Green Infrastructure for Roadside Air Quality

An evidence-based approach to reducing roadside exposure to road transport pollution

GI4RAQ Guidance

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Contents

1. Purpose of this Guidance & FAQs

Green Infrastructure for Roadside Air Quality, 'GI4RAQ', is an initiative by James Levine and Rob MacKenzie at the Birmingham Institute of Forest Research (BIFoR), University of Birmingham, to promote and facilitate evidence-based use of green infrastructure to reduce roadside exposure to road transport pollution. This guidance document describes the development of an evidence-based, albeit *qualitative*, approach to GI4RAQ with Yvonne Brown, Principal Policy Analyst for Air Quality and Climate Change at Transport for London (TfL). It includes essential guidance on the use of the 'GI4RAQ Decision Tree' – a differential diagnostics approach, visualised using a PowerPoint Show with embedded links. Whilst the approach has been developed for TfL and refers to case studies in London, both this guidance and the GI4RAQ Decision Tree are applicable to roads in all towns and cities, and the authors hope that these resources will find widespread use.

The GI4RAQ Decision Tree guides the user through a short series of questions to identify the critical characteristics of the street in which they are seeking to reduce roadside exposure to road transport pollution. Subject to these characteristics, *robustly beneficial* green infrastructure interventions are identified, as well as ones potentially *beneficial to some at the expense of others*; the terms in italics will be explained in due course. The accompanying guidance, provided here, builds on the "Reduce, Extend, Protect" concept introduced in the Trees & Design Action Group's guide, 'First Steps in Urban Air Quality for Built Environment Practitioners' (Ferranti et al., 2019): first *reduce* the emissions of pollutants, then *extend* the distance between people and the sources of these emissions (i.e., vehicles) and, finally, *protect* those most vulnerable to their health impacts. This guidance is also consistent with, but elaborates on, that recently published by the Greater London Authority, 'Using Green Infrastructure to Protect People from Air Pollution' (GLA, 2019).

Within TfL, this evidence-based approach to reducing exposure to road transport pollution supports TfL's Healthy Streets Approach in putting people and their health at the centre of design decisions and the use of public space; it is also integrated into TfL's Environmental Evaluation Tool, designed to capture and manage the impacts of projects not requiring a full Environmental Impact Assessment under Town and Country Planning Regulations 2017 (MHCLG, 2017). 'Clean air', however, is just one of ten positive outcomes sought via TfL's Healthy Streets Approach, and green infrastructure contributes to a further eight (see 'Indicators Explained' section of Healthy Streets Check for Designers spreadsheet). Likewise, whilst this guidance focuses on improving roadside air quality, we recognise that green infrastructure can (simultaneously) deliver further, major benefits; we will highlight the opportunities for co-benefits throughout the document. Improved air quality is just one benefit of – and one consideration in – the planning, planting and investing in green infrastructure for the long term.

Frequently Asked Questions

The following questions and answers provide an abbreviated introduction to GI4RAQ, including the principles behind it and the potential of it to improve public health. Note, however, that they neither cover the recommendations made in the remainder of this guidance regarding the *implementation* of GI4RAQ, nor prepare you to use the GI4RAQ Decision Tree. It is important that all users of the Decision Tree read this GI4RAQ Guidance document in full.

What is *green infrastructure*?
Green infrastructure (GI) refers collectively to all vegetation in urban areas, including: parks, green open spaces, woodlands, gardens, street trees, hedges, green walls and green roofs. In the context of GI4RAQ, however, we refer specifically to the instances of these elements found within, or immediately adjacent to, city streets.

What do we mean by *roadside air quality*?
For the purposes of GI4RAQ, roadside air quality (RAQ) refers to the air quality at street level on either side of roads – from the kerb, up to and including the properties bounding the street. The latter may be of any 'use' (e.g. residential, commercial etc), may include buildings (with facades meeting the outer edge of the pavement, or set back to accommodate front gardens, forecourts etc) or simply comprise open space (e.g. parks and school playgrounds). We focus on the concentrations of nitrogen dioxide (NO_2) and particulate matter (PM) to which people are exposed here. (NB carbon dioxide (CO_2) is pivotal regarding climate change but not relevant to RAQ.)

How much pollution does green infrastructure *remove*?
At regional and national scales, vegetation plays an important part in removing certain pollutants from the atmosphere (see, e.g., ONS, 2018). At the scale of realistic urban planting schemes, however, GI removes very little pollution: only a few percent of PM, and even less NO_2, is typically removed by vegetation in the urban environment; see AQEG (2018a). Furthermore, what NO_2 is removed (by deposition to leaf surfaces) is offset by emissions of NO (rapidly converted by chemical reactions to NO_2) from the soils accompanying GI.

How does green infrastructure reduce *exposure*?
Given that GI within urban planting schemes *removes* very little pollution, you might wonder how GI can significantly reduce *exposure* to road transport pollution. The answer lies in its ability, not to remove this pollution per se, but to alter its distribution relative to people (i.e., reduce the concentrations of NO_2 and PM in those parts of the street predominantly occupied by people). In highly localised areas, and under the right wind conditions, 'vegetation barriers' (e.g. hedges, and

hedges combined with dense lines of trees) can much reduce the concentrations of pollutants in their immediate wake. AQEG (2018a) conclude that they can as much as halve the concentrations of pollutants (originating immediately upwind of the barrier) to which people are exposed immediately downwind.

'*But I thought you just said that vegetation removes little pollution..*'

Yes, vegetation barriers do little to remove pollutants. Instead, their influence is to divert the main flow of pollution. Just by forcing polluted air to take a longer path from 'source' (e.g. car exhaust pipe) to 'receptor' (i.e., a person), for example up and over a hedge, we reduce the concentrations of pollutants *at point of exposure*: as that parcel of air moves from one to the other, it mixes with surrounding air – on a busy street, this may still be polluted but, importantly, less polluted – and, the further it has to travel, the more it mixes, and is thereby diluted, en route. Where the wind blows fairly consistently from source to receptor, the addition of a vegetation barrier between the two can further reduce exposure immediately downwind by creating a vortex in its wake – a relatively isolated region of recirculating air largely bypassed by the pollution originating upwind.

Does green infrastructure itself emit gases (*volatile organic compounds)*?

Yes, all forms of vegetation emit gases known as volatile organic compounds (VOCs). In already polluted environments (i.e., moderate-to-high NO and NO_2 concentrations), these VOCs – like VOCs emitted from human-related sources – participate in chemical reactions that produce further pollutants. VOC emissions from GI, however, comprise a minor fraction of total urban VOC emissions and, at the scale of realistic urban planting schemes, their impact is both small and mainly felt at a distance downwind; again, see AQEG (2018a). The VOCs emitted from GI are of disbenefit for air quality, but of minor disbenefit, just as the deposition of pollutants to GI is of benefit, but of minor benefit. The value of GI4RAQ lies in the ability of GI to alter the dispersion, and thereby the distribution, of road transport pollution close to its sources (i.e., close to vehicles).

'*Isn't green infrastructure just treating the symptom rather than tackling the cause*'?

Yes, by altering the distribution of road transport pollution relative to people, GI4RAQ is reducing the impact of that pollution on public health, but it is not reducing the amount of pollution emitted in the first place. We strongly advocate, firstly, reducing emissions at source – this is the best way of improving urban air quality; secondly, extending the distance between sources and receptors; and, thirdly, protecting receptors via GI4RAQ for instance. This 'Reduce, Extend, Protect' principal was first introduced by Ferranti et al. (2017; revised 2019) in the Trees and Design Action Group's 'First Steps in Urban Air Quality for Built Environment Practitioners', and has since been reiterated in the Forestry Commission's Urban Tree Manual (2018), and underpins the detailed guidance recently published by the Greater London Authority (GLA, 2019), 'Using Green Infrastructure to Protect People from Air Pollution'.

'*Won't the ban on sales of petrol and diesel vehicles from 2040 solve the problem*'?

No. Road transport emissions of NO_2 are expected to decrease significantly following the UK Government's ban on sales of petrol and diesel vehicles in 2040. Unfortunately, however, this ban will not achieve the same reduction in emissions of PM from vehicles, as these include a significant non-exhaust fraction produced by brake, tyre and road wear. Further means of reducing the impacts of road transport pollution on public health are therefore sought well beyond 2040 as we continue to evolve our transport systems towards greater active travel and public transport.

Why is reducing *exposure* important for *public health*?

The impact of road transport pollution on public health is a function, not only of the concentrations of pollutants (at point of exposure), but also of the numbers of people exposed, the length of time for which they are exposed, and their inherent *vulnerability*; the very young and the elderly are particularly vulnerable to the impacts of air pollution, as are people with certain pre-existing medical conditions, such as chronic obstructive pulmonary disease. We can, and should, reduce this impact on public health by reducing the emissions of pollutants at source, but we should <u>also</u> strive to reduce *exposure* to what is emitted: this is a means of <u>further</u> reducing the public health impact. (NB Reducing exposure where the numbers of people, duration of exposure, vulnerability of those exposed *and* concentrations of pollutants combine to have greatest impact will, not only ensure maximum benefit for population-wide public health – maximum cost-effectiveness – but also act to reduce inequalities in health outcomes.)

'*So.. green infrastructure removes some pollution but isn't a magic bullet*'?

No. We shouldn't underestimate the benefit of reducing exposure (as well as reducing emissions). We also shouldn't conflate the limited ability of GI to *remove* pollution in the urban environment with its great potential to alter the distribution of this pollution, and thereby reduce the public's exposure to it. It is not effective at the first, but highly effective – when used strategically, in a site-specific manner – at the second: it is not simply mediocre at doing both. Let's employ *strategic* GI4RAQ to reduce exposure markedly where it will most benefit population-wide public health.

Is *all* green infrastructure good for roadside air quality?

No. Unfortunately, this is not objectively the case. Whilst all GI removes a small amount of pollution by deposition, and emits a small quantity of VOCs (see earlier), the much more influential effect it has on the distribution of pollution depends critically on its location: not only is the position of vegetation barriers relative to sources and receptors important, but also the geometry of the street in question (i.e., local urban form) and its orientation relative the prevailing winds. The latter together determine *what* GI4RAQ interventions, located *where* within the street, will be of benefit (or potentially disbenefit) to *who*. Just as the right GI in the right place can reduce exposure to road transport pollution, the wrong GI in the wrong place can increase exposure: there is no '*one size fits all*' solution.

Are *street trees* good for roadside air quality?

The influence of street trees on RAQ (and urban air quality more generally) has attracted much attention. The short answer is, it depends. On a highly trafficked street, where the air quality at street level is generally worse than the background air quality above the surrounding buildings, the addition of trees packed so tightly together that they form a near-continuous canopy, is of disbenefit for RAQ; a dense canopy impedes vertical mixing of the more polluted air at street level with the less polluted air aloft, and risks trapping pollution where people predominantly reside. On a street carrying little or no traffic, however, the air quality at street level is generally better than that aloft, and that same dense tree canopy could provide effective protection against the import of pollution from above the surrounding buildings. In this case, we can start to envisage multiple co-benefits stemming from the creation of a clean 'green corridor' that, at once, improves RAQ and incentivises active travel along this route (i.e., encouraging people to walk or cycle in preference to driving. Note, a modal shift towards active travel latter could thereby: draw people away from more polluted areas into cleaner ones, reducing their exposure to road transport pollution; reduce total vehicle use and ease traffic flow, reducing road transport emissions; and increase individuals' physical exercise, leading to further health benefits besides those related to air quality.

In the vast majority of cases, however, street trees are not planted this close to each other: they may sometimes be planted close enough together to form a dense line of trees – these may be used very effectively in conjunction with hedges to provide barriers to the *horizontal* transport off pollution (see later) – but they rarely form near-continuous canopies spanning the entire street. In all but exceptional circumstances, street trees (see below) will have little effect on RAQ either for good or ill. They will, however, deliver further major benefits irrespective of their influence on RAQ and, in so doing, should be valued, protected and planted for future generations.

Should we only invest in green infrastructure where it improves roadside air quality?

No. Improved RAQ is one benefit of GI, when employed strategically in a site-specific manner, whilst GI consistently delivers further major environmental, health and economic benefits. These include: increased biodiversity through the provision of new habitats and the linking of existing niches; increased urban resilience, particularly in the context of climate change (e.g., creation of cooler microclimates and contribution to sustainable urban drainage); the physical health benefits of improved thermal comfort (as well as improved RAQ) and the mental health benefits linked to access to green space (e.g. for relaxation and recreation) and a connection to nature; and the (socio-)economic benefits, including not only health-costs saved and heating/cooling costs avoided, but attractive placemaking that benefits businesses and communities alike. We should invest in high-quality GI installations, including their long-term maintenance, to take advantage of these valuable benefits, many of which can be realised simultaneously with careful planning.

Is green infrastructure a long-term investment?

Yes. GI4RAQ has a role to play in reducing exposure to road transport pollution beyond the 2040 ban on petrol and diesel vehicle sales (see above). Meanwhile, GI has a part to play in catalysing a modal shift towards increased active travel that, in conjunction with increased use of public transport, can reduce total vehicle use – the ultimate solution to RAQ and urban air quality at large. At the same time, the environmental, health and economic benefits of high-quality GI installations and maintenance will only increase as our climate continues to warm: the need for cooler microclimates for improved thermal comfort outdoors, and reduced operational-energy demands (i.e., reduced air conditioning) indoors, will increase – and increase most swiftly in our towns and cities due to the urban heat island effect; the frequency of high rainfall events is projected to increase, putting pressure on mains drainage; rising air temperatures put increasing physical stress on the human body, whilst the need for interventions to relieve mental stress, and help other mental health conditions, is also on the rise; and economic growth, coupled with equitable use of the additional resources thereby generated, has its part to play in tackling these challenges. GI is classed as a form of *infrastructure* in recognition of the valuable services it provides. It is amongst the most valuable infrastructure – to both people and planet – we can invest in for the long term.

2. Introduction to GI4RAQ

According to the World Health Organization (WHO, 2016), air pollution constitutes the greatest environmental risk to human health: outdoor air pollution claims approximately 3,000,000 lives each year worldwide; and 90% of the world's urban population live in cities exceeding its air quality guidelines. In the UK alone, Landrigan et al. (2017) estimate that outdoor air pollution foreshortens of the order of 50,000 lives each year, and the Government's Department for Environment, Food and Rural Affairs (DEFRA, no date) identifies road transport as the main source of pollution in urban areas. In this document, we describe the development of an evidence-based approach to GI4RAQ: using *strategic* green infrastructure to reduce *exposure* to road transport pollution.

Note, we chose our language carefully in the last sentence. Firstly, the potential of green infrastructure (GI) to improve roadside air quality (RAQ) predominantly lies, not in its ability to strip pollution out of the air, but in its ability to alter the distribution of pollution and thereby reduce the public's *exposure* to it; the underlying science is summarised in section 4 of this document. Secondly, there is no 'one size fits all' solution – only the right green infrastructure, in the right location, will be robustly beneficial. In section 5, we introduce the GI4RAQ Decision Tree, which will enable you to identify suitable, *strategic* interventions on a site-by-site basis. We then present a series of case studies in section 6 demonstrating *how* the GI4RAQ Decision Tree could be applied to a range of real-world scenarios. In the remainder of this section, we define what we mean by GI and RAQ, and explain why GI4RAQ represents a valuable investment for the long term; and, in section 2, we briefly outline the further, major environmental, health and economic benefits (i.e., besides improved air quality) delivered by GI.

'GI' refers collectively to all vegetation in urban areas. This includes all scales of vegetation, from parks, green open spaces, woodlands and gardens, to individual street trees, hedges, green walls and green roofs. It is classed as a form of *infrastructure* in recognition of the *services* it provides to the people living and working in our towns and cities, delivering health, environmental and economic benefits. In the context of GI4RAQ, however, we refer specifically to the instances of these elements found within, or immediately adjacent to, city streets. We likewise use 'RAQ' to refer to the air quality at street level either side of the roads in these streets – from the kerb, up to and including the properties bounding the street. These properties could be houses (with or without front gardens), non-residential buildings (with facades meeting the outer edge of the pavement, or set back to accommodate forecourts etc) or open areas, such as parks and school playgrounds. The Mayor has launched audits of the most polluted schools and nurseries across London to identify measures to reduce children's exposure to poor air quality. A £6million Air Quality Fund was announced in September 2018 to support projects across London that tackle pollution hotspots. The role of GI is recognised in these projects, alongside the Greener City Fund, to: increase urban tree planting, provide strategic GI projects, and create new urban woodlands.

For clarity, it is important we differentiate between the challenges posed by, and indeed efforts to mitigate, air pollution and climate change. Reducing emissions of carbon dioxide (CO_2), and other greenhouse gases, is essential to mitigating further climate change, and vegetation has a vital role to play in reducing the atmospheric burden of CO_2. CO_2 is not relevant to RAQ, however, and the sequestration of CO_2 by trees and other vegetation is therefore not considered within GI4RAQ. RAQ is essentially characterised by the concentrations of pollutants emitted from road transport known to be harmful to human health. We are particularly interested in the concentrations of nitrogen dioxide (NO_2), which local authorities strive to ensure comply with a legislated threshold (40 $\mu g/m^3$), and particulate matter (PM), for which there is no 'safe' threshold (e.g. COMEAP, 2009 and 2010). GI4RAQ is therefore concerned with the impact of GI on the concentrations of these substances at the roadside. Some of the substances emitted from vehicles participate in chemical reactions that result in the formation of further pollutants, so-called secondary pollutants. The latter include gases, such as ozone (a respiratory aggravant), and further components of PM. We do not explicitly consider secondary pollutants in GI4RAQ; we will, however, discuss the *minor* role of volatile organic compounds emitted from vegetation in their formation in section 3.

The best way to improve RAQ is to reduce road transport emissions. This tackles the root cause of the problem and improves air quality, not only locally (i.e., at the roadside), but also regionally (i.e., downwind). To this end, TfL is engaged in a dual-strategy aimed at reducing vehicle use: encouraging both active travel (e.g. creating Cycle Superhighways) and the use of public transport (e.g. investing in the new Elizabeth Line and wider Cross Rail connectivity); and, simultaneously, discouraging the use of the most polluting vehicles (e.g. introducing the Ultra Low Emissions Zone and extending the realm of the existing London Congestion Charge). TfL is also making efforts to reduce the emissions per vehicle (e.g. replacing diesel buses with electric and hydrogen-fueled ones) and smoothing traffic flow (e.g. phasing more than 6000 sets of traffic lights).

We note that road transport emissions of NO_2 are expected to decrease significantly following the UK Government's ban on sales of petrol and diesel vehicles in 2040. Unfortunately, however, this ban will not achieve the same reduction in PM emissions from vehicles, as these include a significant non-exhaust fraction produced by brake, tyre and road wear. Further means of reducing the impacts of road transport pollution on public health are therefore sought, not only between now and 2040, but well beyond 2040 as we continue to evolve our transport systems. It is in this context that we should use all means at our disposal to reduce public exposure to what is emitted – and these measures will have considerable long-term value.

Smaller particles are more harmful to human health than larger ones owing to their ability to travel further into our respiratory systems; the smallest particles can interact with lung tissue and even cross the air/blood interface. 'Fine particles' are strictly particles of diameters less than 2.5μm ($PM_{2.5}$) and these include the subset of so-called 'ultrafine particles' with at least one dimension of less than 0.1μm ($PM_{0.1}$). The UK's Air Quality Expert Group (AQEG, 2012) concluded that, on average, regional background PM accounts for 60-80% of $PM_{2.5}$ in urban areas (by mass) but that $PM_{2.5}$ directly emitted from road transport may account for as much as a third of $PM_{2.5}$ at the kerbside. The precise fraction attributable to non-exhaust vehicle sources remains uncertain, as does the relative importance of Ultra Fine $PM_{0.1}$ (compared to $PM_{2.5}$) for impacts on human health (see, e.g., AQEG, 2018b). Even the metric most pertinent to these impacts is subject to further research: it isn't yet clear whether we should be primarily concerned with particle *mass* concentration, or *number* concentration (i.e., the mass of particles, or the number of particles, per unit volume of air); see, again, AQEG (2018b). Speculation that the surface area of particles, rather than their mass, predominantly determines their toxicity has led to suggestions that $PM_{0.1}$ may be particularly harmful (see, e.g., HEI, 2013) and, whilst $PM_{0.1}$ may only account for a small fraction of total PM mass concentration, it accounts for well over half total PM *number* concentration (AQEG, 2018b).

What we do know is that the UK Government's Committee on the Medical Effects of Air Pollutants (COMEAP, 2010) estimated that: removing all human-made $PM_{2.5}$ from the atmosphere would save approximately 36.5 million life years over the next 100 years (equivalent to a six month increase in UK average life expectancy from birth); and reducing the annual average $PM_{2.5}$ mass concentration by just 1μg/m_3 (less than 10% of the mass concentrations typically encountered in urban areas) would save around 4 million life years. In its new Clean Air Strategy (DEFRA, 2019), the UK Government pledges to 'reduce people's exposure to $PM_{2.5}$' and 'reduce $PM_{2.5}$ concentrations across the UK, so that the number of people living in locations above the WHO guideline level of 10 μg/m^3 is reduced by 50% by 2025'. The Mayor of London goes further in the London Environment Strategy, aiming to meet the WHO guidelines by 2030. Reducing exposure to $PM_{2.5}$ at the roadside is a good place to start and, as road transport is the main source of $PM_{0.1}$ in urban areas (AQEG, 2018b), this is the priority environment in which to reduce exposure to $PM_{0.1}$ too.

Reducing *exposure* means reducing the number of people exposed to pollution, the length of time for which they are exposed and/or the concentrations of pollutants to which they are exposed. Of course, the concentrations of pollutants will decrease as we reduce emissions, but it is their concentrations *at point of exposure* that determine pollution impacts on human health, and we can further reduce these with appropriate interventions. We can also prioritise steps to reduce the exposure of the most vulnerable people exposed (i.e., the very young, the elderly and people with certain pre-existing medical conditions, such as chronic obstructive pulmonary disease). TfL is already carefully positioning bus stops and stands to this end, and introduced Low Emission Bus Zones. Meanwhile, the current collaboration between BIFoR and TfL was forged to realise another powerful means of reducing exposure: GI4RAQ – the 'careful positioning' of GI to control the distribution of road transport pollution relative to people.

As noted at the start of this document, improved RAQ is just one benefit of – and one consideration in – the planning, planting and investing in GI for the long term. We briefly outline the further, major benefits of GI in the next section.

3. Further Major Benefits of GI

Perhaps the most widely recognised benefit of GI is its support of greater biodiversity, through the provision of new habitats and the linking of existing niches. The ‘environmental net gain’ called for by DEFRA (2018) in its latest 25 Year Environment Plan is not limited to increased biodiversity, however, and GI can make other major contributions to this. GI is increasingly recognised to be a key ingredient in building urban resilience, particularly in the context of climate change. It can mitigate the impact of global warming on thermal comfort (exacerbated by the so-called urban heat island effect) through the provision of shade and creation of cooler microclimates through evapotranspiration – the uptake of rainwater and subsequent release of water vapour. Meanwhile, integral in sustainable urban drainage systems (SUDS), GI can reduce the pressure on mains drainage by storing and attenuating the release of rainwater during high rainfall events.

Improved RAQ is but another environmental benefit to add to the list – and another benefit for human health. Note, the combination of improved thermal comfort and reduced exposure to road transport pollution has considerable potential for improving the health outcomes of urban inhabitants. The 35,000+ premature deaths attributed to the European heat wave of 2003 (see, e.g., Bhattacharya, 2003), for instance, resulted from the combination of thermal stress *and* exposure to higher concentrations of pollutants (partly driven by the higher air temperatures). Meanwhile, parks, nature reserves and even private gardens provide space for recreation and physical activity that bring benefits for mental as well as physical health (see, e.g., WHO, 2017). In a presentation at the Trees, People and Built Environment III conference (University of Birmingham; 5-6 April, 2017), Public Health England’s Deputy Director for Health and Wellbeing, Dr Ann Marie Connolly, went as far as to say, “If green infrastructure was a pill, every GP in the country would be prescribing it.”

These health and environmental benefits translate into economic benefits. For example, the UK’s Office for National Statistics (in collaboration with the Centre for Ecology and Hydrology) recently estimated that the country’s vegetation removed 1.3 billion kg of air pollutants in 2015, and this translated into health-costs saved totalling roughly £1 billion (ONS, 2018). Likewise, Moss et al. (2019) have used a variety of methods to estimate the costs saved from reduced air conditioning in inner London, as a result of GI’s local effects on climate: an enthalpy-based calculation suggests the saving in inner London alone could be as great as £84 million per year, whilst bottom-up model simulations suggest a somewhat lower figure of between £2.1 million and £20 million. GI delivers further economic benefits through attractive placemaking: local businesses benefit from increased footfall, translating into increased sales of products or services; and clusters of related businesses, for example within the creative and innovation sectors, benefit from increased productivity as a result of chance encounters – the so-called 'business of serendipity'. For estimates of the many and varied benefits of London's GI, see 'Valuing London's Urban Forest: Results of the London i-Tree Eco Project' (Rogers et al., 2015); their total estimated value is some £132.7 million per year.

We note the increasing ability to *quantify* the benefits of GI *at planning*, supporting cost-benefit analyses to justify investment in high-quality installations and their long-term maintenance. Alongside Moss et al.'s (2019) progress towards quantifying the benefits of GI for thermal comfort (as captured by reduced air-conditioning costs; see above), the Construction Industry Research and Information Association's Benefits of SUDS Tool (B£ST) provides quantitative estimates of the economic benefits of GI for sustainable urban drainage. To complement the qualitative approach to GI4RAQ set out in this document, the University of Birmingham has developed *quantitative* software – the prototype GI4RAQ Platform (www.GI4RAQ.ac.uk) – to facilitate and inform, amongst other things, 'pre-app' planning discussions. To this end, the prototype GI4RAQ Platform has been co-designed with representatives of its target end-users – environmental consultancies preparing air quality assessments on behalf of developers, and local authorities determining the developers' planning applications. It enables users to estimate the site-specific impacts of roadside vegetation barriers on the dispersion of road transport pollution, accounting for local conditions of wind and urban form. Coupled with suitable epidemiology and cost models, it should ultimately be possible to estimate the health-costs saved as a result of GI4RAQ interventions.

4. Scientific Basis of GI4RAQ

GI4RAQ focuses specifically on the potential of GI to reduce the concentrations of road transport pollutants, especially NO_2 and PM, to which people are exposed at the roadside. This section summarises the physical science underpinning the *direct* influence of one on the other. We note, however, that GI also has a major *indirect* part to play in reducing exposure to these pollutants, and indeed reducing their emissions in the first place. Through the creation of clean 'green corridors' and networks of green space, GI can help draw people away from busy, polluted areas into less polluted ones, and thereby reduce their exposure. Meanwhile, by incentivising active travel – getting people out of their cars and, instead, walking or cycling – GI has the potential to support a modal shift in transportation and reduce vehicle emissions. Whilst we focus on the direct benefits of GI for RAQ, these co-benefits are important – particularly important in the long term.

The UK's Air Quality Expert Group (AQEG, 2018a) recently vetted the existing literature, and ultimately reviewed over 70 publications regarding the 'Impacts of Vegetation on Urban Air Pollution' for DEFRA and the devolved authorities. The bottom line of their report was that GI has a significant role to play, but perhaps not the one we might first suppose. As we have already alluded to, the value of GI in improving RAQ lies, not in its ability to remove pollution per se, but in its ability to control the distribution of pollution relative to people, and thereby reduce the public's exposure. For completeness of argument, however, we will briefly summarise in this section the science surrounding each of the three ways in which vegetation can, at least in principle, influence RAQ (for good or ill): the removal of pollutants via *deposition* to leaf surfaces; the formation of secondary pollutants – in already polluted areas – as a result of the emission of *volatile organic compounds (VOCs)*; and the increase (or decrease) of pollution *dispersion*, altering its distribution.

At regional and national scales, *deposition* to leaf surfaces plays an important part in removing certain pollutants from the atmosphere; we referred in the last section to recent estimates of the pollution removed, and associated health-costs saved, published by the ONS (2018). At the scale of realistic urban planting schemes, however, deposition is of limited benefit. Large parks may offer some benefit, and we note that some plant species are more efficient than others at removing pollutants (see, e.g., Chen et al., 2017) but, overall, the AQEG (2018a) concluded that deposition removes just a few percent of PM and perhaps even less NO_2 in the urban environment. Furthermore, what NO_2 is removed by deposition to vegetation is offset by emissions of nitrogen monoxide (NO) from the soils accompanying that vegetation. In the presence of sunlight, NO_2 is rapidly converted into NO and vice versa, so additional NO somewhat negates reduced NO_2. Thus, deposition is of benefit in so far as it removes a small amount of PM, and removing pollution is beneficial both locally and regionally (i.e., downwind), but it is is of very limited benefit.

The story surrounding *VOCs* emitted from vegetation is somewhat similar. In the presence of moderate-to-high NO and NO_2 concentrations (i.e., in already polluted areas), VOCs participate in chemical reactions that produce secondary pollutants (i.e., not directly emitted from vehicles). The latter include ozone and further components of PM. VOC emissions from vegetation, however, comprise a minor fraction of total urban VOC emissions and, at the scale of urban planting schemes, their impact is both small and mainly felt at a distance downwind; see recent paper by Hewitt et al. (2019) in addition to AQEG (2018a) and the references contained therein. Therefore, whilst VOCs emitted from vegetation are of disbenefit for air quality, they are of minor disbenefit.

We nevertheless note that some VOCs are more reactive than others, and VOC emissions from vegetation could change as our climate changes. Isoprene is a particularly reactive VOC, and it may be prudent to plant a mixture of tree species to avoid planting solely those species known to emit above-average amounts of isoprene; see Donovan et al.'s (2005) 'Urban Tree Air Quality Score' for further information. Meanwhile, at a global scale, projections of future isoprene emissions suggest that the effects of rising air temperatures, which tend to increase isoprene emissions from vegetation, and rising concentrations of atmospheric CO_2, which tend to reduce these emissions, may roughly cancel each other out. These projections are, however, subject to large uncertainties surrounding future changes in soil moisture, and these changes could be highly localised, leading to a patchwork of regions of increasing and decreasing emissions. Furthermore, the net effect of these influences on the emissions of other VOCs from vegetation is not yet clear; for further details, see Peñuelas and Staudt (2010) and the references contained therein. Here, we stress that tree species selection should take account of many other factors besides emissions of VOCs, particularly those governing the likelihood of successful long-term growth (e.g. resilience to changes in climate, pests and disease), and tree officers should be entrusted with this selection. For the latest advice on selection and procurement, see the Urban Tree Manual recently produced for DEFRA (Forestry Commission, 2019), 'The Right Tree in the Right Place for a Resilient Future'.

The influence of vegetation on the *dispersion* of pollution is somewhat different, as it neither adds to nor reduces the total amount of pollution across a city region. It does, however, alter its distribution, and thus has the potential to alter the concentrations of pollutants in the areas people predominantly occupy. Dispersion collectively refers to the transport of pollutants by the wind away from their sources (i.e., vehicles) and their concomitant mixing with surrounding air. Even in a highly trafficked street, that surrounding air – although still polluted – is less polluted than the parcels of air originating at vehicle exhaust pipes and, indeed, brakes, tyres and point of contact between tyres and road. Mixing with surrounding air thus results in the dilution of pollutants and, the further pollution must travel from its sources to 'receptors' (i.e., people at the roadside), the greater the dilution en route, and the lower the concentrations of pollutants they are exposed to. Much of the value of GI4RAQ lies simply in lengthening the 'source-receptor pathway' by putting a vegetation barrier between source and receptor, and forcing air to take a more circuitous route from one to the other. This principle was central to the Trees and Design Action Group's guide, 'First Steps in Urban Air Quality for Built Environment Practitioners' (Ferranti et al., 2017; revised 2019); it has been reiterated in the Forestry Commission's Urban Tree Manual (2018); and it is a key ingredient in the detailed guidance, 'Using Green Infrastructure to Protect People from Air Pollution', recently published by the Greater London Authority (GLA, 2019). The principle is integral in GI4RAQ too.

According to AQEG (2018a), in the right locations and under particular wind conditions, vegetation barriers can reduce the concentrations of pollutants *in their immediate wake* by as much as a factor of two. This dramatic but highly localised reduction is the result of a further effect beyond simply lengthening the source-receptor pathway. If the wind is blowing directly from source to receptor, and a vegetation barrier is added between the two, the polluted air is forced up and over the barrier in such a way that it creates a vortex – a relatively isolated region of recirculating air – immediately downwind of the barrier that is largely bypassed by the pollution originating upwind.

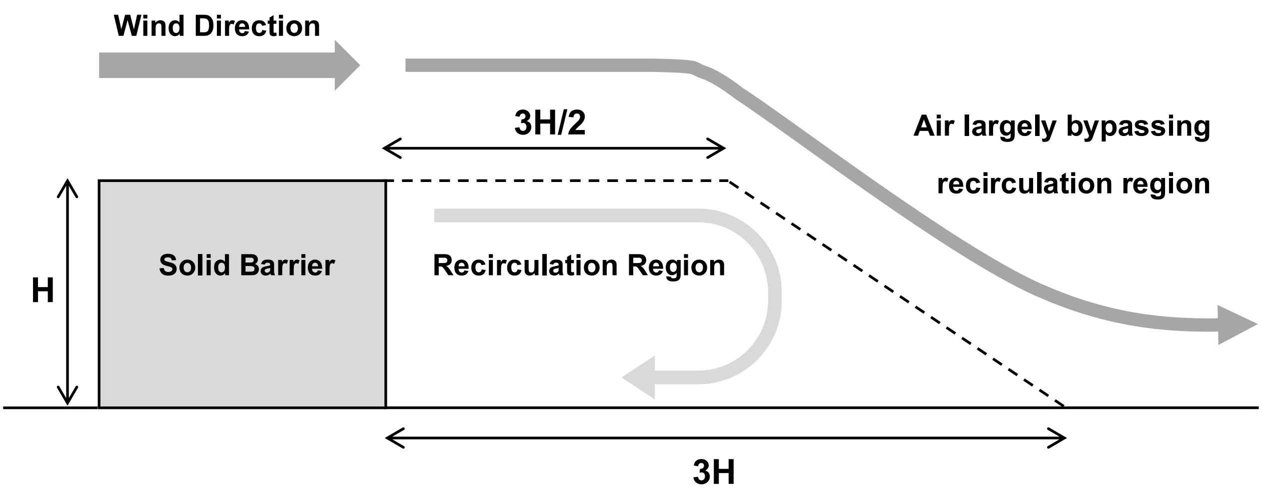


Figure 1. Shape and dimensions of trapezoidal 'recirculation zone' downwind of a solid barrier of height, H, illustrated in vertical section; based on Figure 2 of Harman et al. (2004).

Studies of the flow of air around solid barriers such as buildings – both theoretical studies based on computational fluid dynamics (CFD) and observational ones in the real world and/or employing scale models in wind tunnels – have established the approximate shape and dimensions of this 'recirculation region'. Harman et al. (2004) reviewed a number of such studies, concluding that it takes a trapezoidal shape (in vertical section) of dimensions dependent on the height of the barrier as illustrated in Figure 1 above. Note, these dimensions will vary somewhat in response to the amount of turbulence in the air above the buildings and the shape of those buildings, particularly the geometry of their roofs, but are (to first order) independent of wind speed. Critically, however, the dependence on barrier height, H, proposed by Harman et al. (2004), suggests the flow of air at street level is largely restored to upwind conditions a distance of 3H downwind of the barrier.

Assuming a dense vegetation barrier affects the flow of air in a similar fashion, the recirculation region generated in its wake will also extend a maximum distance of 3H downwind. Owing to the shape of the recirculation region (i.e., tapering towards the ground), however, the barrier will not protect people from pollution to this full distance. Taking the height of a person to be 2m has two implications for the dimensions of a vegetation barrier, as illustrated in Figure 2 below, if it is to provide effective protection to people in its immediate wake:

- The vegetation barrier must extend continuously from the ground to a height, H≥2m.

- The maximum distance people are protected downwind, D = 3H-3 (metres) where H≥2m.

Or A barrier of height, H ≥ D/3 +1 (metres) is needed if it is to offer any protection at distance, D.

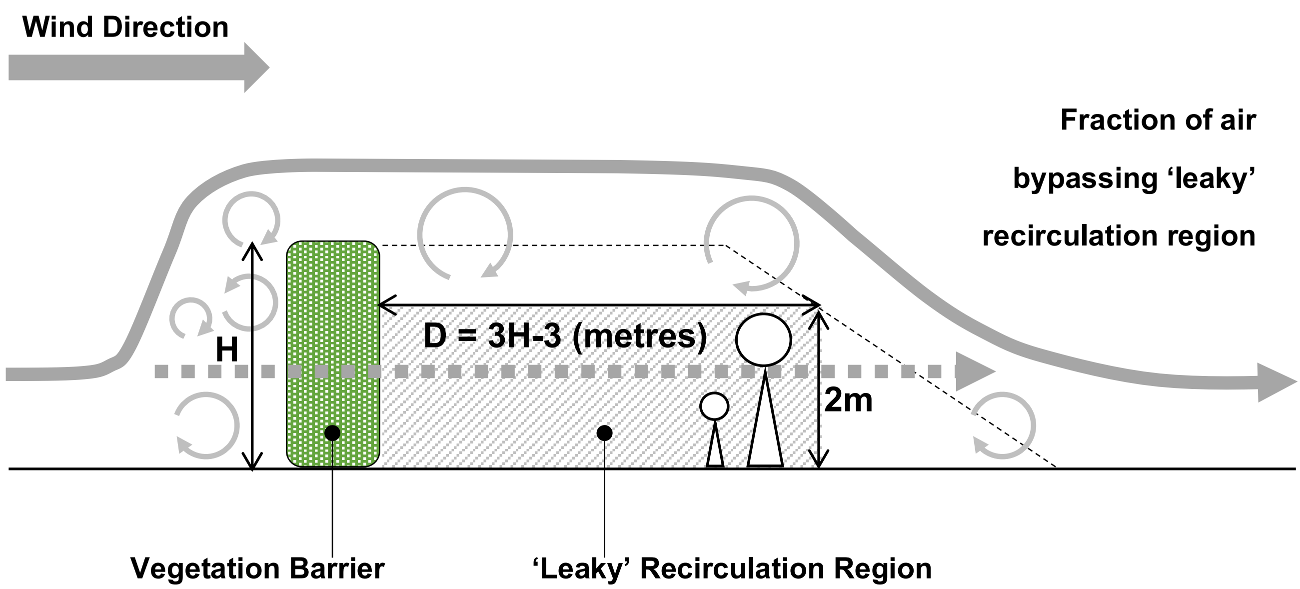


Figure 2. Modified version of Figure 1, illustrating the 'leaky' recirculation zone expected downwind of a vegetation barrier of height, H, and the dimensions of the region in which people are somewhat protected from pollution originating upwind.

Unlike solid barriers, vegetation barriers are porous; even the thickest and most dense hedge will permit the passage of some air through its foliage. The recirculation zone generated downwind of a vegetation barrier is therefore likely to be more disturbed and more 'leaky', if you will, than one generated in the wake of a solid barrier such as a building. Figure 2 illustrates how a fraction of air will be forced up and over the vegetation barrier, and bypass the leaky recirculation region in its wake (solid thick grey arrow). Meanwhile, some air will inevitably pass through its foliage into this recirculation region (dotted thick grey arrow). The disturbance of the recirculation region will lead to some mixing of the air taking these two paths (depicted by the small, circular grey arrows). To maximise the protection of people in the immediate wake of the barrier, from pollution originating upwind, we want to maximise the fraction of air forced up and over the barrier, minimise the fraction permitted to pass through the barrier, and minimise mixing between the two. To do so, and in view of Deshmukh et al.'s (2019) recent findings, we make two further recommendations:

- For year-round protection, vegetation barriers should be formed from evergreen trees.
- For effective protection, vegetation barriers should have leaf area densities ≥3m^2/m^3.

NB Effective protection depends on sufficient *density* of foliage (i.e., not merely breadth of barrier).

We focus on the use of vegetation barriers to block the *horizontal* transport of pollution (i.e., from vehicles towards people at the roadside). Note, for clarity, we refer to the dimension of a barrier perpendicular to the road as its breadth, and its extent parallel with the road as its length. To be effective, vegetation barriers need to extend as continuously as possible (i.e., with as few gaps as possible) both in height and along their length – on the stretch of road where we wish to reduce exposure to road transport pollution. We therefore make three final recommendations:

- As a rule of thumb, vegetation barriers should only be employed where they extend to an overall length ≥20m, with gaps totalling ≤10% of this overall length. For example, a 20m stretch of hedge, including 2m of gaps, could be employed as illustrated in Figure 3:

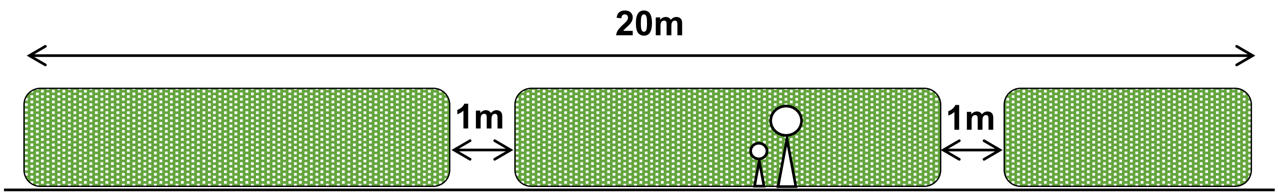


Figure 3. Example of a hedge extending to an overall length of 20m, with gaps totalling ≤10% of its overall length (2m).

- Where a higher vegetation barrier is required than can be provided by a hedge alone (recall, a barrier of height, $H \geq D/3 + 1$ (metres) is needed to offer any protection to people at a distance, D, downwind of the barrier) a hedge can be combined with a dense line of trees. The line of trees is used to block horizontal transport at the height of their crowns, and should be planted as close as possible to the hedge, as illustrated in Figure 4a below. Meanwhile, the hedge must be of sufficient height to block horizontal transport below the crowns of the trees. The effective height of the vegetation barrier, H, can thereby approach the height of the trees; again, see Figure 4a. Note that the trees alone, however, would not block the horizontal transport of pollution at ground level: the hedge is a critical component.

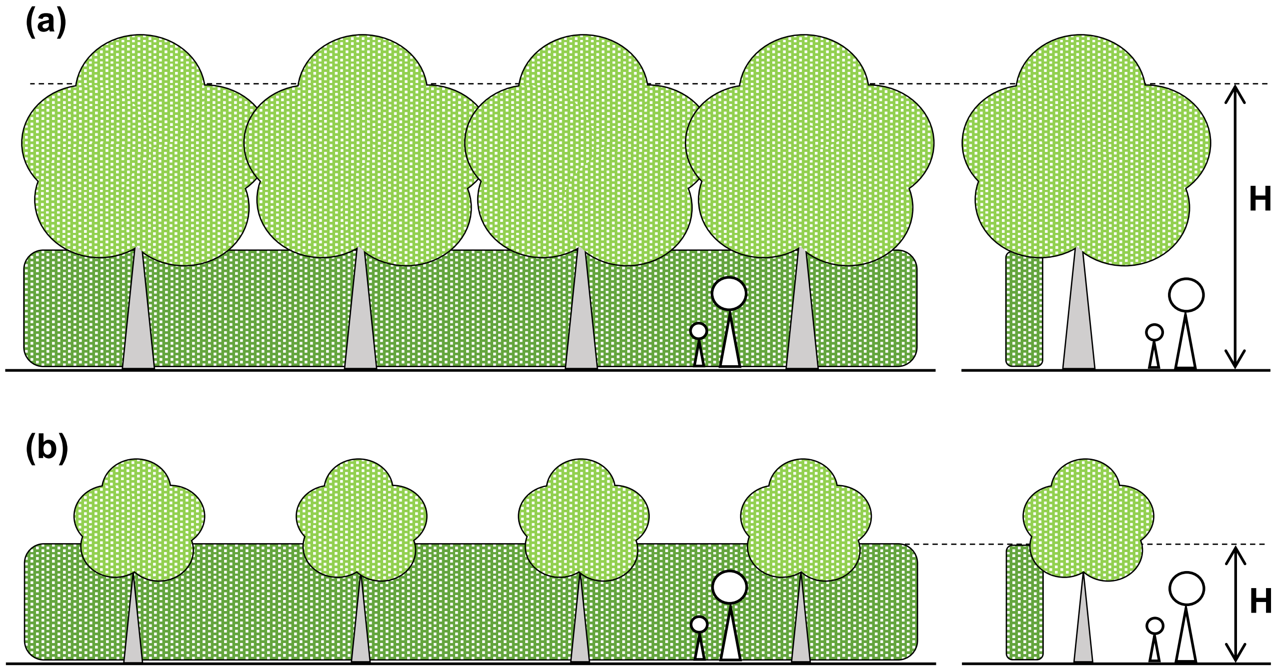


Figure 4. (a) Example of a hedge combined with a dense line of trees to provide a higher vegetation barrier, illustrated in elevation (left) and vertical section (right): the effective height of the barrier, H, approaches the height of the trees. **(b)** A variation on (a) to illustrate that, if the crowns of the trees do not meet (i.e., if the trees are planted too far apart, or have yet to reach maturity), the effective height of the vegetation barrier, H, will be limited to the height of the hedge.

- Ideally, the trees should be planted sufficiently close to each other that their crowns meet once they have reached maturity. This will of course take time, until which point the effective height of the vegetation barrier will be limited to the height of the hedge alone, as illustrated in Figure 4b.

Note, where we refer to 'hedges', you could consider any combination of the following elements, provided they join together to form a near-continuous barrier to the horizontal transport of pollution: traditional hedges, proprietary 'living wall' systems (e.g. including flowering plants), signage and advertising placards (e.g. to mitigate any concerns of local businesses regarding visibility) and grey infrastructure alternatives to GI (e.g. fences or walls) where there is insufficient space for planting.

Note, whilst fences or walls may be as effective at reducing exposure to local road transport pollution as GI, they will not deliver the *many* further benefits of GI outlined in section 3. Finally, it is important to consider the maintenance of each and every element; some living walls, for example, may require significant maintenance to ensure they remain healthy and effective barriers.

Most of the recommendations above were included in the GLA's (2019) recent guidance. For TfL, however, we take a further step in introducing more rigorous consideration of the influence of local urban form (i.e., the size and proximity of buildings either side of a road) on the distribution of pollution within a street. We use Harman et al.'s (2004) relationship between barrier height (H) and the shape and dimensions of the recirculation region generated in its wake (Figure 1) to characterise this influence, and determine its implications for what GI4RAQ interventions will be of benefit (or disbenefit) to people in different locations. Accordingly, the GI4RAQ Decision Tree (introduced in the next section) starts with questions regarding: the orientation of the street relative to the prevailing winds; the height of the nearest buildings upwind; and the distance between these buildings and (i) the road and (ii) receptors downwind. For rigor, we ensure that this characterisation, and the guidance we subsequently provide on appropriate GI4RAQ interventions, conform with our understanding of the underlying science (as outlined above). The Decision Tree is thus intended to give you a means of justifying (e.g. to your managers) that a proposed intervention will prove beneficial to those you are seeking to protect from road transport pollution.

The science, however, is not free from uncertainties, and some discretion is needed in applying the theory to practice; we will illustrate this with the aid of real world case studies in section 6. In particular, urban form is often more complex (i.e., more varied and/or possessed of finer-scale features) than has been explored computationally (via CFD calculations) or empirically (with scale models in wind tunnels). Other factors, such as vehicle movements, further disturb and complicate the movement of air within real streets, and it has sometimes proved a challenge to demonstrate through observations how the theory translates into practice (see, e.g., Karra et al., 2017). Moreover, the wind direction in any given location will naturally vary around the prevailing wind direction(s) and, ideally, we would assess the benefits (or disbenefits) of proposed interventions based on a full climatology of wind conditions encountered in that location – and projections of how that could change in the future. Whilst this is not yet practicable, we believe that these confounding factors (generally) just temper, or somewhat reduce, both the benefits and the potential disbenefits of GI4RAQ interventions: the enhanced protection resulting from the 'recirculation region' created immediately downwind of a vegetation barrier may be realised less frequently; the risk of trapping pollution behind such barriers (under unfavourable wind conditions) for any significant length of time is likely also reduced; and, meanwhile, simply lengthening the source-receptor pathway remains a reliable means of reducing public exposure.

5. The GI4RAQ Decision Tree (available at https://doi.org/10.25500/epapers.bham.00003398)

Figure 5. Screenshot of GI4RAQ Decision Tree: a differential diagnostics approach visualised via a PowerPoint Show.

The GI4RAQ Decision Tree is a differential diagnostics approach, visualised via a PowerPoint Show with embedded links (see Figure 5 above), to: identify the critical characteristics of the street in which you are seeking to reduce exposure to road transport pollution; and determine what GI4RAQ interventions will be of benefit (or disbenefit) to people in different locations within that street. It leads you through a series of five binary questions (Q1-5 below) and, depending on your answers to these, identifies the street as one of seven distinct types (Type A-G). As illustrated in Figure 6 overleaf, you may not need to answer all five questions to determine the street type. For instance, if the answer to Q1 is 'parallel', this alone is sufficient to identify the street as of Type A.

Please note, Types A-G do not correspond to TfL's Street Types. The latter were developed to describe the different functions of the road network (for the people who influence how it is used) to ensure delivery of a consistent service across TfL and London-borough roads. They are based on three categorisations of the significance of a road with respect to *movement* (M1-3) and *place* (P1-

3), from *local* to *strategic*, yielding TfL's matrix of nine street types. *Movement* includes the movement of people and goods, as well as motorised vehicles, whilst *place* captures the variety of valuable contributions streets make to the economy, environment and overall quality of public life. Our Types A-G depend on very different factors – physical characteristics of streets, such as the orientation of the road relative to the prevailing winds – that can vary on much shorter spatial scales. As a result, a stretch of road classified as just one TfL Street Type (e.g. M2/P2, such as a High Street) could change back and forth between Types A-G several times within just half a mile. The physical characteristics of streets critical to GI4RAQ underpin questions, Q1-5 below:

Q1. Are the prevailing winds predominantly parallel with, or perpendicular to, the road?

Q2. Does the road (i.e., traffic) lie within 3x the height of the nearest buildings upwind?

Q3. Do people passing on the downwind kerbside lie within 3x the height of these buildings?

Q4. Do people or buildings beyond the downwind street boundary lie within 3x their height?

Q5. Are there buildings within this region beyond the street boundary, or is it open space?

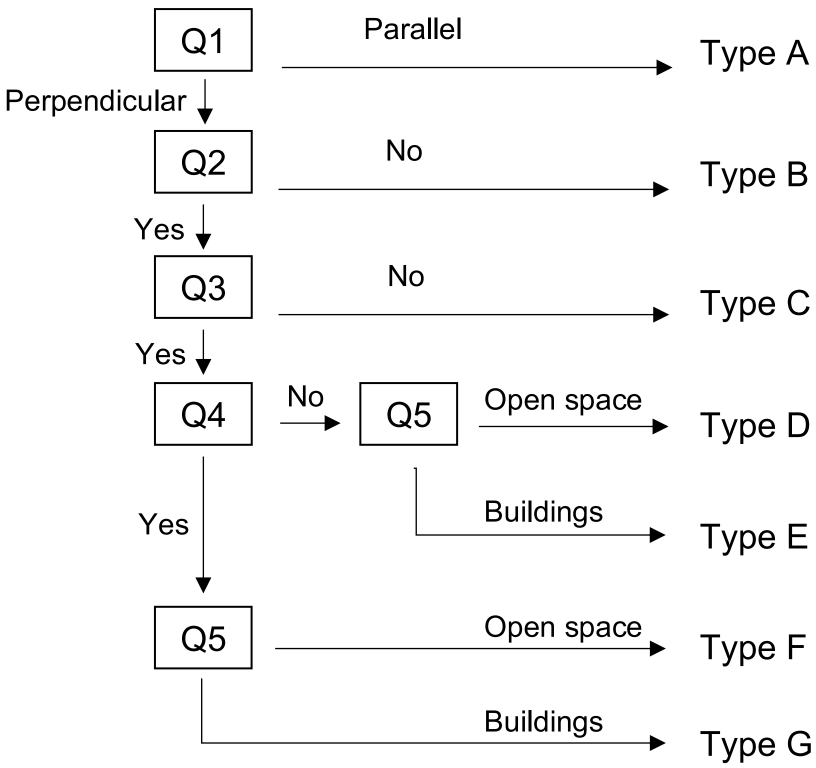


Figure 6. Flow chart illustrating how the answers to five binary questions, Q1-5, determine which of seven distinct street types, Types A-G, a street belongs to for the purposes of GI4RAQ. This street type determines what GI4RAQ interventions will be of benefit (or disbenefit) to people in different locations within that street. **NB** Types A-G do <u>not</u> correspond to TfL's Street Types for London and can vary on much shorter spatial scales (e.g. changing several times within half a mile).

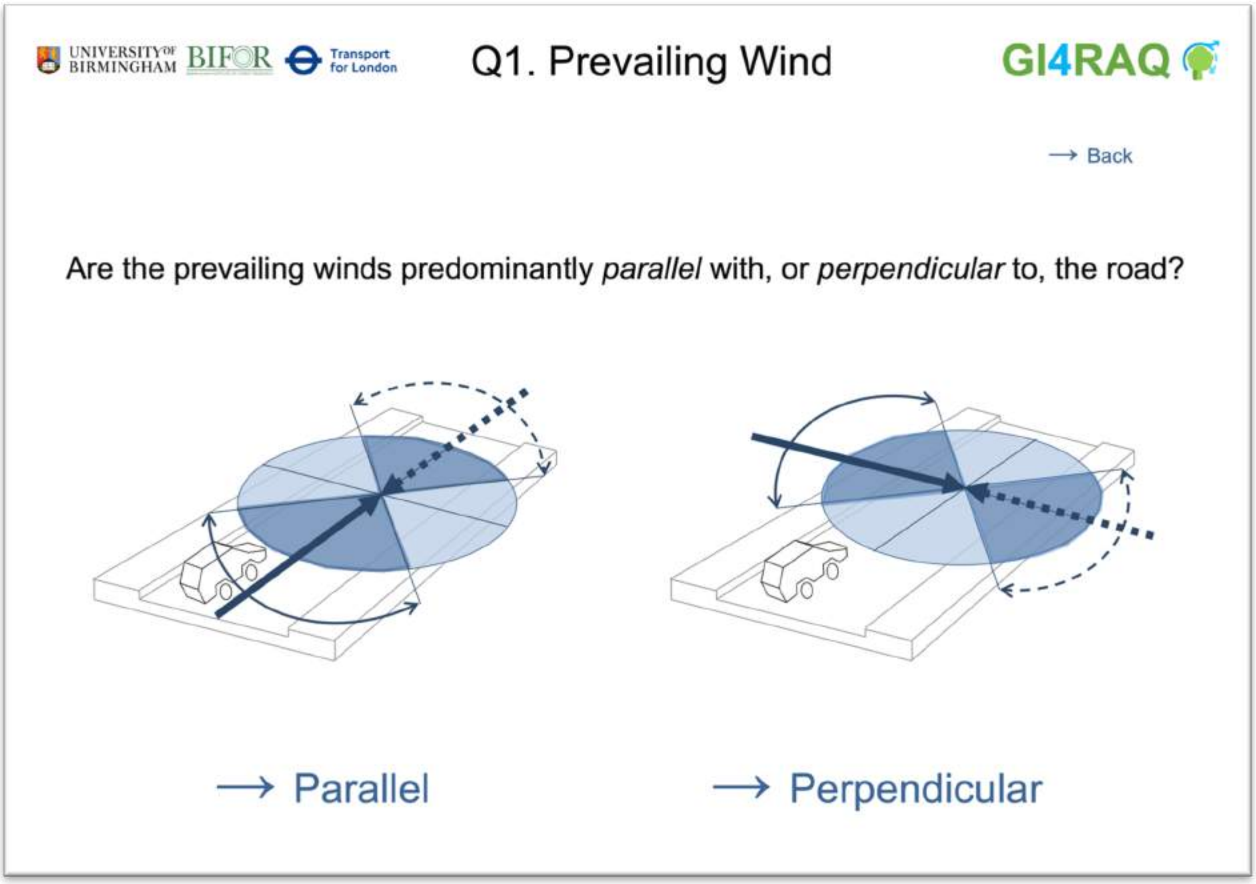


Figure 7. Screenshot of the first of five binary questions (Q1) and accompanying illustrations to guide the user.

The questions are accompanied by illustrations to guide the user, as per the screenshot of Q1 in Figure 7 above. Recall, answering 'parallel' to Q1 is sufficient to identify the street as of Type A (see Figure 5). If we continue with this example, clicking on → Parallel thus takes you directly to the 'Top Level Guidance' for this street type; see Figure 8 overleaf. Importantly, this guidance includes information on what GI4RAQ intervention(s), if any, will be *robustly beneficial* in a street of this type, and what interventions will be *beneficial to some at the expense of others*, according to the definitions below; we will explain later in this section the potential value of the latter.

- *Robustly beneficial* interventions are those judged to be of appreciable benefit to people in at least one location within the street in question **and** of disbenefit to no one. **NB Our approach to GI4RAQ only considers impacts in roadside locations (labelled in red in Figure 10); it neglects potential increases in exposure of road-users between kerbs.**

- Interventions judged to be of appreciable benefit to people in at least one location within the street, but of disbenefit (including appreciable disbenefit) to people in other locations within that same street, are described as *beneficial to some at the expense of others.* **NB Again, our approach to GI4RAQ does not consider impacts on road-users between kerbs.**

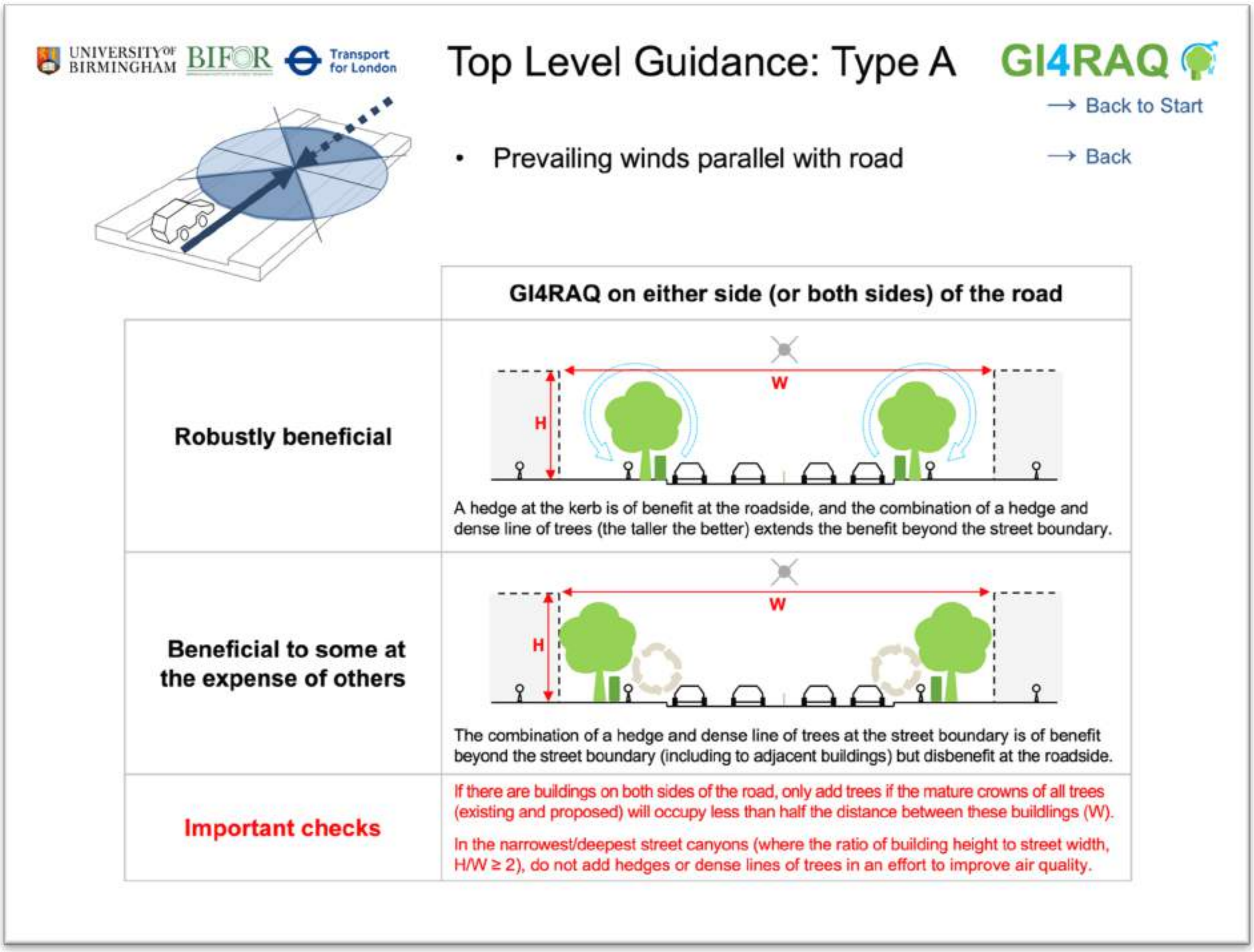
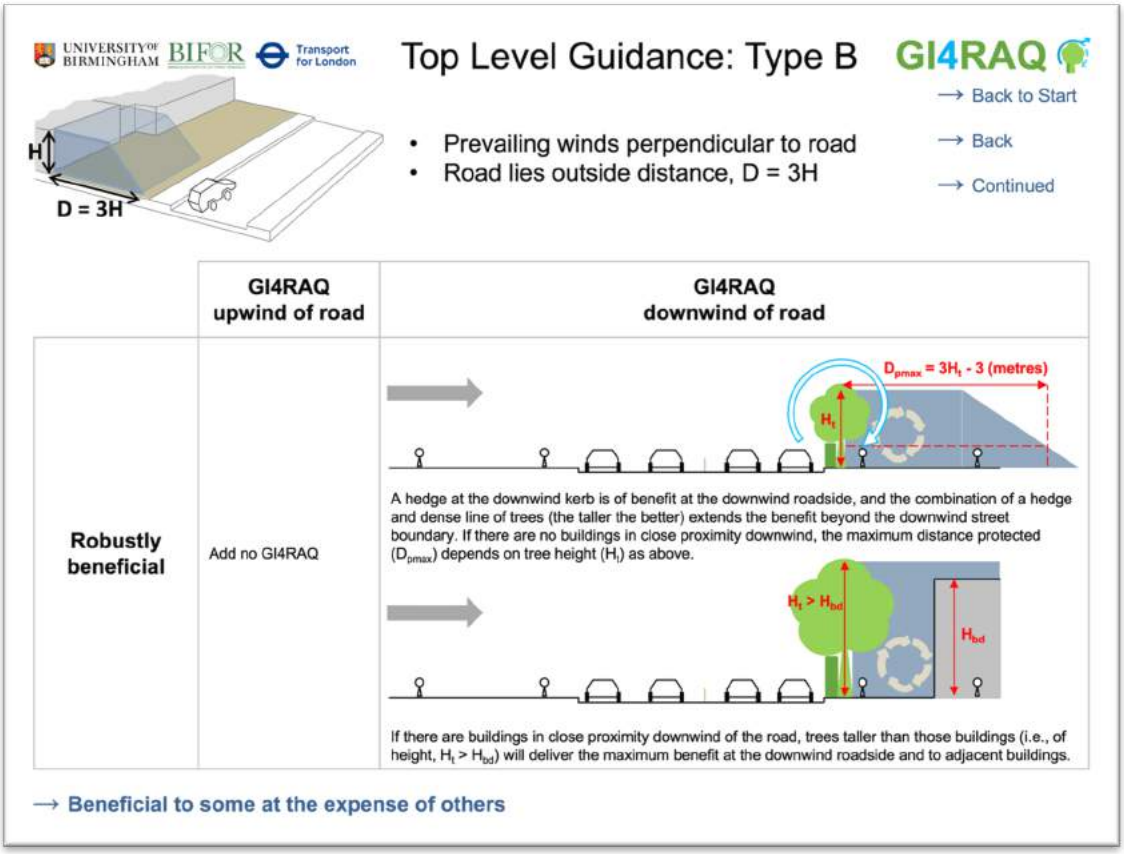


Figure 8. Screenshot of 'Top Level Guidance' for streets identified for the purposes of GI4RAQ as of Type A, including guidance on what GI4RAQ intervention(s), if any, would be *robustly beneficial* in a street of this type, and what interventions would be *beneficial to some at the expense of others* as defined in this document. The guidance also includes *important checks* to ensure any proposed interventions do not cause any inadvertent disbenefits.

For streets of Type A, the two sides of the street are ostensibly the same and the same guidance is applicable to either side (or both sides). Note, however, that symmetrical interventions (e.g. adding a hedge at the kerb on *both* sides of the road) are not necessary, and may not be advantageous. A degree of heterogeneity (i.e., varying size and shape) of green infrastructure, as much as buildings, is generally beneficial for urban air quality: it tends to disrupt the large-scale patterns of otherwise-laminar air flow, and thereby stimulate vertical mixing between the air that people are exposed to at street level (somewhat polluted) and the air above (somewhat cleaner). For all other street types (i.e., Types B-G), the interaction between the urban form and prevailing wind (predominantly perpendicular to the road) renders the two sides of the road different from each other, and separate guidance is given for GI4RAQ upwind, and downwind, of the road. Figure 9, for instance, shows the 'Top Level Guidance' provided for streets of Type B (split over two pages; navigated by clicking on → Continued and → Back in the top right hand corner of each page).



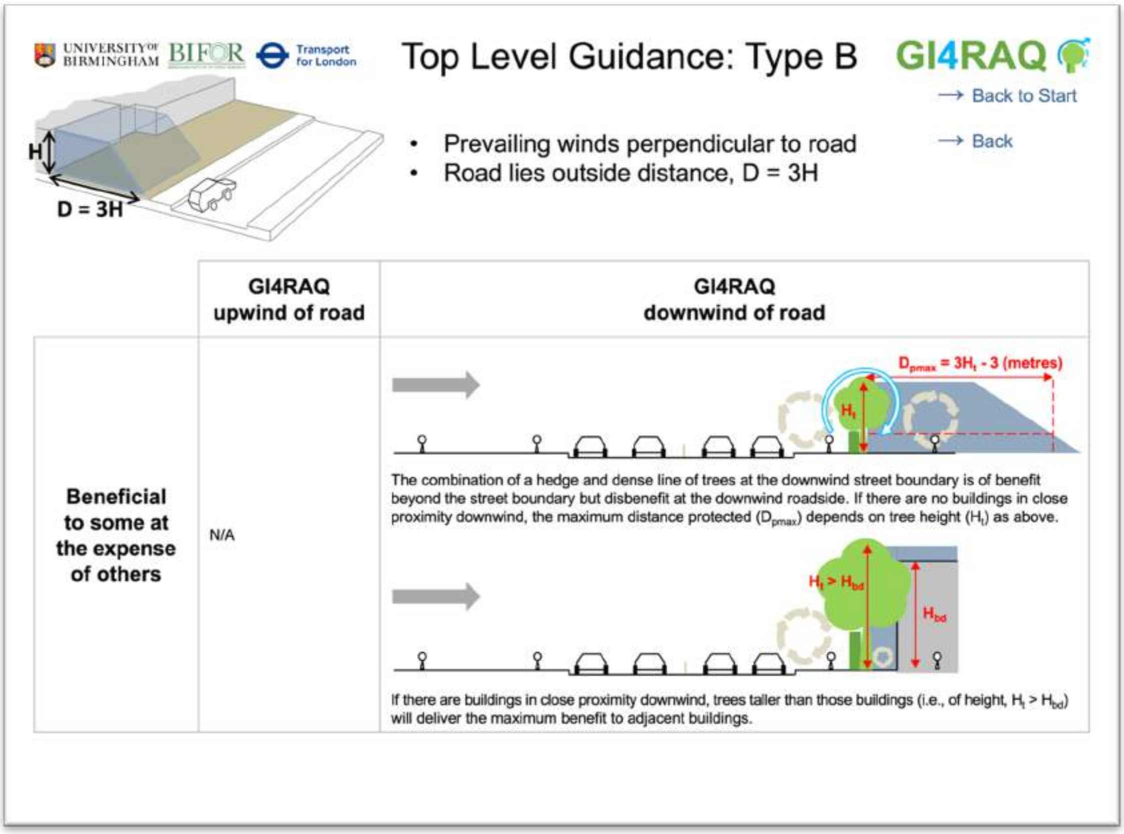


Figure 9. Screenshots of 'Top Level Guidance' for streets identified for the purposes of GI4RAQ as of Type B, including guidance on what GI4RAQ intervention(s), if any, would be *robustly beneficial* (top panel), and what interventions would be *beneficial to some at the expense of others* (bottom panel) upwind and downwind of a road in a street of this type.

You can see from Figures 8 and 9 that the Top Level Guidance for each street type begins with one or more bullet points summarising the answers the user has given to determine that the street is of that type; these are the physical characteristics *critical* to GI4RAQ. [Please note that some effort is needed by the user here to ensure their answers are accurate; they will need to decide what street – indeed what stretch of a street – they are focussing on, and determine the wind direction, height of the nearest buildings upwind of the road and width of the road in that location (e.g. from Surface Playbook). Inaccurate answers will lead to inaccurate GI4RAQ guidance.] Streets of Type A have a single, defining characteristic: 'Prevailing winds parallel with road'. For Type B, there are two critical characteristics: 'Prevailing winds perpendicular to road'; and 'Road lies outside distance D = 3H'. Note that we are starting to consider the effects of local urban form: H is the height of the nearest buildings upwind; D = 3H is the extent of the recirculation zone generated downwind of these buildings (see Figure 1 and the accompanying text in section 4); and, in streets of Type B, it follows that the road lies outside this zone. By implication, this recirculation zone (shaded blue in the 3D sketches in the top left hand corner of each screenshot in Figure 9) is not expected to trap pollution emitted from vehicles on that road. The prevailing wind is carrying that pollution away from people at the upwind roadside.

If we were to add a vegetation barrier at the upwind kerb, it would create its own recirculation zone, albeit a 'leaky' one; see Figure 2 and the accompanying text in section 4. This would tend to draw air at street level from the road towards receptors upwind, and would thereby risk increasing their exposure to road transport pollution. For this reason, the guidance on *robustly beneficial* GI4RAQ interventions upwind of the road is, 'Add no GI4RAQ' (see top panel of Figure 9). Meanwhile, the addition of a hedge, ideally in combination with a dense line of trees, at the downwind kerb would reduce the exposure of receptors downwind of the road at no air quality cost (neither of benefit nor of disbenefit) to receptors upwind, and is therefore identified as *robustly beneficial* (see again top panel of Figure 9). As outlined in the guidance, if there are no buildings in close proximity downwind, the taller the vegetation barrier the better: the maximum distance protected, D_{pmax}, increasing with the height of the trees employed in conjunction with the hedge, H_t, according to: $D_{pmax} = 3H_t - 3$ (metres). If there are buildings in close proximity downwind, the maximum benefit between the street boundary and those buildings – and to people in those buildings, opening their windows onto this space – will be achieved with trees taller than the buildings downwind ($H_t > H_{bd}$).

Moving on to GI4RAQ interventions *beneficial to some at the expense of others* (lower panel of Figure 9), we make no recommendation upwind of the road but identify potential benefits and disbenefits of a vegetation barrier downwind of the road – at the street boundary. Such an intervention is only worth considering if *robustly beneficial* interventions are precluded (e.g. due to unalterable routing of services above or below ground, lack of available space at the kerb, the need to retain access at the kerb to buses, taxis and so on, the need to preserve safety-critical sightlines and vision splays at junctions, and rights to light). For a street of Type B, the addition of a hedge and dense line of trees at the downwind street boundary could bring significant benefits to people beyond this boundary (i.e., further downwind). It would, however, be of disbenefit to people at the downwind kerbside, where it would reduce the dispersion of road transport pollution and, thereby, somewhat increase their exposure. One might judge this intervention to be of net public health benefit where a larger number of people are exposed, or the same number of people are exposed for longer, and/or are of higher vulnerability, beyond the street boundary than at the kerbside. This could apply, for example, where a school playground directly borders the street.

You will note that, besides differentiating between the two sides of a road (upwind and downwind), we distinguish between the region directly beside the road on either side, the 'kerbside', and the region immediately 'beyond the street boundary'. The kerbside could be a pavement, grass verge or cycle lane (whether this is physically separated from, or adjoining, road lanes carrying other vehicles), or some combination of the above. Meanwhile, the region beyond the street boundary could be open ground (e.g. a school playground, as in the example above, or park) or it could include buildings, whether their facades are aligned with the street boundary (e.g. shop fronts) or set back from it (e.g. houses with front gardens or businesses with forecourts). This conceptual picture of a street (illustrated in Figure 10 below) yields four generic locations in which we can introduce GI4RAQ (labelled in green) and four areas of interest with regards to its impacts on exposure to road transport pollution (labelled in red). Note, we do not consider the impacts of GI4RAQ on the exposure of road users in the lanes carrying vehicles constituting sources of road transport pollution; drivers of these vehicles, and other road users sharing these lanes, will experience increased exposure but, unless at a standstill, for relatively short periods of time.

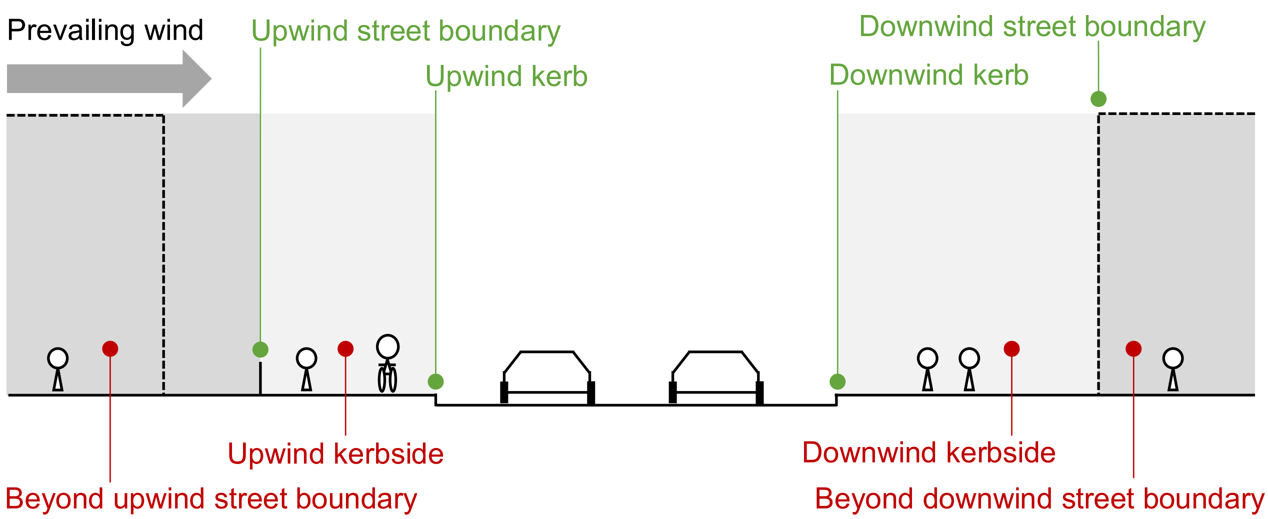


Figure 10. Conceptual picture of a street yielding four generic locations within the street where we could introduce GI4RAQ (labelled in green) and four areas of interest regarding exposure to road transport pollution (labelled in red).

Within this framework, we have considered the impact of each possible GI4RAQ intervention (i.e., hedge; hedge + dense line of small trees; hedge + dense line of tall trees), in each of the four possible locations, on people in each of the four areas of interest, within each type of street (A-G). The Top Level Guidance constitutes a synthesis of detailed consideration of roughly 100 scenarios. Whilst it is beyond the scope of this GI4RAQ Guidance to take the reader through the reasoning, and conclusions reached, in each of these scenarios, TfL has an extended version of the GI4RAQ Decision Tree that includes detailed notes on each for future reference. Meanwhile, despite this underlying complexity, the Decision Tree will often lead you to identify the same, or very similar, GI4RAQ interventions as *robustly beneficial* or *beneficial to some at the expense of others*. The addition of a hedge at the kerbside, for instance, is almost always *robustly beneficial*, and its benefits are usually extended beyond the street boundary (on the same side of the road) if augmented with a dense line of trees. There are important exceptions, however, and the dimensions of trees relative to buildings in close proximity are sometimes critical. The Decision Tree should therefore always be used to check (and justify to managers etc) that a proposed intervention will be beneficial to the people you seek to protect.

Despite the scientific basis outlined in the last section, there are scenarios in which a GI4RAQ intervention has opposing effects on exposure to road transport pollution (i.e., both a beneficial effect, and one that presents a disbenefit). There are therefore instances where our assessment of which effect is dominant, and hence whether or not the intervention is of net benefit for RAQ, is based on our expert judgement (tested against that of colleagues). The extended version of the Decision Tree is thus the 'developer-version', from which a new 'user-version' can be recompiled as the evidence base continues to develop. Our *quantitative* software – the prototype GI4RAQ Platform (www.GI4RAQ.ac.uk) - supports more rigorous assessment of borderline scenarios and, in time, this software will be confronted with fit-for-purpose measurements to test its predictive skill.

One of the limitations of the current approach is the consideration of streets in essentially just two dimensions; see, for example, our conceptual picture in Figure 10. In reality, city streets are interconnected, forming three dimensional networks of street canyons, between which air pollution can flow via connecting roads and/or 'spill over' the buildings between them. We do not currently consider these interactions between roads. Likewise, as noted at the end of the last section, the wind direction in any one location will naturally vary about the prevailing wind direction(s), and will rarely be precisely parallel with, or perpendicular to, a street. When the wind blows across a street canyon at some angle in between the two, it produces complicated helical patterns of air movement within the street. Again, we cannot currently capture the consequences of this movement in full. Even resolving this within a state-of-the-art computer model is far from straightforward. In the prototype GI4RAQ Platform, we take an intermediate step of breaking down the climatological (i.e., typical) observed variability in background wind conditions in the location of interest into four wind sectors, broadly perpendicular to the street (left to right, and right to left) and broadly parallel with the street (into, and out of, the plane of the street's cross section). The results presented to the user then reflect a suitably time-weighted average of the calculations performed by the software subject to each of these wind scenarios, accounting for the interactions between these background wind conditions and the user-specified urban form on that location. The 'average' of these interactions will, at best, provide an approximation of the real-world complexities. We note that the commercial air-quality platform provider, Cambridge Environmental Research Consultants (CERC), has begun developing a model of air flow in three-dimensional networks of street canyons in collaboration with the Hong Kong University of Science and Technology.

Meanwhile, the simple two-dimensional approach outlined in this document provides guidance on the benefits (and disbenefits) of GI4RAQ interventions for exposure to road transport pollution *along any length of street for which the critical physical characteristics of the street (identified by the user) remain the same* <u>*and*</u> *the GI4RAQ intervention is implemented*. A 20m long hedge, for instance, can at best offer a degree of protection to people along that 20m stretch of the street. In reality, it will offer protection to people along a somewhat shorter stretch of the street since, at either end of the hedge, polluted air has the opportunity to flow around it (i.e., horizontally) as well as over it (i.e., vertically). These 'edge effects' reduce the overall effectiveness of a vegetation barrier and, it was for this reason, we included the recommendation that, as a rule of thumb: vegetation barriers should only be employed where they extend to an overall length ≥20m, with gaps totalling ≤10% of this overall length.

6. Real World Case Studies

11 sites have been adopted as real-world case studies where challenges to achieve legal compliance with NO_2 limit values persists. They all lie within Greater London and comprise stretches of TfL's Road Network, but otherwise vary considerably; see Figure 11 below. They range from suburban dual carriageways flanked by residential and/or industrial properties, to inner city streets that are predominantly commercial in nature and receive high footfall. With reference to TfL's street types, the sites are all classified as relatively high *movement* (i.e., M2 or M3) but vary in terms of *place* (i.e., P1, P2 or P3). These sites currently suffer from poor RAQ, and means of reducing the public's exposure to emissions from road transport here are sought to complement TfL's efforts to reduce those emissions at source.

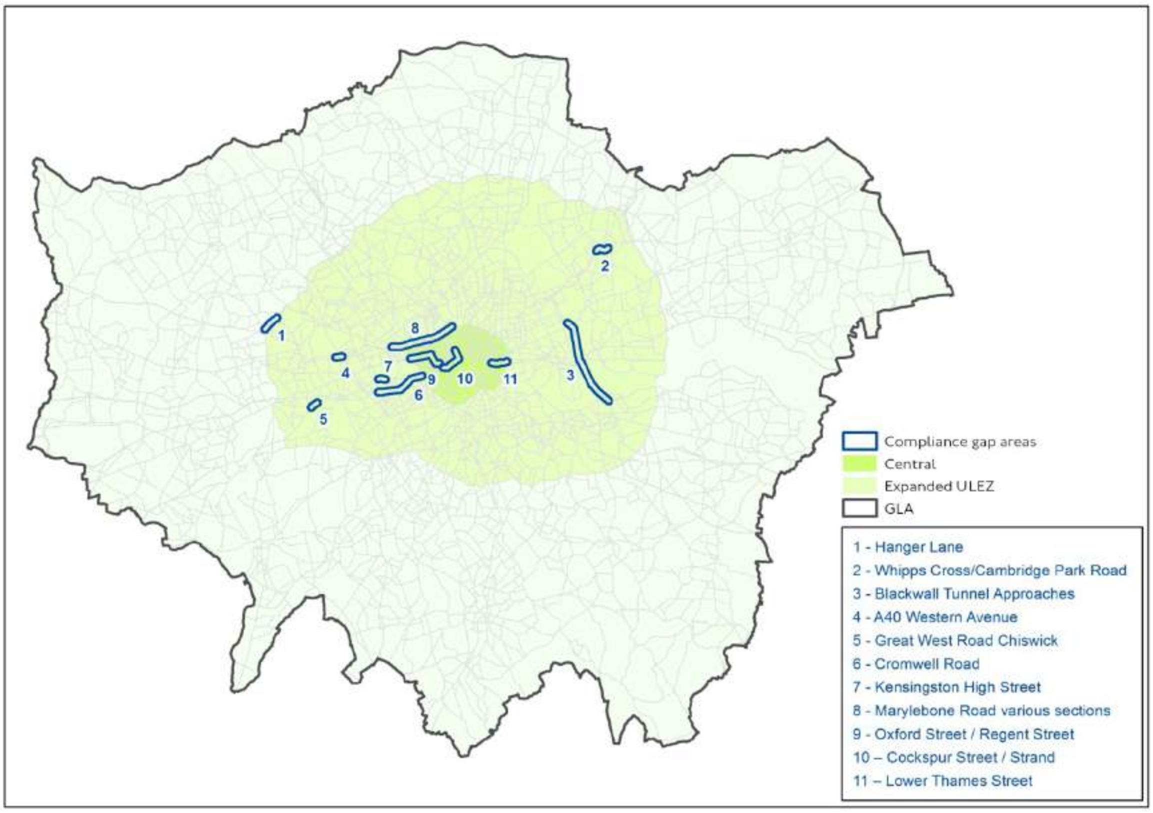


Figure 11. Map showing the locations of the 11 areas in London adopted for the purposes of GI4RAQ case studies.

Following the introduction of the GI4RAQ Decision Tree in the last section – designed to identify the critical characteristics of a street governing what GI will be robustly beneficial for RAQ *in that street* – it is hopefully apparent that there is no 'one size fits all' GI4RAQ intervention. Moreover, the critical characteristics governing what will or will not be beneficial, and in what location within the street, could vary on relatively short spatial scales and therefore do not map directly onto TfL's Street Types (based on *movement* and *place*); see Section 5 for more details. Where TfL's street types are more pertinent to GI4RAQ is the practical constraints determining what GI4RAQ interventions are practically viable without wholesale redesign of the street. The case studies suggest a correlation, but not a direct correspondence, between street type and constraints. We elaborate on this in the remainder of this section – structured around four overarching findings from our consideration of the real-world application of the GI4RAQ Decision Tree (summarised below). **Note, the case studies are best described as 'thought experiments': the deliverability of the interventions illustrated has been neither fully assessed nor discussed with the boroughs.**

- There is **potential to introduce GI4RAQ beside some major suburban roads**: the availability of space beside these roads permits GI4RAQ interventions at the kerb; and the combination of less access required at the kerb (e.g. to buses and taxis) and more widely spaced junctions (presenting fewer constraints regarding sightlines and vision splays) allows interventions to be employed more continuously over greater distances. Attention does however need to be paid to the maintenance requirements of any GI which is installed and the access arrangement for this. It can be difficult and expensive to maintain GI which is located very near to relatively high-speed carriageways.

- By comparison, inner city roads present greater constraints (i.e., less available space, more access required at the kerb, and more safety-critical sight lines to preserve). There are, however constraints and opportunities on roads of all types. Each road is unique, and there are **exceptions to every rule**.

- Where redesign is possible, there are **opportunities to reimagine our inner city streets**. We can rebalance provisions for vehicles, pedestrians and cyclists, and make space for GI to: create healthier streets with, not only improved RAQ, but also improved thermal comfort; build environmental resilience, with greater biodiversity and sustainable urban drainage; and make attractive public spaces that foster social cohesion and fuel economic prosperity.

- Where redesign is not possible, **we should still seek to protect the most vulnerable**. Local constraints may preclude the introduction of GI4RAQ interventions with continuity over considerable distances. There may nevertheless be opportunities to introduce GI4RAQ where those most vulnerable to the impacts of poor RAQ are exposed to high concentrations of pollutants: the very young, such as children in school playgrounds bordering busy streets; the elderly, including residents of care homes situated on such streets; and those with particular pre-existing medical conditions (e.g. chronic obstructive pulmonary disease; COPD) accessing health care facilities, such as general practices and hospitals, in heavily polluted areas.

6.1 Considerable Suburban Potential

We start by looking closely at three suburban sites (1, 2 and 5) illustrating potential for GI4RAQ in such areas; we will not examine the remaining eight sites in the same level of detail.

6.1.1 Site 1: Hanger Lane & North Circular

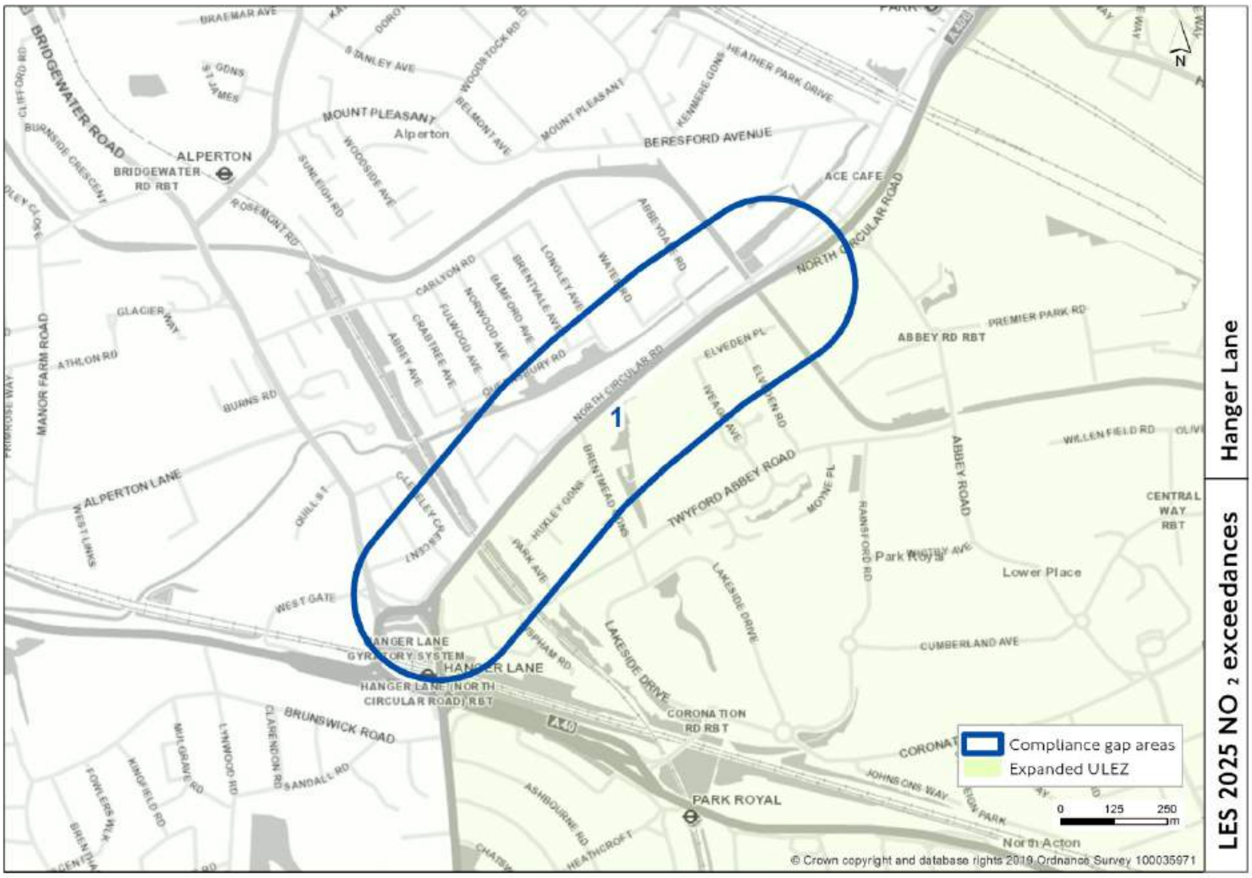


Figure 12. Map of case study area 1: Hanger Lane & North Circular.

Figure 12 shows the extent of site 1, from the north side of Hanger Lane roundabout (bottom left) to the North Circular Aqueduct (top right). This stretch of the North Circular (A406) carries three lanes of traffic in each direction (i.e., six lanes in total) with pedestrian and cycle ways immediately adjacent to the road, and a combination of houses and places of work at the street boundary. Following the Decision Tree, we identify that this site is almost entirely characterised as Type A:

- Prevailing winds parallel with road

Accordingly, the addition of a hedge at the kerb on either side (or both sides) of the road is robustly beneficial. Furthermore, each hedge can be combined with a dense line of trees to provide a taller vegetation barrier, and extend the protection of people at the roadside beyond the street boundary (e.g. to residents of houses bordering the street). Below, we present a series of images in an exploration of potential interventions.

Priory Gardens runs parallel with (and adjacent to) the A406, just north of the Hanger Lane roundabout; see left. Since there is much less traffic on Priory Gardens than the A406, the addition of a hedge between the two – screening people walking to the shops or cycling to work along this minor road from the adjacent six lanes of traffic – would improve RAQ here, albeit punctuated by spikes associated with Priory Gardens traffic; note, the existing trees (pictured in blossom) offer no significant benefit for RAQ. However, adding the hedge would in practice require removing parking on the right to create a gap between it and the A406.

Figure 13. Looking north east along Priory Gardens (adjacent to the A406, north of Hanger Lane) pictured as it is at present (top) and with proposed GI4RAQ (bottom); the latter is only illustrative, and TfL's arboriculture team should be consulted on all planting.

There is a short stretch just north of Priory Gardens, again adjacent to the A406, where there is insufficient space to add GI4RAQ at the kerb (see left); note, the existing barrier between vehicles and pedestrians permits polluted air to travel freely from one to the other, and thus provides no benefit for RAQ. For more than half a mile beyond, however, there is potential to add a vegetation barrier at the pavement kerb on the minor road (confusingly called ‘North Circular Road’) provided it does not compromise personal security; see right of photo below. This would improve RAQ on the pavement; note, the existing grassed area and tree (pictured on the left in the photo below) offer no significant benefit for RAQ.

Figure 14. A stretch of pavement (looking north east), less than 100 yards in length, adjacent to the A406 between Priory Gardens and the bridge carrying the Uxbridge branch of the Piccadilly line (top); more than half a mile of minor road adjacent to the A406 (looking south west) – confusingly called the ‘North Circular Road’ – stretching from the bridge to the North Circular Aquaduct (bottom).

Within the half-mile stretch of 'North Circular Road' adjacent to the A406, there are several hundred yards of pedestrian and cycle ways; see left. The addition of a hedge and dense line of trees at the kerb would improve RAQ here. The proposed dense line of trees would be particularly effective here if located such that their crowns meet those of the existing trees (pictured on the left), creating a 'green oasis' where cleaner air is contained within touching tree canopies (Hewitt et al., 2019). However, in addition to the practical challenges of maintaining trees directly beside a carriageway, risks to personal security would again need to be considered.

Figure 15. Looking north east along pavement and cycleway adjacent to the A406, pictured as it is at present (top) and with proposed GI4RAQ (bottom); the latter is only illustrative, and TfL's arboriculture team should be consulted on all planting.

Where access at the kerb is needed on 'North Circular Road' (e.g. for bus stops; see below), a hedge and dense line of trees could be added between the minor road and the A406; see right. Due to the much lower traffic on this minor road, the tall vegetatrion barrier should still reduce average exposure here, albeit punctuated by spikes in pollution accompanying HGV/LGV deliveries. In practice, a lane of traffic would have to be removed from the 'North Circular Road' to avoid planting trees directly beside the dual carriageway, which would copromise the passage of vehicles.

Figure 16. Looking north east along 'North Circular Road' adjacent to the A406, pictured as it is at present (left) and with proposed GI4RAQ (right); the latter is only illustrative, and TfL's arboriculture team should be consulted on all planting.

On the opposite side of the A406 to 'North Circular Road', there is insufficient space to introduce a vegetation barrier at the kerb without compromising the passage of people on the pavement and/or vehicles on the carriageway.

Figure 17. Looking south west along pavement to the south east of the A406 (south of the North Circular Aqueduct).

Likewise, approaching Hanger Lane roundabout on the south west side of the A406, the existing planting could perhaps be bolstered to offer a degree more protection to the line of houses in close proximity to the traffic, but there is not enough space to add a new vegetation barrier at the kerb where one does not already exist.

Figure 18. Looking south west along pavement and line of adjacent houses on the south west side of the A406 (just to the north of Hanger Lane roundabout).

Although strictly just outside site 1, there is an opportunity to protect people from road transport pollution on the stretch of Priory Gardens immediately to the north of Hanger Lane roundabout; see left. A hedge and dense line of sufficiently tall trees (i.e., major bolstering of the existing planting), could offer some protection, as illustrated below.

Figure 19. Looking east along Priory Gardens (immediately north of Hanger Lane roundabout) pictured as it is at present (top) and with proposed GI4RAQ (bottom); the latter is only illustrative, and TfL's arboriculture team should be consulted on all planting.

6.1.2 Site 2: Whipps Cross & Cambridge Park Road

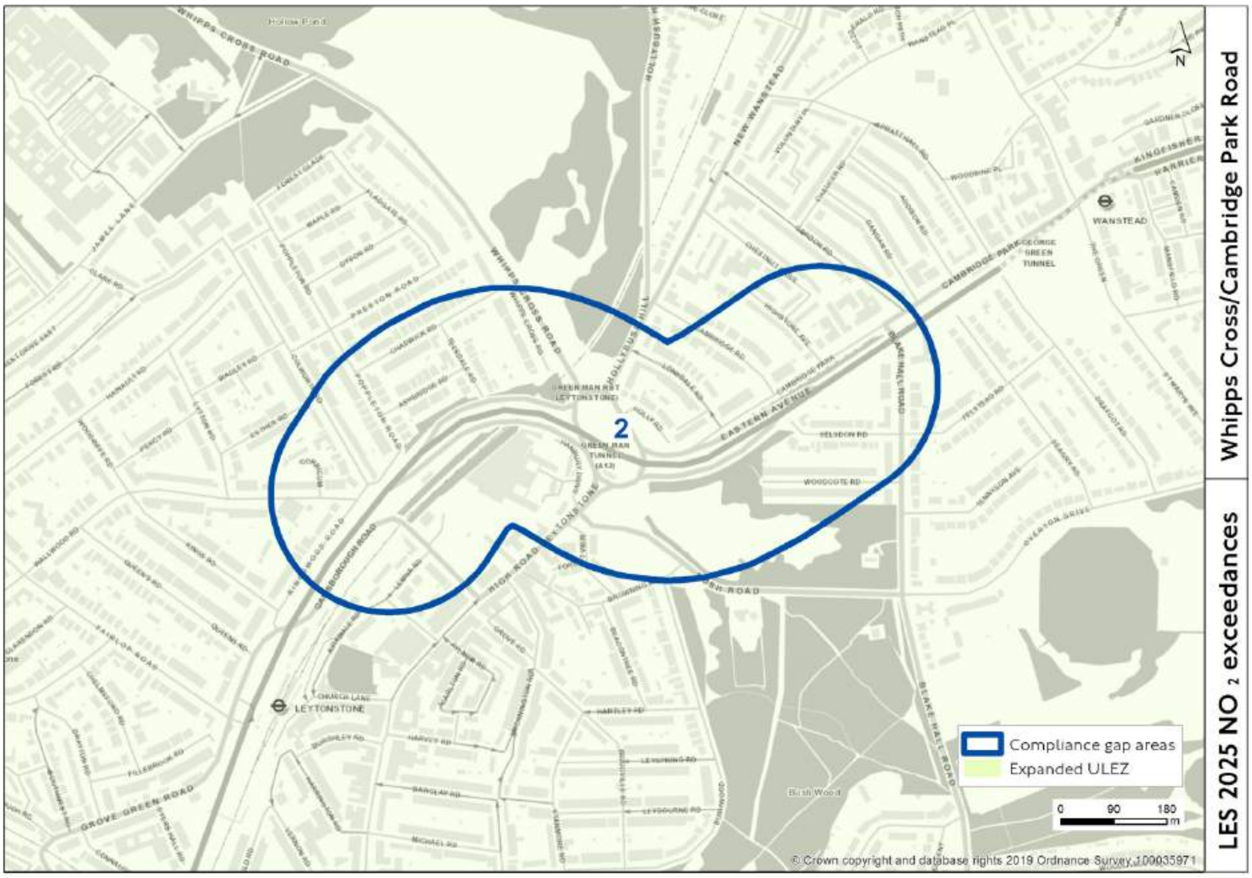


Figure 20. Map of case study area 2: Whipps Cross & Cambridge Park Road.

The second suburban site with potential for GI4RAQ is a stretch of the A12 straddling the Green Man Tunnel in Whipps Cross or, more specifically, the residential roads running parallel with it immediately to the north, such as Kingswood Road. We will start here, although site 2 strictly starts from Colworth Road in the west and finishes around Highstone Avenue in the east. Like the A406, the A12 is comprised of three lanes of traffic in each direction (i.e., a total of six lanes) and, although partially concealed in a cutting (i.e., depressed relative to its surroundings), lies very close to residential areas; see Figure 21 below.

Figure 21. Looking north across the A12 at residential properties on Cambridge Park Road in close proximity to this dual carriageway and accompanying slip roads (east of the Green Man Tunnel).

The site exhibits an S-shape from west to east but, when we take out the Green Man tunnel section in the middle, the roads of interest are broadly oriented south west – north east. Following the Decision Tree, we identify that this site is again almost entirely characterised as Type A:

- Prevailing winds parallel with road

Accordingly, the addition of a hedge at the kerb on either side (or both sides) of the road is robustly beneficial and, in combination with a dense line of trees, can offer protection to people somewhat beyond the street boundary (e.g. residents of adjacent properties). As before, we present a series of images exploring the potential for their introduction.

In the photo of Kingswood Road on the left, the A12 lies in a cutting just over the wall on the right. Extending from ground level on Kingswood Road, this wall offers modest protection from pollution from the A12 to people on the right hand pavement, which could be increased and extended to pedestrians on the left hand pavement, and the residents of adjacent houses, if the low level planting were supplemented and a dense line of trees added; see below. Great care must be taken, however, to avoid any damage to the retaining wall of the cutting.

Figure 22. Looking north east along Kingswood Road (adjacent to the A12, west of the Green Man Tunnel) pictured as it is at present (top) and with proposed GI4RAQ (bottom); the latter is only illustrative, and TfL's arboriculture team should be consulted on all planting.

At first glance, it looks like a similar situation on Cambridge Park Road (see left) with the A12 in a cutting just beyond the wall on the right hand side. Here, however, there are only isolated pockets of existing planting, and insufficient space to introduce new planting where it does not already exist without compromising the passage of people on the pavement and/or damaging the retaining wall of the cutting.

Figure 23. Looking north east along Cambridge Park Road (adjacent to the A12, east of the Green Man Tunnel).

There is less housing immediately to the south of this stretch of the A12. East of the Green Man Tunnel, however, there are pedestrian and cycle ways that could be further protected from the air pollution emanating from it; see left. Provided it did not compromise personal security, the pedestrian way could in principle be moved to where the grass verge currently lies on the left, leaving space on the right to plant trees whilst avoiding damage to the wall on this side – again a retaining wall for the A12 cutting.

Figure 24. Looking south west along pedestrian-cum-cycle way running parallel with, and immediately to the south of, the A12 (east of the Green Man Tunnel) pictured as it is at present (top) and with proposed GI4RAQ (bottom); the latter is only illustrative, and TfL's arboriculture team should be consulted on all planting.

6.1.3 Site 5: Great West Road (Chiswick)

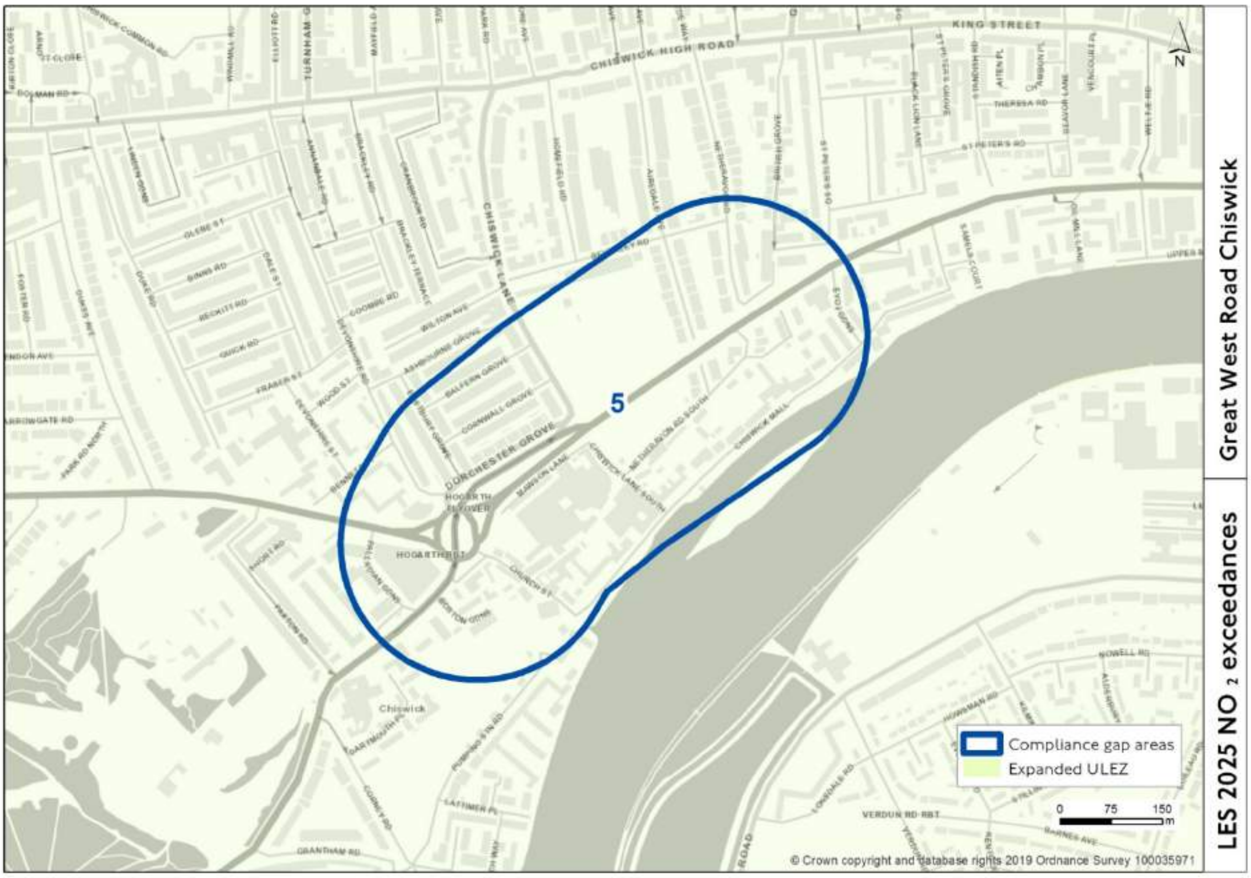


Figure 25. Map of case study area 5: Great West Road (Chiswick).

Figure 25 shows the extent of site 5, from Hogarth Roundabout (bottom left) to Netheravon Road South (top right). This stretch of the A4 (Great West Road) consists of three lanes of traffic in each direction (i.e., six lanes in total). Following the Decision Tree, we identify the entire site as again Type A, characterised like sites 1 and 2 as follows:

- Prevailing winds parallel with road

Accordingly, the addition of a hedge at the kerb on either side (or both sides) of the road is robustly beneficial and, in combination with a dense line of trees, offers protection to people somewhat further from the road (e.g. residents of adjacent properties).

Mawson Lane (pictured to the right in the photo on the left) runs parallel with and adjacent to Great West Road. Carrying much less traffic than the adjacent dual carriageway, a vegetation barrier between the two might offer a modest improvement in RAQ on Mawson Lane. There is, however, limited space to add one, and the already modest potential benefits would be felt by few people; the western end pictured is a no-through road and appears to be used for parking.

Figure 26. Looking north east along Mawson Lane (adjacent to Hogarth Lane, east of Hogarth roundabout).

At the eastern end of Mawson Lane, the footpath (and now cycle path) continues directly adjacent to Great West Road (pictured to the left in the photo on the left). The bottom left photo, taken from the opposite direction, shows the proximity of the path to heavy traffic. There is sufficient space to add a hedge and dense line of trees in between the two, but the presence of extensive existing vegetation at the boundary to Homefield Recreation Ground South (pictured to the left in the bottom left photo, and to the right in the bottom right photo) raises an interesting question: could a healthier path be established parallel with the road via the recreation ground?

Figure 27. Great West Road and Homefield Recreation Ground South (east of Hogarth roundabout): looking north east at entrance to the recreation ground at the east end of Mawson Lane (top); looking south west along existing footpath adjacent to the recreation ground, in close proximity to heavy traffic (bottom left); and looking north east at a potential alternative route through the recreation ground (bottom right).

The approach to the underpass on the south side of Great West Road, close to the junction with Netheravon Road South, presents another opportunity to introduce GI4RAQ (see left) and an example of one where the road is elevated relative to the people we wish to protect. In this situation, the vegetation barrier should extend upwards from the level of the road to ensure it provides most effective protection. There may currently only be space to introduce a hedge, and trees here would threaten the structural integrity of the subway's retaining wall, but trees could be added between the existing ones (pictured to the right in the photo below). The latter would offer some protection – in combination with the existing wooden fencing – to the houses beyond.

Figure 28. Looking north east along access to underpass to the south of Great West Road, close to the junction with Netheravon Road South, pictured as it is at present (top) and with proposed GI4RAQ (bottom); the latter is only illustrative, and TfL's arboriculture team should be consulted on all planting.

On the opposite side of Great West Road (i.e., to the north), the addition of a hedge at the kerb could raise concerns about personal security, as it would create a dark, narrow 'tunnel' of vegetation at night; see right. It is a similar situation, however, to the area beside Homefield Recreation Ground South. The larger part of the recreation ground lies on this northern side of the road, and is bounded by thick vegetation. As there is already a pedestrian route of access running parallel with the footpath pictured below, but to the far side of the existing vegetation (pictured to the right), it raises the question whether pedestrians could simply be guided to use the healthier route.

Figure 29. Looking south west along Great West Road (east of Hogarth roundabout): approaching Homefield Recreation Ground from the east (top); and beside the recreation ground (bottom).

6.2 Suburban and Inner City Exceptions

At the start of section 6, we contrasted suburban sites with inner-city ones, identifying generally fewer constraints to continuous, long vegetation barriers in the former than the latter. This subsection, however, presents two notable exceptions – to illustrate the need to assess each site individually. The opportunities to introduce GI4RAQ, and practical constraints on its introduction, broadly correlate with TfL's street types, but there will be many exceptions to the 'rule'.

6.2.1 Site 4: A40 (Western Avenue)

Figure 30. Map of case study area 4: A40 (Western Avenue).

Figure 31. Looking east along the south side of Western Avenue, level with Ellenborough House, pictured as it is at present (left) and with proposed GI4RAQ (right); the latter is only illustrative, and TfL's arboriculture team should be consulted on all planting.

Site 4 comprises a stretch of the A40 (Western Avenue) to the west of the junction with the A3220, consisting of three lanes of traffic in each direction (i.e., six lanes in total) and flanked by a mixture of low-rise houses, high-rise flats, offices, hotels and open ground. The critical characteristics governing what GI4RAQ interventions will be robustly beneficial within this site change, and change again, on relatively short spatial scales. The main message here, however, is that whilst there may be more straightforward opportunities to introduce GI4RAQ on the south side of this road (see, e.g., Figure 31 above), it would take more imagination in redesigning the street to do so on the north side; see top panel of Figure 32 (below). It is here, however, that houses lie in closest proximity to Western Avenue: only a parking bay separate them from a total of six lanes of traffic.

This stretch of Western Avenue is orientated neither clearly parallel with, nor clearly perpendicular to, the prevailing wind: it is a borderline case. Following the Decision Tree, its characteristics are thus borderline between those of Types A (below left) and G (below right):

- **Prevailing winds parallel with road**

- **Prevailing winds perpendicular to road**
- Road lies within distance, D = 3H
- People at downwind kerb lie within D = 3H
- People beyond street boundary lie within D = 3H
- Buildings present downwind of road

If Type G, it is not robustly beneficial to add any GI4RAQ downwind of the road (i.e., on this northern side): the addition of a hedge and dense line of trees at the downwind kerb would be of benefit to people downwind – both at the roadside and beyond the street boundary (i.e., the residents of the adjacent houses) – but at the cost of people upwind of the road. If Type A, however, the addition of a vegetation barrier at the northern kerb would be robustly beneficial (i.e., of benefit to people to the north, and of no disbenefit to people to the south). Given the orientation of the road (and natural variations in wind direction), we suggest the benefit downwind of a tall vegetation barrier at the northern kerb would be significant, whilst any disbenefit on the southern side would be relatively modest. If such a barrier were to be added at the downwind kerb, the next question would be, how could it be accommodated whilst retaining access to the parking bays?

Figure 32. Looking east at westernmost end of site 4: a stretch of the eastbound A40 (Western Avenue) flanked by houses, pictured as it is at present (top) and wholly reimagined with, but not limited to, the addition of GI4RAQ (bottom). The latter is only illustrative, and TfL's arboriculture team should be consulted on all planting.

In the lower panel of Figure 32, we imagine a very different setup on this stretch of the A40: the creation of a street within a street that still provides parking for the residents of these houses, and buys space for a tall vegetation barrier, at the expense of one lane of traffic. If, for example, the central reservation and one of the six lanes of traffic were removed, perhaps one of the remaining five lanes could be used for inbound traffic in the morning and outbound at night. This sort of wholesale redesign of the street is completely speculative but would be transformative. In terms of air pollution, local residents would benefit from both the protection conferred by the vegetation barrier, and the increased distance from nearest traffic. They would also benefit from noise reduction and the creation of a more family-friendly space offering natural beauty, shade and shelter.

6.2.2 Site 11: Lower Thames Street

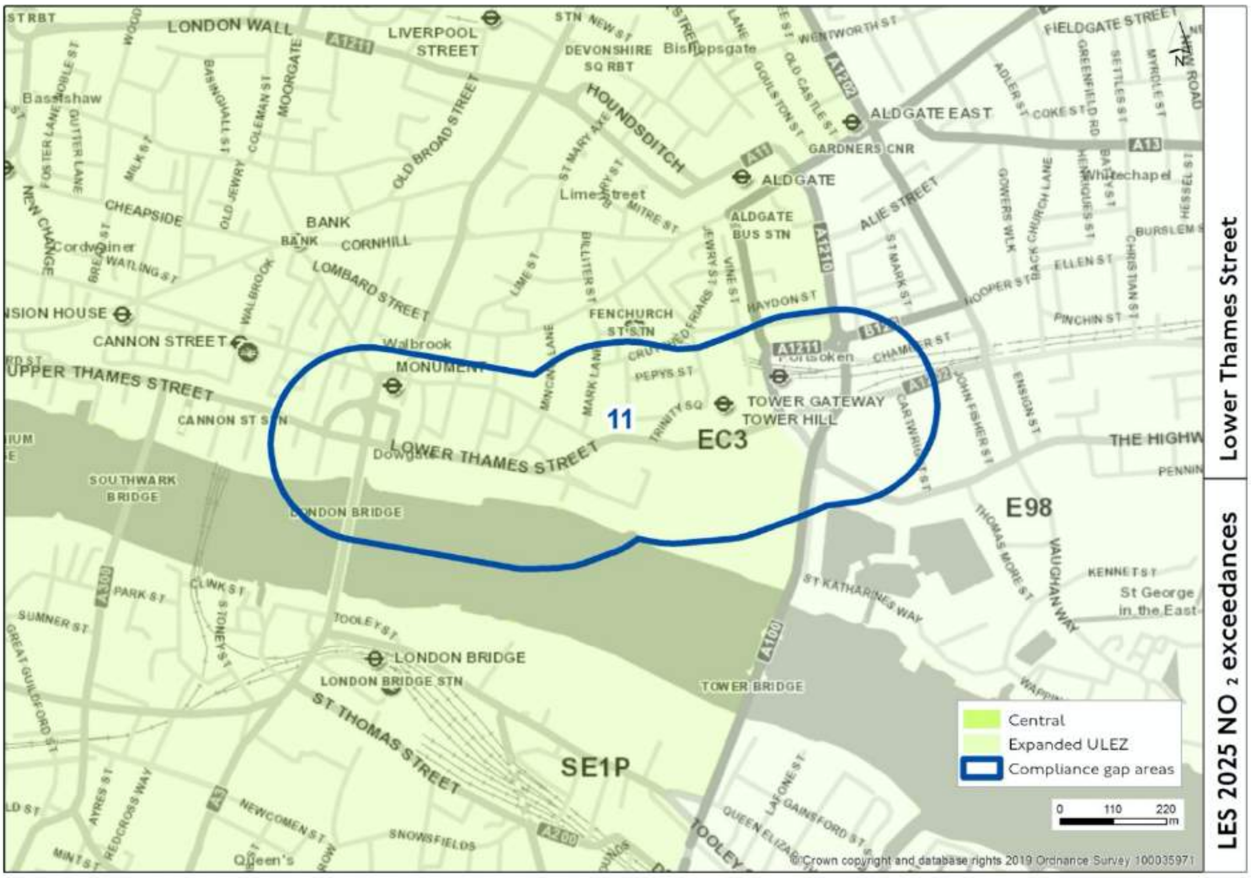


Figure 33. Map of case study area 11: Lower Thames Street.

In contrast to site 4, site 11 –a stretch of Lower Thames Street from London Bridge (left) to the Tower of London (right) – lies in the inner city; see Figure 33 above. Yet, despite its central location, and the constraints this often presents (elaborated on in the next section), much of this site offers an opportunity to introduce a relatively long and continuous GI4RAQ intervention. Lower Thames Street includes one lane of eastbound traffic, two lanes of westbound traffic, segregated cycle lanes (in both directions) located on the north side of the road, and pavements either side of the street. It is flanked by relatively tall buildings, mainly of commercial use, on both sides. Following the Decision Tree, we identify the site as Type G from London Bridge to Custom House and Type A from Custom House to All Hallows by the Tower. The characteristics associated with Types A and G were listed in the last section (6.2.1) and, here too, we must balance the benefits of GI4RAQ interventions for people on one side of the road with potential disbenefits for people on the other. As before, the addition of a tall vegetation barrier at the northern kerb could be of benefit to people on this side of the road in both Type A and Type G environments. In Type A streets, that intervention would not affect people on the southern side but, in Type G streets, it could present a disbenefit. In view of the relatively small number of people observed to use the pavement to the south compared to the number of people observed to walk and cycle on the northern side of the road, we expect that the addition of a hedge and dense line of tall trees between eastbound traffic and (already-segregated) cycle lanes would be of net benefit; see Figure 34 below.

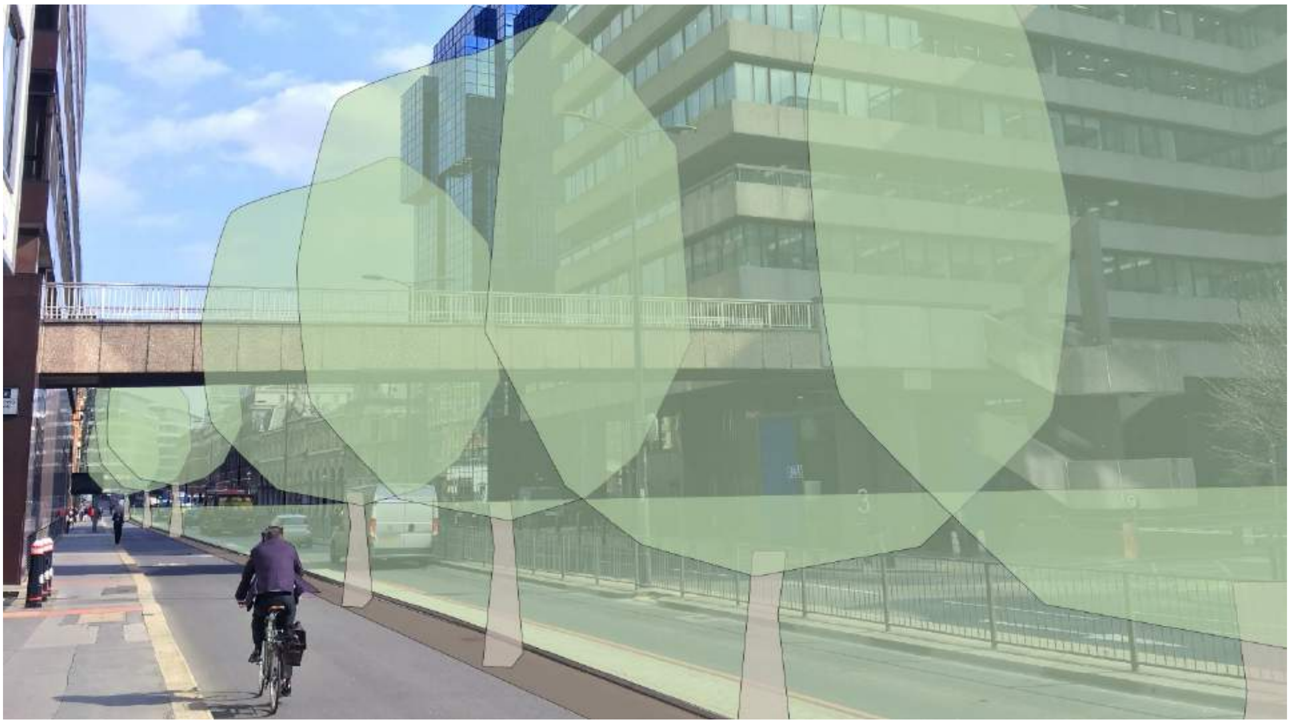


Figure 34. Looking east along the northern side of Lower Thames Street (close to London Bridge), pictured with proposed GI4RAQ; this is only illustrative, and TfL's arboriculture team should be consulted on all planting.

Usually, in such a central location, the need to preserve vision splays at frequent junctions, and access required at the kerb (e.g. to buses and taxis), would preclude the addition of lengthy, continuous barriers. This is not the case, however, on this half-mile stretch of Lower Thames Street. Vehicular access, and therefore protection of sight lines, is needed at just two junctions on the eastbound side of the road (the junctions with Great Tower Street and Trinity Square) and these are already controlled by traffic lights.

6.3 Reimagining Inner City Streets

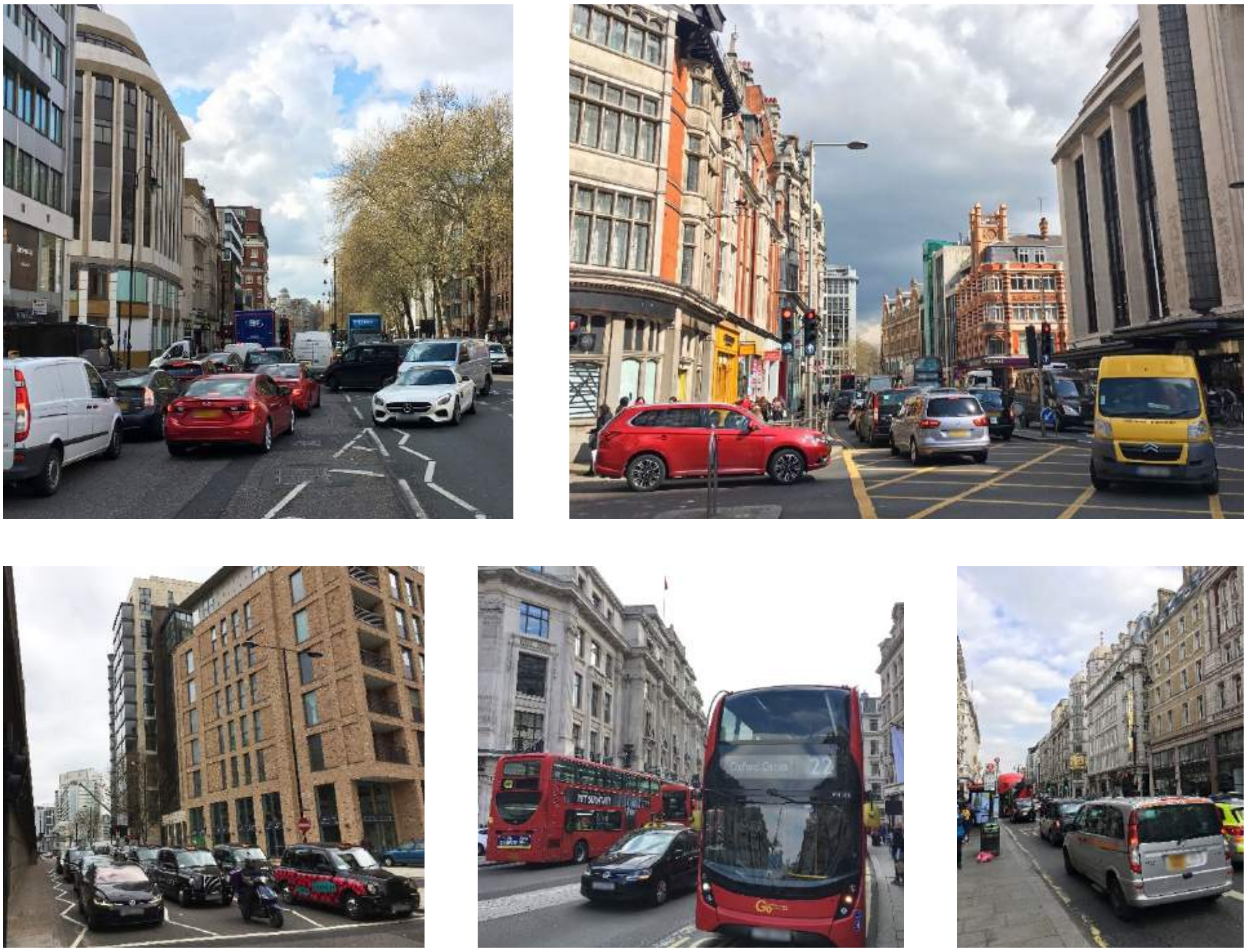


Figure 35. Congestion recorded in sites 6-10, respectively: Cromwell Road (top left), Kensington High Street (top right), Harrow Road, adjacent to Marylebone Road (bottom left), Regent Street (bottom middle), and the Strand (bottom right).

This section is structured differently from the preceding ones. We will not examine each site in detail, but simply present selected photos from the five inner-city sites (6-10) to: illustrate the constraints on GI4RAQ commonly encountered in such areas; and form a basis of reimagining our inner city streets – rebalancing provisions for vehicles, pedestrians and cyclists, and making space for GI for all the health, environmental, social and economic benefits it brings. Faced with scenes such as those pictured in Figure 35 above, we reiterate that, whilst reducing exposure to road transport emissions is a complementary means of reducing their public health impacts, the best way to improve RAQ, and urban air quality at large, is to reduce road transport emissions at source. Ultimately, this means reducing total vehicle use through modal shift towards increased active travel in conjunction with public transport. Cleaner, greener streets are not only desirable outcomes of this evolution of our transport system, but also agents of change in driving this evolution.

6.3.1 Common Constraints (Sites 6-10)

On inner-city streets, access is more often than not needed at the kerb, for example, to bus stops and stands (see Figure 36), taxi ranks and parking bays (see Figure 37) and more frequent pedestrian crossings (see Figure 40 later in this section). Subject to the current design of these streets, the opportunities to introduce vegetation barriers that extend to an overall length ≥20m with gaps totalling ≤10% of this overall length (as we recommended in section 4) may be limited.

Figure 36. Access at the kerb to bus stops and stands: looking west along Cromwell road (left) and looking east along Kensington High Street (right).

Figure 37. Access at the kerb to taxi ranks and parking bays: looking east along Cromwell Road (left) and looking north east along the Strand (right).

Whilst access at the kerb may preclude GI4RAQ, the width of pavements is usually sufficient to accommodate a hedge at the kerb – to extend the critical source-receptor pathway between vehicles (the sources of pollution) and people on the pavement (potential receptors of that pollution). There are inevitably some locations, however, where there isn't sufficient space due to the narrowness of the pavement, pinch points created by street furniture, or simply the amount of footfall the existing pavement receives; see left, middle and right panels of Figure 38 respectively.

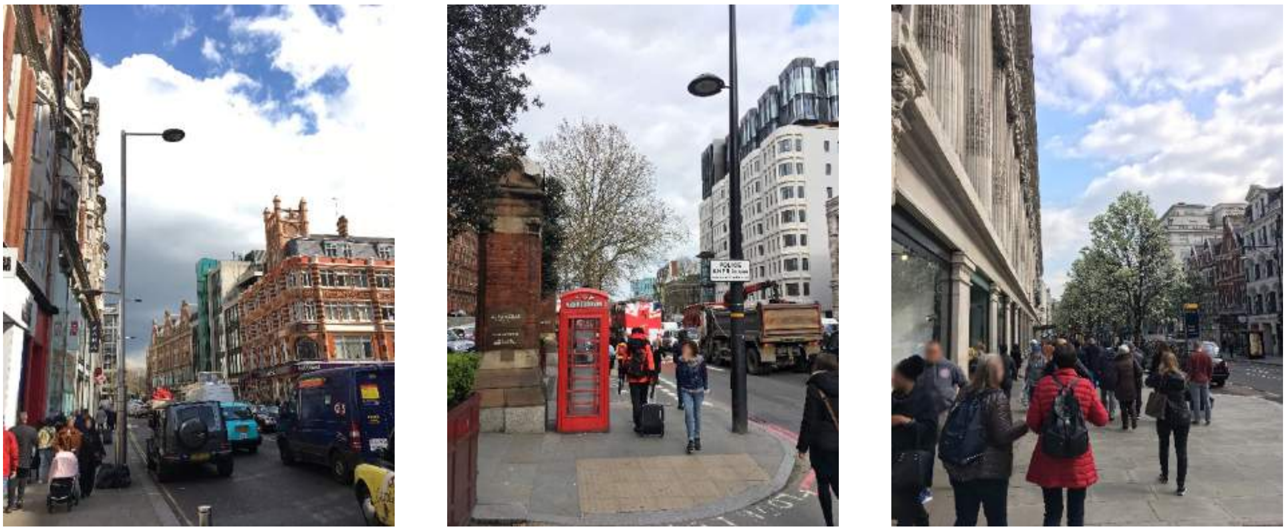


Figure 38. Shortage of space at the kerb: looking west along Kensington High Street (left), looking east along Marylebone Road (middle) and looking east along Oxford Street (right).

Besides access at the kerb, and sometimes a shortage of space here too, the need to preserve safety-critical sightlines and vision splays also restricts where GI4RAQ can be introduced. In the inner city, road junctions are less widely spaced, and thus pose a greater constraint on the addition and continuity of GI4RAQ, than in the suburbs; compare, for example, the photographs in Figure 39 below with those featured in Figures 14-18 in section 6.1.1. Pedestrian crossings, not only require access at the kerb, but also present further requirements regarding sight lines (Figure 40).

Figure 39. Frequent junctions requiring preservation of safety-critical vision splays: looking west along Cromwell Road (left) and looking north along Kingsway – off the Strand (right).

Figure 40. Pedestrian crossings, not only requiring access at the kerb, but presenting further requirements regarding safety-critical sightlines: looking east along Kensington High Street (left) and looking east along the Strand (right).

6.3.2 Rebalancing Provisions (Sites 6-10)

Figure 41. Looking south along Regent Street, pictured as it is at present (top) and reimagined with GI4RAQ (bottom). The latter is only illustrative, and TfL's arboriculture team should be consulted on all planting.

The constraints identified above limit the opportunities in many inner-city streets to introduce GI4RAQ of significant length and continuity. We could, however, reimagine these streets – rebalancing provisions for vehicles, pedestrians and cyclists – to reap the benefits of GI for, not only improved RAQ, but further health, environmental, social and economic benefits; see section 3. We use Regent Street (site 9) and Kingsway (off the Strand; site 10) as examples in Figures 41 (above) and 42 (below) to illustrate alternative provisions for active travel and motorised transport respectively. Regent Street is typical of many central London streets with two lanes of traffic in each direction, one of which is used for bus stops and so forth, separated by a central strip of paving half a lane in width; see top panel of Figure 41. Suppose we could reduce this total of four and half lanes to three and a half. In principle, for example, we could restrict access during peak periods to buses, taxis and emergency vehicles; lorries and private vehicles could have off peak access. The reduced number of vehicles could potentially then be served by just one lane in each direction, provided all vehicles had appropriate places to stop (i.e., bus stops and stands, taxi ranks and parking bays). A single central zone, one and a half lanes wide, could perhaps offer these spaces, alternately serving one side of the road then the other; see bottom panel of Figure 42. Central zones of this sort, albeit somewhat narrower than that proposed here, are already used to accommodate taxis on the Strand, and bicycle racks on Kingsway; see top panel of Figure 42.

By removing a lane of traffic, each side of the street could gain 1.5-2m for GI and greater provisions for pedestrians and/or cyclists (i.e., wider pavements and/or dedicated cycle lanes); see bottom panel of Figure 41. In so doing, we are already increasing the average length of the all-important source-receptor pathway (i.e., even in the absence of GI4RAQ). Access to buses and taxis is no longer needed at the kerb, and vegetation barriers can now be added here to further lengthen this pathway. Of course, people will need to cross the road to access the central zone serving buses and taxis, not to mention the shops either side of the street. If pedestrian crossings were located directly beside road junctions (as is conventional in the American city block system and already commonplace in central London), they could simultaneously serve to preserve the safety-critical sightlines and vision splays needed at these junctions, whilst minimising breaks in the vegetation barriers. Meanwhile, generous planting could create attractive spaces either side of the road that offer shaded, sheltered, safer and quieter public spaces, in addition to ones of improved RAQ. That same vegetation, if suitably planted with good cellular root systems, could also alleviate pressure on mains drainage during periods of unusually high rainfall by taking up and storing rainwater, and create cooler environments in which to walk, cycle, socialise and shop during periods of intense heat by subsequently releasing that rainwater as water vapour (i.e., evapotranspiration). The investment in planting and maintaining this GI would thus reap dividends in both the short term and the long term – in quality of public realm and increased resilience to climate change.

Figure 42. Looking south along Kingsway (off the Strand) pictured as it is at present (top) and reimagined with GI4RAQ (bottom). The latter is only illustrative, and TfL's arboriculture team should be consulted on all planting.

6.4 Protecting the Most Exposed and Most Vulnerable

This final section uses the largest case study area, site 3 – a four mile stretch of the A12/A102 including the Blackwall Tunnel Approaches (Figure 43) – to illustrate: the priority to protect those most exposed and/or most vulnerable to road transport pollution; and how small-scale GI4RAQ interventions can offer effective protection to groups of such people concentrated close to busy roads (e.g. children in a school playground bordering the street). Recall, interventions to improve RAQ deliver greatest benefits for population-wide public health where the concentrations of pollutants, the number of people exposed to these, the vulnerability of those exposed and the duration for which they are exposed combine to have greatest health impacts. The most vulnerable demographics include: the very young, the elderly and those with certain pre-existing medical conditions. Schools, care homes and medical facilities bordering polluted roads therefore present prime targets for GI4RAQ. In general, so do residential buildings in close proximity to these roads, as more deprived communities tend to live in areas of worse air quality (see, e.g., Aether's 2017 report to the GLA re London, and AEA Technology's 2006 report to DEFRA re the UK as a whole) and exhibit higher incidences of relevant medical conditions, such as COPD (see NHS England, 2018). Reducing exposure in these areas will, not only offer major benefits for population-wide public health, but also reduce socio-economic disparities in health outcomes.

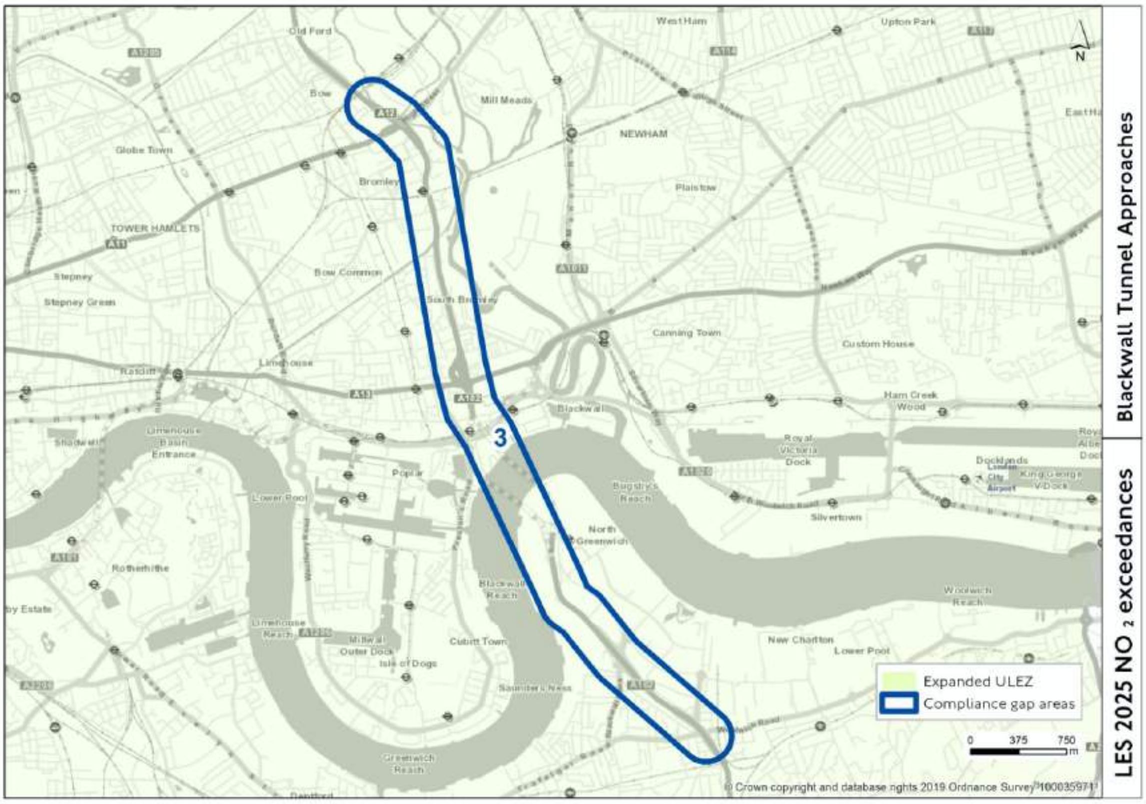


Figure 43. Map of case study area 3: Blackwall Tunnel Approaches.

6.4.1 Site 3: Blackwall Tunnel Approaches - Northern

Figure 44. Looking south along the western side of the A12, from the junction between the A12 and A11 (left); and looking east over of the industrial yard immediately adjacent to the eastern side of this stretch of the A12 (right).

We start at the northern end of site 3, close to the junction between the A12 and the A11, and work our way south towards the northern entrance of the Blackwall Tunnel. The left panel of Figure 44 shows the residential buildings south west (i.e., upwind) of the A12, south of the A12/A11 junction. The two lanes on the left of the photo merely comprise the slip road off the northbound carriageway of the A12: a further five lanes lie beyond these: four lanes corresponding to the A12 itself (two in each direction) and a single-lane slip road serving its southbound carriageway. Following the Decision Tree, we identify that this stretch of the street is Type F, characterised by:

- Prevailing winds perpendicular to road
- Road lies within distance, D = 3H
- People at downwind kerb lie within D = 3H
- People beyond street boundary lie within D = 3H
- No buildings present downwind of road

In principle, it is therefore robustly beneficial to add a hedge, with or without a dense line of trees, at the upwind kerb. There is, however, insufficient space to plant trees here without compromising the passage of people on the pavement and/or vehicles on the carriageway, and it is questionable who would benefit from a hedge alone. A hedge would only protect people at the upwind kerbside (i.e., it would offer little or no protection to the people living in the adjacent buildings, besides perhaps those on the lowermost floor) and, at the time of visiting at least, the pavement here received little footfall (i.e., the number of people exposed here was low). Meanwhile, this is one of the street types, for which it is not robustly beneficial to add any vegetation barrier downwind of the road (i.e., either at the downwind kerb or the downwind street boundary). As it happens, directly opposite the residential buildings, there is little need for protection from pollution emanating from the A12, as the adjacent property comprises an industrial yard (see right panel of Figure 44). To ensure best use of resources to improve population-wide public health, and health equality, it is good to ask ourselves both *whether* an intervention would be beneficial and *who* it would benefit. In the remainder of this section, we present a series of images highlighting the potential to protect vulnerable groups concentrated close to the A12 via targeted, small-scale GI4RAQ interventions.

Following the Decision Tree, the stretch of the A12 directly beside Bow School is Type G whilst the approaches to the school from the north and south vary between Types B, C, F and G. It follows that a vegetation barrier at the downwind kerb (i.e., on the school side of the A12) is alternately robustly beneficial and beneficial to some at the expense of others (beneficial on the school side). In view of children’s vulnerability, we believe a barrier here could be of net benefit for public health but there is little space to add one at the kerb. On the southern approach (pictured left and below), a relatively minor road (Gillender Street) lies between the A12 and potential receptors. The addition of a barrier between the two carriageways should still offer those receptors some protection, albeit punctuated by spikes of pollution from Gillender Street traffic, provided it is sufficiently tall: the existing, low level railings (that currently present no obstruction to polluted air flow) could be replaced with a 2m high hedge or grey infrastructure alternative (e.g. fence or wall) and a dense line of trees; planting of the latter would require the removal of a lane of traffic from Gillender Street.

Figure 45. Looking north along Gillender Street (parallel with, and adjacent to, the A12), pictured as it is at present (middle left) and with proposed GI4RAQ (bottom); the latter is only illustrative, and TfL’s arboriculture team should be consulted on all planting. The front façade of Bow School, bordering Gillender Street, is also pictured (top left).

Continuing south on the downwind (i.e., eastern) side of the A12/A102, Culloden Primary School lies within 5-15m of the road, separated only by a wedge-shaped pedestrianised area (pictured left). The A12 lies immediately beyond the semi-transparent screen on the right hand side of the picture, whilst the school playground lies just beyond the wire netting (and limited existing vegetation) on the left. Following the Decision Tree, we identify this stretch of the A12 as Type B and a vegetation barrier at the downwind kerb (i.e., the right hand side of the picture) as robustly beneficial. The taller this barrier, the greater the distance for which people will benefit from a degree of protection downwind (i.e., to the left). The semi-transparent screen already poses an obstruction to the flow of polluted air from the A12 air at low levels, and could be augmented by a dense line of trees to block air flow above (see below). Meanwhile, to maximise protection of the playground (to the left of the picture below), the existing vegetation at its boundary (marked by the green mesh fence) could be bolstered with a further dense line of trees. Where the two lines of proposed trees converge, there is potential to create a 'green oasis'; see Hewitt et al. (2019) for more details. An avenue of trees of this sort could thereby maximise protection, not only of children in the school playground, but also in this area likely frequented by both children and parents before and after school.

Figure 46. Looking south along pedestrianised area between the A12/A102 to the right and Culloden Primary School to the left, pictured as it is at present (top) and with proposed GI4RAQ (bottom); the latter is only illustrative, and TfL's arboriculture team should be consulted on all planting.

Finally, at the southern end of the Northern Approach to the Blackwall Tunnel, Woolmore Primary School lies on the upwind (i.e., western) side of the A102. Following the Decision Tree, we identify this stretch of the A102 as Type C and a vegetation barrier at the upwind kerb as robustly beneficial. The school is separated from the dual carriageway by a minor road, Robin Hood Lane (see left). As was the case for Bow School, due to the limited space available, the most effective intervention may be to replace the low level railings between Robin Hood Lane and the A102 (that currently present no obstruction to the flow of polluted air) with a 2m high hedge or grey infrastructure alternative (e.g. fence or wall) and dense line of trees. In practice, planting of the latter would likely require the removal of the parking bay on Robin Hood Lane.

Figure 47. Looking south along Robin Hood Lane between the A102 to the left and Woolmore Primary School to the right, pictured as it is at present (top) and with proposed GI4RAQ (bottom); the latter is only illustrative, and TfL's arboriculture team should be consulted on all planting.

6.4.2 Site 3: Blackwall Tunnel Approaches – Southern

On the southern approach to the Blackwall Tunnel, from the Greenwich Peninsula to the junction between the A102 and A206, there are many places where it is questionable *who* would benefit from GI4RAQ – even if GI4RAQ is in principle beneficial. The use of the surrounding land could change rapidly, and we must be alert to developments that introduce groups of exposed and/or vulnerable people, but there are currently significant stretches of the A102 bordered by areas of industrial use and/or derelict buildings, and few people were observed to use the pavements beside it; see top panels of Figure 48. Additionally, the partial protection offered by GI4RAQ is limited to immediately downwind of a vegetation barrier positioned close to the source of pollution (i.e., a busy road): it is unfortunately of limited benefit in protecting the occupants of buildings, particularly medium and high-rise buildings, set a considerable distance back from the road, such as the hotel pictured in the bottom left panel of Figure 48. It is also not easy to implement GI4RAQ in an effective manner where the road is significantly elevated relative to the people we wish to protect, such as where the A102 flies over the A2203; see bottom right panel of Figure 48.

Figure 48. Examples of industrial areas (top left), derelict buildings (top right), high-rise buildings set a considerable distance back from the road (bottom left) and locations where the road is elevated relative to receptors (bottom right); all bordering the A102 south of the Blackwall Tunnel, and pictured looking approximately to the south east.

At the end of this guidance document, the southern approach to the Blackwall Tunnel provides an opportunity to reiterate that reducing emissions from vehicles is the best way to improve urban air quality. GI4RAQ then offers a complementary means, in appropriate locations, of reducing public exposure to what is emitted: a means of further reducing the public health impacts of this pollution.

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Green Infrastructure for Roadside Air Quality (GI4RAQ) is an initiative by **Dr James Levine** and **Prof Rob MacKenzie** at the University of Birmingham's Institute of Forest Research (BIFoR) to promote and facilitate the evidence-based use of green infrastructure to reduce exposure to road transport pollution. The current GI4RAQ Guidance, and accompanying GI4RAQ Decision Tree, have been developed and written with **Yvonne Brown** at Transport for London (TfL).

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