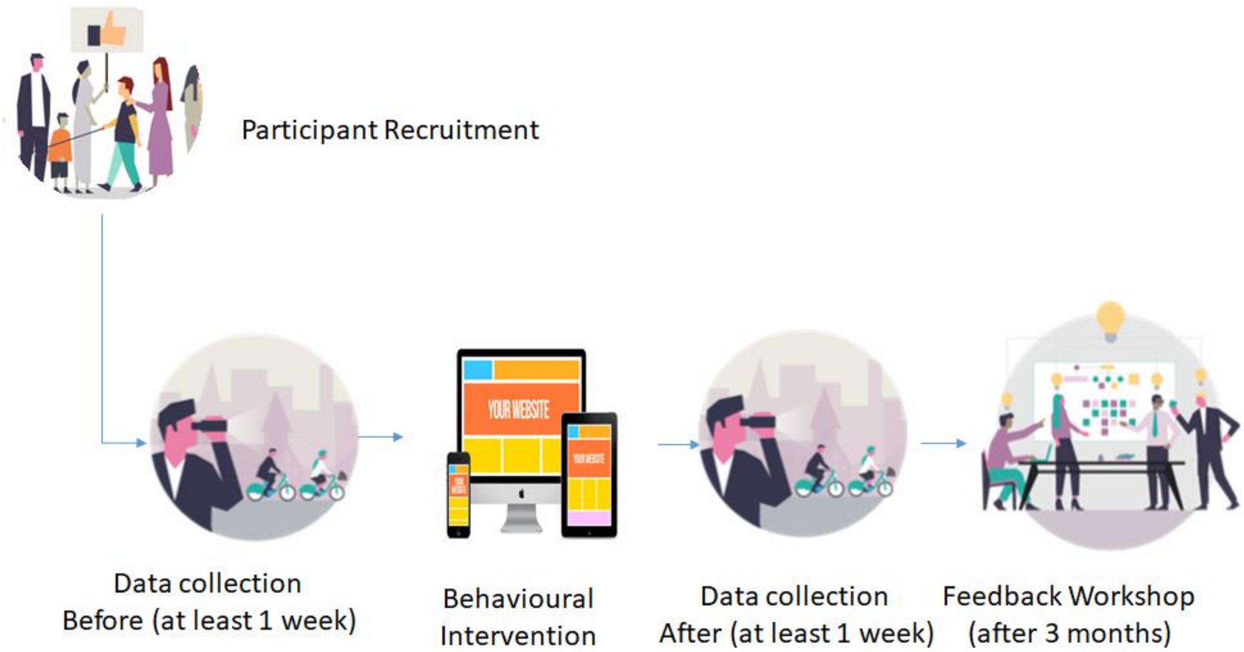


Figure 39 Intervention Study Design

The study was implemented by recruiting 53 Hasselt citizens in the month of June and July 2017. Participants were asked to record their activity travel diary for 2 weeks using GPS based smartphone application. Pro-environmental activity travel potential of each individual is detected along with its impact. The intervention, i.e. "Customized Information Package" comprising of actual and suggested activity travel choices along with their consequences, was shared with each participant. Participants were asked again to record their activity travel behaviour for 1 more week to assess the effectiveness of the intervention.

6.2.2 Effectiveness of the Intervention

The effectiveness of the intervention is assessed by comparing the activity travel behaviour of an individual before and after the intervention. In this regard, PEATB (Pro-environmental activity travel behaviour) indicator is used to know the difference in behaviour quantitatively. Furthermore, it is important to involve the control group (a group of participants who have not received informational intervention package) here as it tells that how much change in individual activity travel behaviour occurred due to some external factors. As the study is conducted in the month of June and July, activity-travel behaviours can be considerably different due to a variety of reasons,

[3] An AB design is a two part or phase design composed of a baseline ("A" phase) with no changes, and a treatment or intervention ("B") phase. If there is a change then the treatment may be said to have had an effect.

e.g. in the month of July schools are closed for the summer vacation. Presence of children in homes may cause a considerable shift in activity-travel routine.

Table 6 provides the PEATB measures in control group and treatment group (those individuals who go through all the steps mentioned in Figure 39). PEATB indicator is described by four measures i.e. car use in VKT[4], cold starts, activity travel mode involvement and PT (Public Transport) usage. It is important, that the numbers mentioned in Table 6 below are properly understood. Details for car VKT (VKT for Car trips within 3 km) are follows. In the pre-intervention phase for each participant based on the VKT travel in the car mode are estimated in % based on the total VKT in an entire week. Based on the estimated % an equidistant rank from 1 to 5 is assigned to each participant in control and treatment group. A similar approach is adopted in the post-intervention phase. As the ranks are equidistant, a simple difference is taken for pre and post-intervention phase, and this difference is then summed over all participants in control group and treatment group. Table 6 presents this sum measured for each indicator of PEATB. There is a considerable difference noted in the sum for each group and for each measure, which depicts that informational strategy has some influence on the travel behaviour routine of individuals.

Groups	PEATB Measures			
	Car VKT (≤ 3km)	Cold Starts	Active Mobility	PT Use
Control	-1	3	-16	-7
Treatment	11	9	-33	-3

Table 6 PEATB Measure Summary, Pre and Post intervention Phase for Control and Treatment Groups

Data for each PEATB measure is based on ordinal rank, therefore we used an analysis based on Wilcoxon signed-rank test for both groups, and the results are mentioned as below in Table 7. The Wilcoxon signed-rank test compares the two ranks sample data of the same population and tests whether the two-rank data have any difference statistically. The results are reported as significant (S) and Non-significant (NS) in Table 7. It is clear from the results that in the control group, the paired rank differences among individual are not significant for Car VKT, and Active mobility involvement, However, in the treatment group the differences are significant. This indicates that informational strategy was able to cause some significant differences in the travel behaviour.

[4] VKT stands for Vehicle kilometers travelled. It is the total kilometers traveled by motor vehicles on the road network during a given period of time.

Groups	PEATB Measures			
	Car VKT (≤ 3km)	Cold Starts	Active Mobility	PT Use
Control	NS	NS	NS	NS
Treatment	S	NS	S	NS

Table 7 Wilcoxon Signed-rank test significance results for Control and Treatment Groups (measures at significance level of 0.05)

6.2.3 Limitations of the Intervention

The study has some limitations which are as follows:

- The exposure analysis is limited in this study, as pollutant concentration data is available on very low resolution compared to the GPS based activity-travel routine. This can be improved by providing portable sensors to the individuals in order to know the exact level of pollutant inhalation and exposure to individuals. The availability of such precise information may contribute to develop a more appropriate and comprehensive informational strategy, which certainly has more effect on influencing individual behaviour.
- Some details on travel movements have been asked at the annotation stage. However, it is required to ask more details on it, which may provide ideas in relation to other constraints of travel movements. For example, information about accompanying persons for car trips, information about shopping trips based on the amount of luggage. The knowledge of these constraints will result in a more appropriate algorithm to obtain a replaceable number of trips.
- GPS-connectivity and smartphone issues due to which continuous activity and travel episodes are not appropriately obtained. To improve the continuity of the data, additional step by asking participants manually to fill the missing and undetected stops and trips. This will provide much confidence to participants that their travel movements are recorded with utmost accuracy. It will also increase the accuracy of information extracted from individual activity-travel routine.
- Availability of activity-travel routine data for different months or season, in order to assess the effect of external factors on travel behaviour. This knowledge can be utilised for appropriate effectiveness analysis for intervention.

7 Portfolio analysis for iSCAPE-interventions

In this section, we present the uncertainties related to the economic benefits of interventions, and how these uncertainties and the resulting benefits are correlated between different interventions. If the benefits of two interventions are highly correlated, an intervention with similar equal benefits, but with less correlation with the one with the highest net benefits should be prioritised. The analysis mimics the quantitative portfolio analysis, with the restriction that the preceding analysis of interventions did not quantify the correlation between the environmental impacts of different interventions, and we have to resort to qualitative and thus only indicative portfolio analysis.

7.1 Uncertainties in the economic analysis of interventions

Type of passive control system	Non-market effects	Market effects
Low boundary walls	Modelling uncertainties, as depicted in D3.8, there is a lot of variation in the reduction potential. Health impact uncertainties, the epidemiological evidence related to very-short term reduction in exposure is highly uncertain and assumptions are needed to interpret the response-concentration functions.	n/a
Green infrastructure, i.e. trees	Modelling uncertainties and upscaling uncertainties Based on analysis in different cities, trees can have different impacts on the pollution levels Some uncertainty related to the response-function, confidence interval is applied as in (World Health Organization, 2013) Uncertainty related to using population and employment location data as a proxy for exposed population	Statistical uncertainties for the estimated market benefits: -NO2 unit reduction: 112 €/m2 +/- 12 €/m2 statistical uncertainty (statistically significant at the 99.9% level) -PM2.5 unit reduction: 39.56 €/m2 +/- 19.29 €/m2 statistical uncertainty (statistically significant at the 90% level) -PM10 unit reduction: 82 €/m2 +/- 112 €/m2 statistical uncertainty (statistically insignificant) -Green infrastructure (trees and open fields): 95.55 €/m2 +/- 29.55 €/m2 (statistically significant at the 95% level) -Urban green spaces 10% increase in area: 170 €/m2 +/- 16 €/m2 statistical uncertainty (statistically significant at the 90% level) -Broad-leaved trees 10% increase in area: +/- 37 €/m2 +/- 16 €/m2 uncertainty (statistically significant at the 99.9% level) Other types of uncertainties include: -For NO2, urban green spaces and broad-leaved trees, an additional discount of 10-25% may need to be applied, because asking prices have been uses instead of realized selling prices. -Temporal variation of the above marginal effects depending mainly on macroeconomic conditions and the scarcity of green (in the case of green infra effects). -Spatial aggregation uncertainties, i.e. aggregating address-specific economic behavior into larger areal units. -Land use data uncertainty about green infrastructure. -Average annual concentration of pollutants data uncertainty (modelled or observed).
Photocatalytic coating	Modelling uncertainties: The reduction potential is based on measurements and observations in two street canyons, however, applied to city-scale Some uncertainty related to the response-function, confidence interval is applied as in (World Health Organization, 2013) Uncertainty related to using population data as a proxy for exposed population. Uncertainty related to the total amount of wall area.	n/a

7.2 Correlation table between the benefits and costs between different interventions

Intervention	Green infrastructure	Photocatalytic Coating	Low Boundary Walls	Behavioural Change
Green infrastructure		Correlated benefits: Green infrastructure (trees in Bologna/Guilford): reduced NO2 concentration 20-30% Photocatalytic coating: reduced NO2 concentration 8-17% (Bologna observations and simulations) Both of these benefits are highly dependent on the NO2 concentration level in the city. Both of these benefits are highly dependent on the NO2 concentration level in the city. If concentration with the existing green infrastructure >20, photocatalytic coating highly beneficial (B/C –ratio ~10) Uncorrelated benefits: Green infrastructure has wide range of other benefits: storm-water management, control of PM2.5 pollution (3% reduction in concentration), control of noise pollution, aesthetics, psychological benefits, heat-island effect reduction and resulting reduction in cooling energy demand, urban habitat, waste treatment, pollination, pest regulation, recreation, social cohesion	Correlated benefits: Green infrastructure (trees in Bologna/Guilford): reduced NO2 concentration 20-30% Low boundary Walls: 8% reduction in NO2 concentration, however, for very short-term exposure with possible acute health effects, while trees have an effect on the annual average exposure. Low-boundary walls only have benefits in the most NO2-polluted areas, possible partly due to lack of green infrastructure. Uncorrelated benefits: Green infrastructure has wide range of benefits, listed in element 3.2. in this table.	Correlated benefits: Green infrastructure (trees in Bologna/Guilford): reduced NO2 concentration 20-30%; and PM2 concentration by 3% Behavioural change: Reduced vehicle based NOx emissions by 5-18% Uncorrelated benefits: Reduced vehicle based PM2.5 emissions by 5-17%
Photocatalytic Coating	See element 3.2		Correlated benefits: Photocatalytic coating: reduced NO2 concentration 8-17% (Bologna observations and simulations) Low boundary Walls: 8% reduction in NO2 concentration, however, for very short-term exposure with possible acute health effects, while trees have an effect on the annual average exposure. Photocatalytic coating has potential to reduce the annual average concentration, and thus mitigate chronic effects. Low-boundary walls have an effect only on acute effects, in those areas with very high concentration levels of NO2. Also the benefits of photocatalytic painting have the highest benefits in those areas, but hold benefits in other areas as well. Partial correlation between benefits.	Correlated benefits: Photocatalytic coating: reduced NO2 concentration 8-17% (Bologna observations and simulations) Behavioural change: Reduced vehicle based NOx emissions by 5-18% Uncorrelated benefits: Reduced vehicle based PM2.5 emissions by 5-17%
Low Boundary Walls				Correlated benefits:

				Low boundary Walls: 8% reduction in NO2 concentration, however, for very short-term exposure with possible acute health effects, while trees have an effect on the annual average exposure. Behavioural change: Reduced vehicle based NOx emissions by 5-18% Uncorrelated benefits: Reduced vehicle based PM2.5 emissions by 5-17%

7.3 Tentative results of the optimal portfolio of interventions

Based on the uncertainty and correlation analysis, many of the interventions are effective in terms of controlling the NO_2 related exposure and resulting health impacts.

Most effective solution to reduce NO_2 concentration is the green infrastructure. It was shown in D5.3 that green infrastructure can reduce the NO_2 concentration by 20-30%. The monetised benefit of this reduction is directly dependent on the NO_2 concentration levels of the city; while in Guildford the annual benefits were around 42 million euros per year, in Bologna, for example, the benefits could amount to almost 800 million euros per year. It should be kept in mind that green infrastructure also brings many other benefits to the urban population, and the market benefits that were studied in D5.3 reflect these benefits. Also, the benefits of photocatalytic coating are highly dependent on the NO_2 concentration. It was shown in D5.3, that photocatalytic coating can reduce NO_2 concentration by 8-17%. While in Guildford this benefit could amount to approximately 30 million euros per year, in Bologna the benefit is already 330 million euros per year. This is directly dependent on those NO_2 concentration levels that are above the threshold of 20 $\frac{\mu g}{m^3}$. Thus, based on the portfolio analysis, green infrastructure is the first in line method to control NO_2 concentration and exposure, while photocatalytic coating has a promising role to play if green infrastructure is not able to reduce the concentration below the threshold. Finally, also low-boundary-walls were shown to reduce the NO_2 exposure. It was shown in the D5.3 that they could be a cost-effective solution in those street segments where the NO_2 concentrations are the highest, and people spend at least some time, such as cross-sections.

Out of the iSCAPE interventions, only green infrastructure and behavioural intervention were proven to decrease the $PM_{2.5}$ related exposure. Green infrastructure was shown to reduce $PM_{2.5}$ concentration in average by 3% in Guildford. However, in Hasselt simulations, it was shown that behavioural intervention can reduce the $PM_{2.5}$ and NO_x emissions from vehicles by 5-18%. For example, Aarnio et al. (2016) have shown that traffic contributes of the total $PM_{2.5}$ concentration between 20-33% in European cities. Thus, the behavioural intervention has the potential to reduce the $PM_{2.5}$ concentration in urban areas by some 1-3%. For NO_2 the source contribution varies more heavily, and it is harder to predict the change in the aggregate concentration.

Thus, based on the portfolio analysis, a mix of green infrastructure and behavioural interventions will bring the highest benefits. In case the NO_2 concentration level within the area is more than 20 $\frac{\mu g}{m^3}$, also photocatalytic coating and low-boundary walls would bring health benefits above their costs.

8 Conclusions

This report has summarised the exposure and socio-economic impact of the iSCAPE interventions. The testing summarised in the present report applied a range of novel measurement and modelling techniques for the study of the passive control systems interventions. Examples include the use of a temporary low-boundary wall, and the dispersion-deposition modelling combination to study the effect of GI in Guildford. Through this, the project has contributed to important methodological developments. Likewise, the results have contributed to a better understanding of the advantages and disadvantages of the individual passive control systems. Examples include the large effects of GI reported for Guildford, UK, as well as the positive effects observed as a result of the behavioural intervention.

Many of the disadvantages listed in the present report relates to aspects of the passive control systems that have not been studied as part of the iSCAPE project. Examples include the emission of primary biological aerosols and volatile organic compounds for trees, the lack of high-resolution air pollution maps for the behavioural intervention and the impact of photocatalytic coating deployed over a larger area. These and other topics are thus potential open questions for the scientific community to resolve in the coming years.

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