3D Visualization of Traffic-Induced Air Pollution Impacts of Urban Transport Schemes

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Abstract: The negative impacts of urban traffic growth are well known, e.g., congestion, increased air pollution, and more traffic noise. Humans can readily see traffic congestion, and can hear traffic noise, but inevitably they are much less aware of odorless, invisible, silent air pollution. Therefore, quite naturally people, whether the general public or transport professionals, struggle to visualize air pollution from traffic, and will find it particularly difficult to visualize changes in air pollution levels resulting from changes in traffic conditions because of the implementation of various urban transport schemes. Hence, there is always a risk of the air quality impacts of potential urban transport schemes being underappreciated. Therefore, this paper contributes to the knowledge by devising a new three-dimensional (3D) visualization approach for modeled air quality before and after the implementation of potential urban transport schemes. Using the Dunkirk area of the City of Nottingham in the United Kingdom as a case study, research has been undertaken to integrate an air pollution dispersion model for the pollutant NO_2 with a 3D digital city model. The modeled NO_2 concentrations, before and after the implementation of an urban transport scheme, were represented in the 3D city model at various heights above the ground: first, as 3D point shapes; second, as 3D planar surfaces; and finally, as 3D volumetric clouds. The 3D volumetric clouds approach used the analogy of people's perceptions of gray clouds in the sky as representing undesirable weather, and hence provided an intuitive 3D visualization of all the modeled NO_2 concentrations, at and above the ground surface, in a single 3D virtual scene. Benefits have been identified in enhancing the level of understanding of the pollution dispersion using this new approach to visualization. This has allowed the visualization process to be used in the development of future traffic scenarios that could be used to alter the design of a proposed transport scheme to increase its air quality benefits. This 3D visualization approach was found to be applicable to other transport schemes in different parts of the City of Nottingham. **DOI: 10.1061/(ASCE)CP.1943-5487.0000198.** © *2013 American Society of Civil Engineers.*

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Introduction

The growth of urban traffic levels is associated with a broad range of problems such as traffic congestion, air pollution, traffic noise, reduced accessibility, and community severance. However, tackling the traffic congestion is deemed to be the main contributor to resolving the other traffic growth-related problems [Nottingham City Council (NCC) and Nottinghamshire County Council (NCC) 2006]. The predominance of the private car is a major contributor to the current and future congestion levels in urban areas (Bell 2006; Pooley and Turnbull 2005). Therefore, many urban transport schemes developed by local authorities involve changing the physical infrastructure to improve the traffic flow and/or to encourage the use of alternatives to the private car to reduce traffic congestion and to reduce the other problems resulting from traffic growth, such as worsening air pollution.

Air pollution dispersion modeling may be used to predict and analyze the air quality impact of a proposed urban transport scheme. Visualization of modeled air quality, both before and after the scheme implementation, should help transport planners and decision makers to select the transport scheme design alternative that maximizes the air quality benefits and/or minimizes the adverse air quality impacts. Having an intelligible visualization of the predicted air quality may also be helpful in the public consultations, which are nowadays an increasingly important part of the planning and decision-making processes. Currently, the results of air pollution dispersion modeling are usually displayed by overlaying two-dimensional (2D) colored contour maps of the air pollution concentrations over 2D digital maps of the area of interest in a geographic information system (GIS) [Cambridge Environmental Research Consultants (CERC) 2010]. This may not be very intuitive and meaningful enough for all the lay people who constitute many of the participants in public consultations about proposed urban transport schemes.

Furthermore, using the traditional 2D contour maps to recognize the change of pollution concentrations with height requires the creation of many scenes, one at each height. The current convention with 2D maps is to use only a somewhat limited spectrum of colors to display the air pollution concentration values at a given height. Therefore, as the height changes, the values of the concentration levels to be displayed change; rather than changing the color

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spectrum, the convention is to adjust the ranges of concentration values to which the colors correspond, which is potentially visually misleading. Consequently, it is easy to confuse the observer of a series of 2D scenes and to impede the observer's understanding of the changes in pollution concentrations with height (Zahran et al. 2010). Therefore, the three-dimensional (3D) visualization of various air pollution concentrations at and above the ground surface in a single 3D virtual scene may achieve improvements in relation to two important factors regarding human-computer interaction (HCI), namely increased information retention and shortened comprehension time (Sears and Jacko 2008).

Wang (2005) integrated the US Environmental Protection Agency's CAL3QHC air pollution model with GIS to prepare the model input data and present the results in a geographic context. The CAL3QHC model was used to predict current and future carbon monoxide (CO) concentrations along a segment of Interstate highway 71 in the Cincinnati, Ohio region. Street segments and buildings were integrated with output CO concentrations to give georeferenced 3D representations. No recommendations were given about the level of details (LOD) of street segments and buildings in these 3D representations. The height of receptors, output points defined in the air pollution model, was fixed at 1.8 m above the ground surface with no chance to change it. In addition, CAL3QHC did not have the option to change the spacing between adjacent receptors according to the pollution gradient. This may mask the rapidly changing CO concentrations' gradient particularly close to the modeled highway segment.

The 3D visualization of CO was attained by using the calculated CO concentration instead of the Z coordinate at every receptor. Then, a 3D planar surface was interpolated between these points to replace the terrain surface. However, taking off the terrain surface affects the degree of realism of the virtual scene. Furthermore, the floating CO surface created the illusion of having such CO concentrations at disparate heights, whereas all the displayed CO concentrations were at 1.8 m above the ground surface.

Wang et al. (2008) further developed CAL3QHC to avoid the manual preparation of CAL3QHC input data that previously required a massive amount of time and labor. In addition, they increased the number of receptors that could be added to a single model run from 60 to 100. However, because their 3D air pollution dispersion interface only managed to display the 3D surface of CO concentrations calculated at just one single height above the ground surface, their developments did not include any improvement to the 3D representation of CO concentrations, although they did identify the true 3D visualization of air pollution as a challenge ahead.

In 2008, the University College London (UCL) Centre for Advanced Spatial Analysis (CASA) collaborated with the Environmental Research Group (ERG) in Kings College London to create an interactive 3D air pollution map (CASA and ERG 2008). The 3D virtual scenes of 63 km^2 (9×7 km) of central London were produced by CASA, and ERG provided the air pollution predictions of NO_2, NO_x, and PM_{10}, which were fused in these 3D virtual scenes to build the 3D air pollution map. The color scheme of air pollution contour bands comprised 20 colors. This large number of colors has the potential to impede, rather than enhance, the understanding of displayed information. Moreover, the 3D air pollution map displayed only the ground-level air pollution concentrations, thus excluding the air pollution at other levels above the ground surface. Therefore, this 3D air pollution map does not overcome the challenge identified previously by Wang et al. (2008).

Research Aim and Objectives

Research has been undertaken to integrate an air pollution model with a 3D digital city model of an urban study area. The research aimed to create an effective 3D air pollution dispersion interface that can provide an intuitive visualization of the air pollution model output data, at and above the ground surface, in a single 3D virtual scene. The anticipated purpose of this interface is to assist planners to design urban transport schemes, taking into account the air quality impacts of the implementation of such schemes. The final development stage of this interface innovatively aimed to display the modeled air pollution, at and above the ground surface, as gray clouds, given that people intuitively perceive grey clouds as representing poor weather: the darker the clouds, the worse the weather will probably be.

To achieve the research aim, the objectives were to undertake investigations into

1. Air pollution modeling;
2. Generating 3D city models for visualization;
3. A methodology to display the output data from an air pollution model in a 3D digital city model;
4. The possibility of using the developed visualization method as a design tool to increase the air quality benefits of a proposed urban transport scheme; and
5. The transferability of the developed visualization method to a range of other urban transport schemes.

These objectives have been investigated and developed using the Dunkirk area of the City of Nottingham in the United Kingdom as a case study. The transferability of the method has been investigated by applying it to two further case studies in central Nottingham.

Research Methodology and Paper Structure

The research air pollution dispersion interface has evolved from displaying modeled air pollution concentrations at various heights above the ground: first, as 3D point shapes; second, as 3D planar surfaces; and finally, as 3D volumetric clouds. Fig. 1 displays a flowchart for the 3D volumetric clouds air pollution visualization method. The Dunkirk Air Quality Management Area (AQMA), an urban study area in the City of Nottingham with NO_2 levels exceeding the permissible levels (NCC 2010a), was used in the development of the research 3D air pollution dispersion interface because various sorts of relevant data were readily available. The interface has been developed to attain a 3D visualization of the future air quality impact of a proposed urban transport scheme, the introduction of a (largely elevated) section of Nottingham Express Transit (NET) Phase 2 running through the Dunkirk AQMA. The NET is a modern urban tram system that, as the network of tram lines develops, should provide an attractive alternative to the car for more and more urban trips in Nottingham (NCC 2010b).

In the following sections of this paper, the creation of air pollution models before and after the proposed implementation of NET Phase 2 in the Dunkirk AQMA is briefly introduced, and the form of output air pollution concentrations is described. Then, in the "Dunkirk AQMA 3D City Model Design and Customization" section, the design criteria and customization of the Dunkirk AQMA 3D city model to attain an efficient 3D visualization of the air pollution dispersion are explained. Consequently, the development of the 3D air pollution dispersion interface is described and illustrated using the Dunkirk AQMA case study. In the "Air Quality Visualization as a Design Tool for Alternative Traffic Scenarios" section, the developed interface is applied in the design of alternative future traffic scenarios that were developed to increase the air quality benefits of NET Phase 2 in the Dunkirk AQMA.

To investigate the transferability of the methodology developed for pollution visualization, the interface has been applied in the

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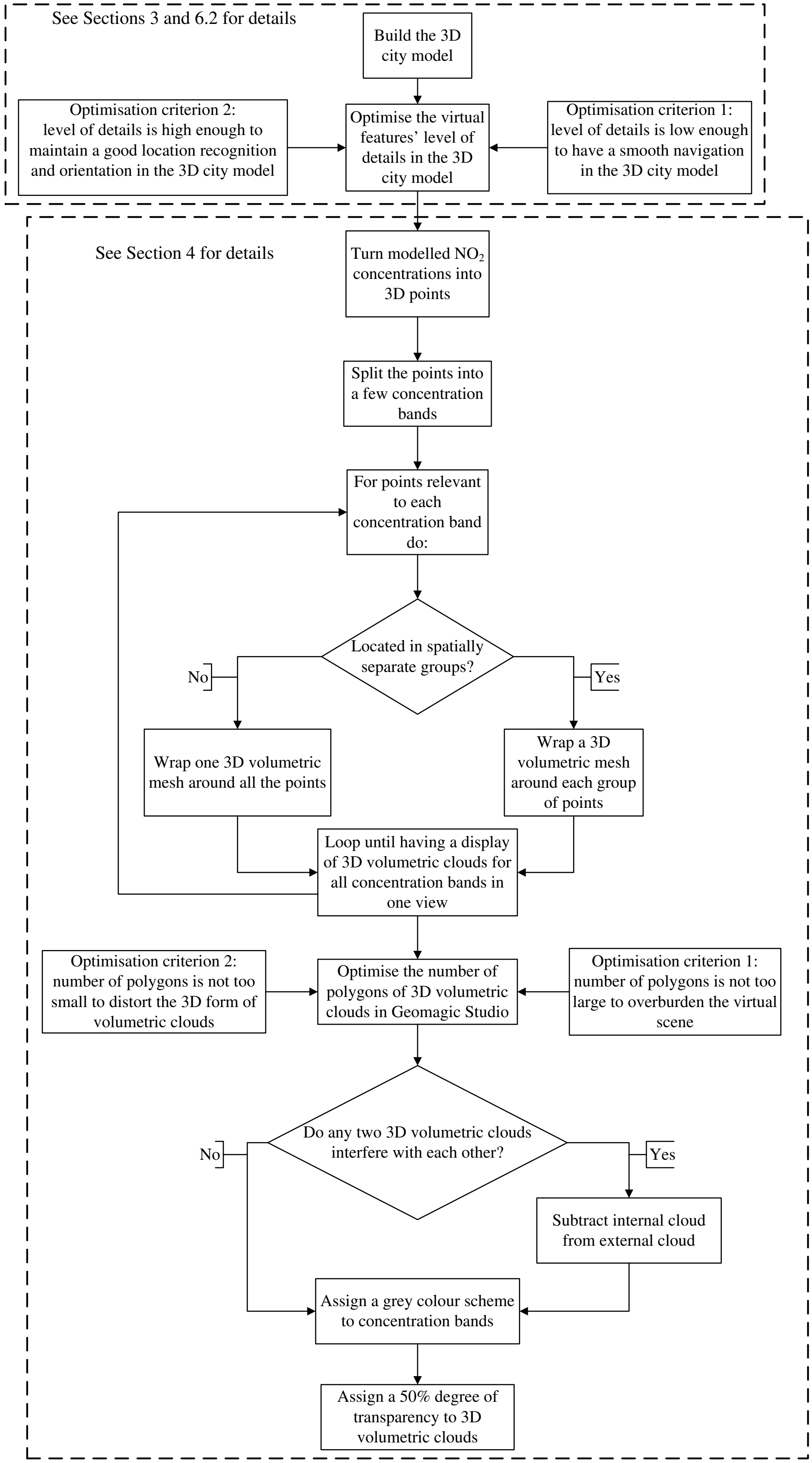

Fig. 1. Flowchart for the 3D volumetric clouds air pollution visualization method

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"Application of the Developed Interface to Two Other Urban Transport Schemes" section to visualize the future air quality impact of the proposed Turning Point East and Broadmarsh Shopping Centre Extension transport schemes in Nottingham City Centre. These transport schemes are anticipated to increase the modal shift from the private car to the more sustainable modes of public transport (NCC 2009a, b). Whereas the NET Phase 2 implementation through the Dunkirk AQMA scheme is concerned with adding substantial new transport infrastructure (for an additional mode of transport) to the existing infrastructure, the Turning Point East scheme is concerned with changing the operation of certain roads, and the Broadmarsh Shopping Centre Extension scheme is concerned with changing the road network in one part of the city center. Finally, a discussion of the research results and conclusions are presented.

Air Pollution Dispersion Modeling in Dunkirk AQMA

The atmospheric dispersion modelling system (ADMS)-Roads version 2.3 was used to output NO_2 concentrations as numerical values at a grid of receptors covering the Dunkirk AQMA. The ADMS-Roads system was developed by Cambridge Environmental Research Consultants (CERC 2006). The first reason for selecting NO_2 was that this is the air pollutant of concern in the Dunkirk AQMA. Therefore, the majority of available air pollution monitoring data required to validate the air pollution model in and around Dunkirk AQMA was NO_2 data. The second reason for selecting NO_2 was that it is emitted primarily from the road traffic. Therefore, with the modal shift from the private car to NET Phase 2, a reduction in the high NO_2 levels in the Dunkirk AQMA is anticipated (NCC and NCC 2006).

The functionality of ADMS-Roads was used to output NO_2 concentrations at an intelligent grid of receptors. The intelligent grid automatically changes the spacing between its receptors according to the pollution gradient. Therefore, the rapidly changing NO_2 concentrations' gradient close to the main roads in the Dunkirk AQMA was well captured.

The modeling year for the air pollution base case scenario model was 2006, which was validated against 2006 NO_2 measurements. The validated air pollution model was configured to output NO_2 concentrations at many heights above the ground surface. A study of NO_2 decay with height was conducted using the validated air pollution model to identify the height step and height limit of the intelligent output grid above the ground surface. A height step of 6 m was selected between the vertically successive output receptors, and the height limit was set at 30 m above the ground surface.

The validated air pollution model was configured to predict annual mean NO_2 concentrations, at and above the ground surface for the 2021 Dunkirk AQMA traffic scenario, with NET Phase 2 (NCC 2010b). Given that NET Phase 2 will not be constructed and in operation for some years yet, and that 2021 (2006 + 15 years) had been used as the 'after implementation' modeling year in some future traffic modeling undertaken for Nottingham City Council, 2021 was also used as the 'after' modeling year in this research.

Dunkirk AQMA 3D City Model Design and Customization

The main components of 3D city models are the ground terrain surface, static and dynamic 3D features, such as buildings, vegetation, and traffic, and photo-textures of building facades. However, buildings, traffic, and vegetation are the most important contents of 3D city models when it comes to location recognition and orientation by the viewer (Zhu et al. 2005).

For creating a 3D city model, an orthoimage, a georeferenced raster image layer that represents terrain surface (Linder 2006), and a digital terrain model (DTM) that represents terrain surface morphology, are required. Leica Photogrammetry Suite (LPS) software was used to produce these products. Leica Photogrammetry Suite is a comprehensive digital photogrammetry package that defines the mathematical relationships between the photos in the aerial image block, the sensor that captured those photos at the time of exposure, and the ground (Leica 2009). The LPS version 9.1 was used with stereoscopic aerial photographs (taken with the UltraCamD digital aerial camera, courtesy of BlomAerofilms Ltd) to generate the orthoimage and DTM of the Dunkirk AQMA.

The main 3D features, which existed in the overlap zones of the Dunkirk AQMA coverage of aerial photographs, were extracted using Stereo Analyst for ERDAS IMAGINE 9.1. This software transformed the manually digitized 2D features from the block of aerial photographs into real-world dimensions by collecting 3D geographic information directly from imagery. The extracted features included the main 3D buildings in the study area, the footbridge over the A52 Clifton Boulevard, and the Derby Road roundabout, as shown in Fig. 2.

Two main criteria were considered to develop the design of the Dunkirk AQMA 3D city model so that an effective visualization of the air pollution dispersion could be attained. A good interface should provide the user with flexible access to the content according to the user's needs and wants (Sears and Jacko 2008). Therefore, the first criterion was for smooth navigation in the virtual scene, which corresponds to a good degree of interactivity in the built-up virtual world. Second, a good level of location recognition and orientation should be provided while navigating the virtual scene.

Attaining a smooth navigation required only simplifying the virtual features of the 3D city model and producing them with a low LOD. Conversely, achieving a high level of location recognition and orientation required realism, thus producing the virtual features with a high LOD. A compromise was necessary, and a midrange LOD was selected to represent the 3D building landmarks of the Dunkirk AQMA in the 3D city model. This LOD was high enough to compensate for the absence of other 3D buildings in the 3D city model, yet maintained a good level of location recognition and orientation in the virtual scene. Because ADMS-Roads does not account for the existence of buildings, these other 3D buildings were not considered important enough to be represented in the 3D city model to not partially obscure the visualization of the air pollution.

The application of a photo-realistic texture to the 3D buildings of the study area overburdened the virtual scene. Consequently, the draping of such a texture impeded smooth navigation in the virtual environment. Therefore, it was decided to take the texture off the facades of the study area's 3D buildings, so that a good degree of interactivity in the created virtual world could be maintained. To compensate for the absence of photo-realistic textures, a dynamic 3D traffic layer was added to the 3D city model. The traffic layer enhanced the location recognition and orientation while navigating the virtual scene, which also compensated further for the absence of other 3D buildings in the study area.

AutoCAD Civil 3D was integrated with 3D Analyst of ArcGIS 9.2 to develop the design of the Dunkirk AQMA 3D city model to incorporate the representation of the dynamic traffic layer into the 3D city model. As far as the traffic-induced air pollution was concerned, the number of 3D vehicles of the dynamic 3D traffic layer was amended so that it was indicatively proportional to

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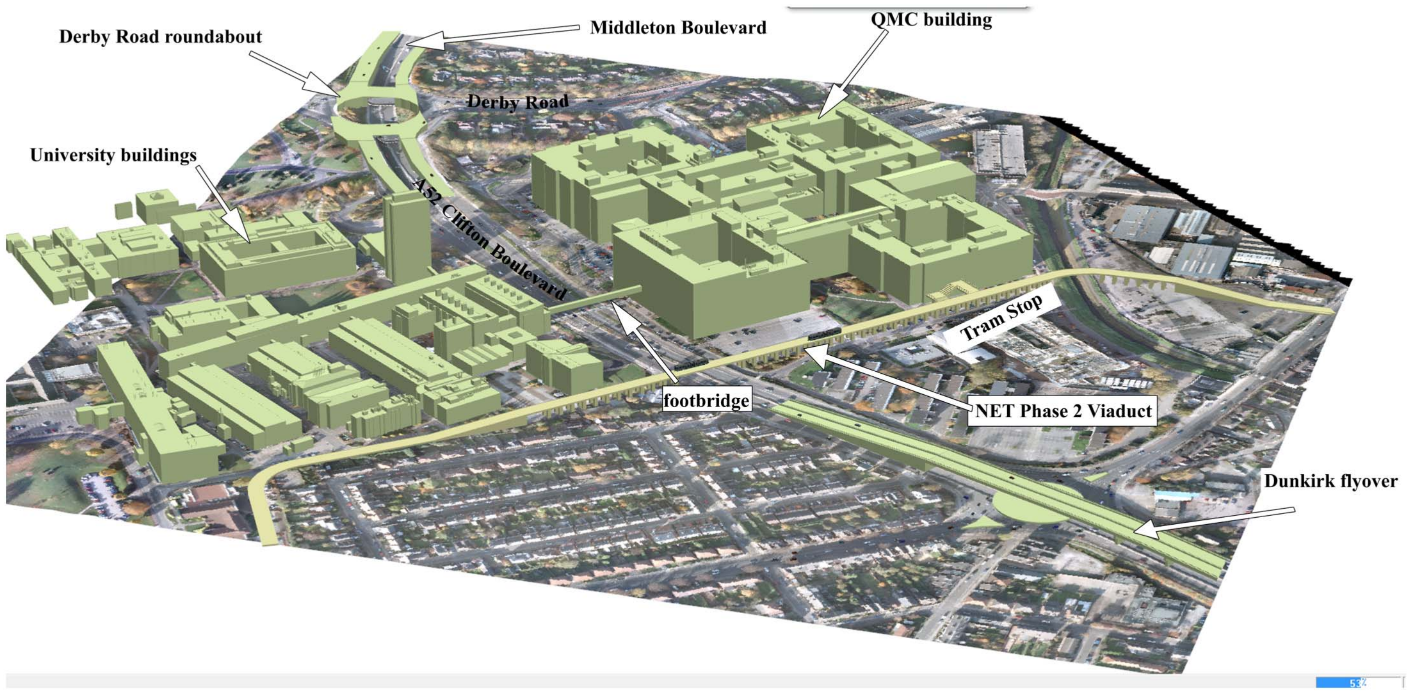

Fig. 2. Dunkirk AQMA 3D city model including envisaged future tram line section

the amount of displayed air pollution. Consequently, the observer could intuitively understand the relationship between moving traffic and the traffic-induced air pollution.

The integration between AutoCAD Civil 3D and 3D Analyst of ArcGIS 9.2 enabled the representation of certain major road network features, such as the Dunkirk flyover and the ramps of Derby Road roundabout for virtual traffic moving between the Derby Road roundabout and Clifton/Middleton Boulevard. Furthermore, such integration between these two software packages enabled the representation of the future viaduct and tram stop of NET Phase 2 in the Dunkirk AQMA 3D city model. The color of the NET Phase 2 viaduct and tram stop is different from the color of the remaining features to distinguish intuitively between the present (existing) features and future additional features. Fig. 2 depicts a screenshot of the resulting Dunkirk AQMA 3D city model to show after the implementation of NET Phase 2, including vehicles on the roads and trams on the viaduct, which move if viewed in the realistic virtual reality (VR) environment.

3D Air Pollution Dispersion Interface Design and Development

As discussed in the "Research Aim and Objective" section, the goal of a good 3D air pollution dispersion interface is to display the output data of an air pollution dispersion model at and above the ground surface in one virtual scene. This single virtual scene should be accessible and intelligible enough so that the observer can intuitively recognize and easily understand the air quality impacts, at and above the ground surface, of the implementation of an urban transport scheme.

The 3D Analyst of ArcGIS 9.2 was used to represent the output NO_2 concentrations of ADMS-Roads in the Dunkirk AQMA 3D city model. The GIS functionality of ArcGIS was used to turn the receptor points of the intelligent output grids at and above the ground surface into a 3D point shape file. The ground surface elevations of this shape file, which were interpolated automatically from the study area DTM using the 3D Analyst of ArcGIS 9.2, were added to the heights of output receptor points above the ground surface to represent the corresponding 3D point shapes at their correct elevations in the 3D city model. Then, every 3D point shape was assigned a color out of 12 colors to reflect the numerical value of the output NO_2 concentration at that point, as shown in Fig. 3. Moreover, this interface offered the option to limit the displayed 3D point shapes to any user-specified range of NO_2 concentrations.

Some principles and guidelines of HCI were selected to develop the design of the Dunkirk AQMA 3D air pollution dispersion interface. Contrast, simplicity, and using a color scheme that reinforces the hierarchy of information were the most important selected principles and guidelines of HCI. To reinforce the hierarchy of information, the color scheme should be composed of a few compatible colors that are defined as those of a monochromatic color scheme or by using differing intensities of the same hue (Sears and Jacko 2008). Complementary colors, which are most opposite to one another in the color scheme, should be used with extreme situations, i.e., to signify highest and lowest bands of hierarchical data.

Consequently, the design of the 3D point shapes air pollution dispersion interface was developed further, according to the selected HCI principles and guidelines, to have a monochromatic color scheme. The color scheme this time was comprised of only four shades of the color gray. For every 3D point shape, the darker was the point color, and the greater the diameter of the 3D point, the higher was the NO_2 concentration at that point, as depicted in Fig. 4. Although this improved the perception of pollution concentration variation, the large number of displayed points still had the effect of making the visualization rather confusing. Furthermore, visualizing points of varying size in a stereo-viewing projection gave a wrong perception of the point location in the 3D virtual space. The points bigger in size seemed closer to the observer than smaller points, although these big points were in fact further away than the small points.

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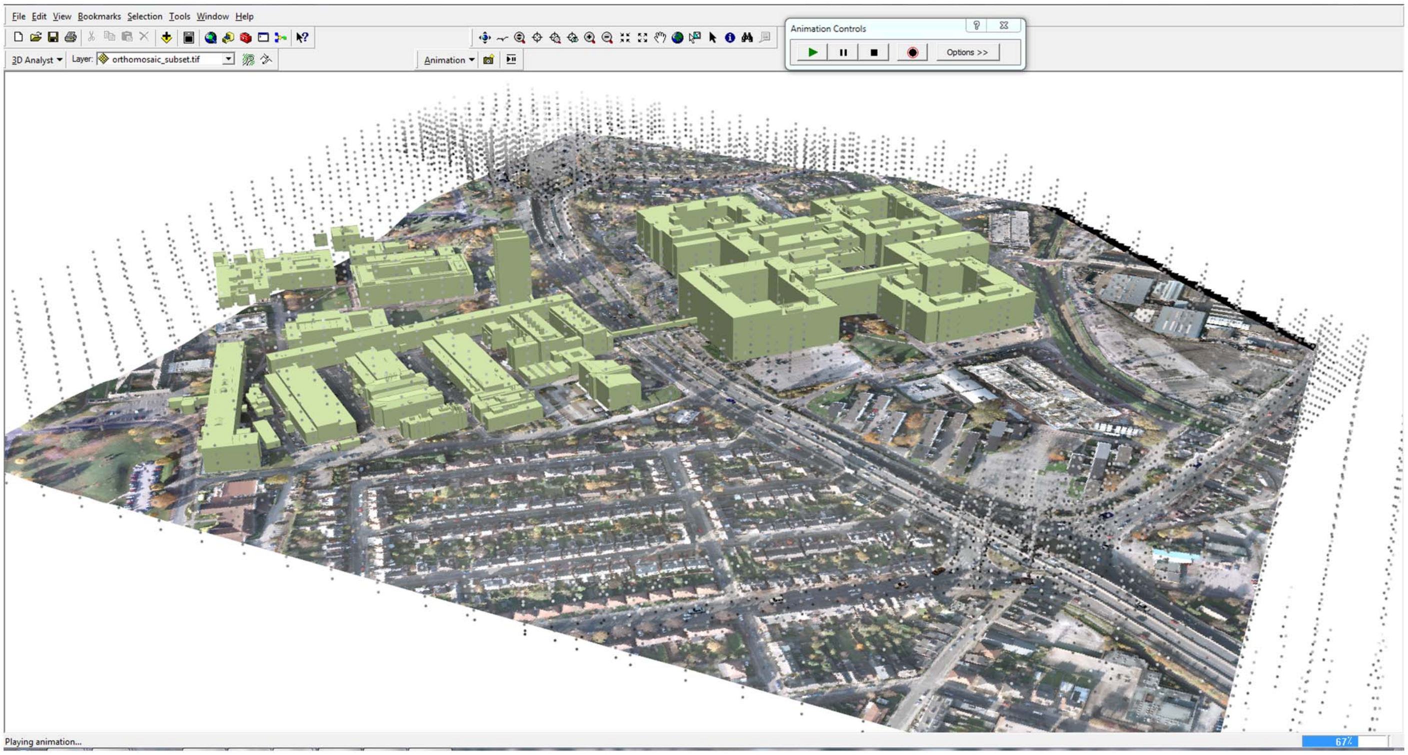

Fig. 3. 3D point shapes with one point size interface

To tackle the complexity of having a large number of points (small components) in the 3D point shapes interface, this large number of points was converted to a smaller number of larger components. A 3D planar surface was interpolated between the points relevant to each band of air pollution concentrations. Then, the number of the air pollution components in the interface design could be reduced to the number of air pollution concentration bands. A color scheme was assigned to the resultant surfaces to

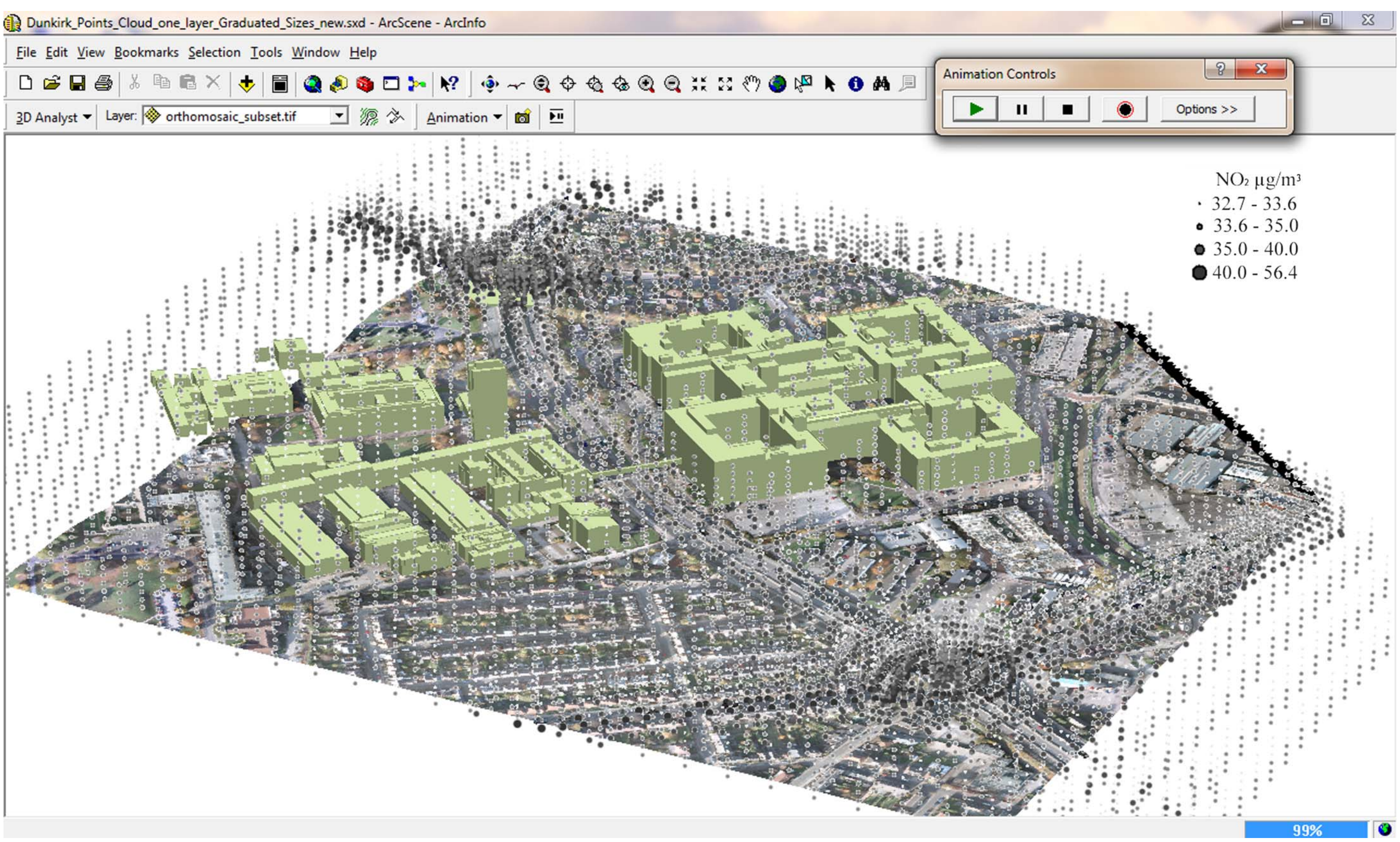

Fig. 4. 3D monochromatic point shapes with graduated point size interface

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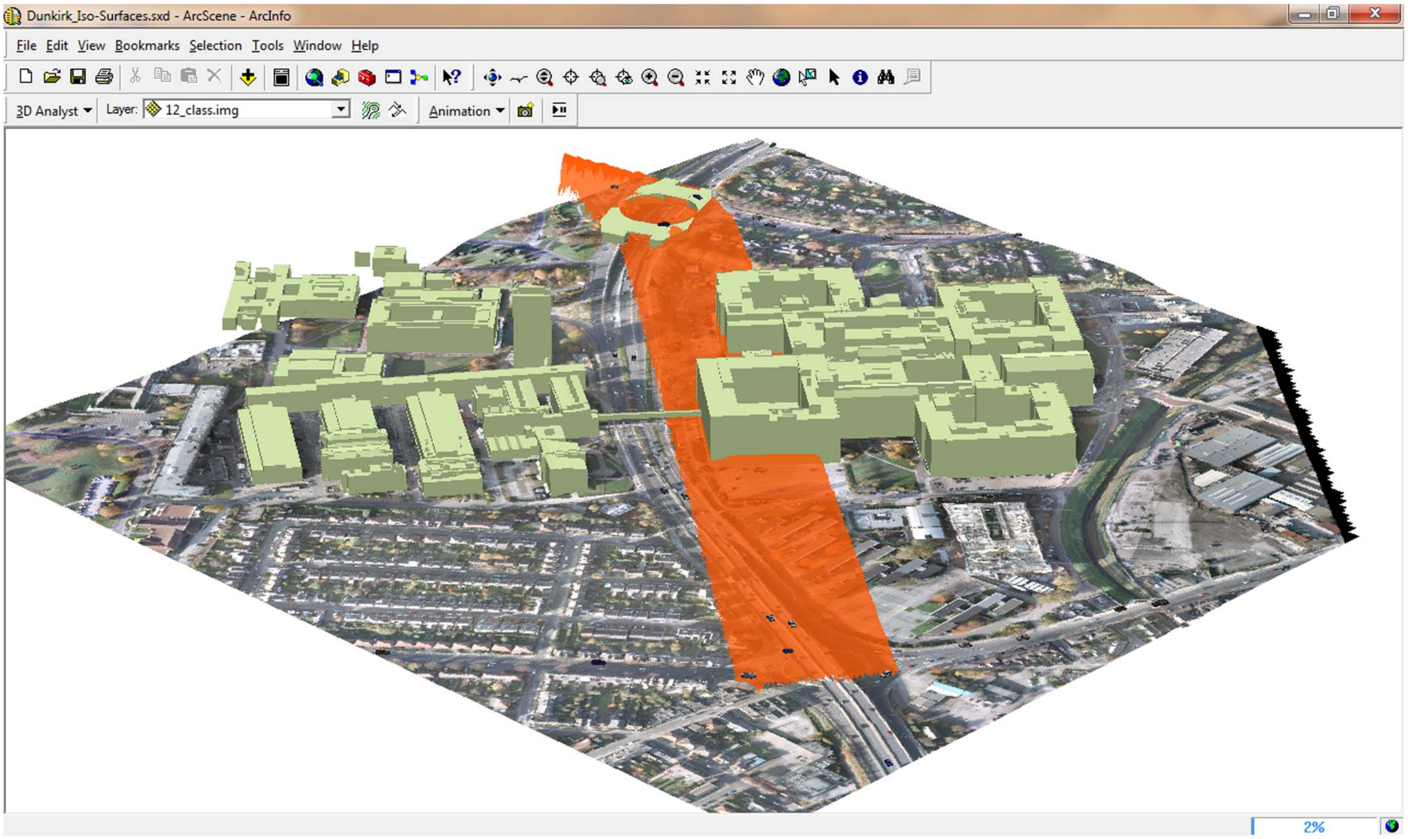

Fig. 5. 44–51 $\mu g/m^3$ NO_2 surface interface

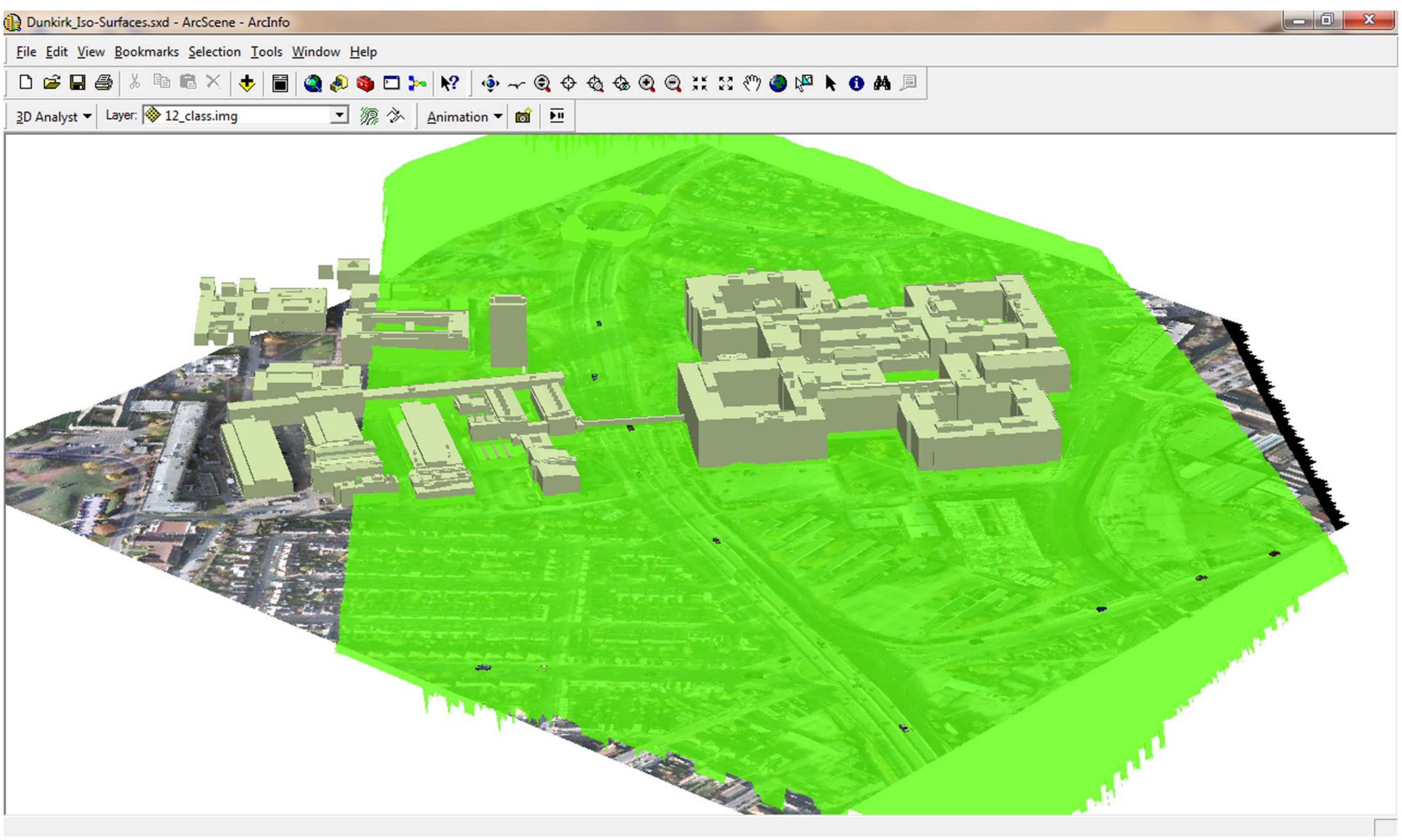

Fig. 6. 35–36 $\mu g/m^3$ NO_2 surface interface

reflect the hierarchy of air pollution concentration bands, as shown in Figs. 5 and 6.

In some cases, the points relevant to one air pollution concentrations band were located in spatially separate groups. Therefore, the surface connecting these points together covered the spaces in between such groups of points, and the points in these in-between spaces were not relevant to that air pollution concentrations band. Consequently, instead of being an improvement, this interface design conveyed a false impression of the air pollution dispersion. Furthermore, the resultant surfaces interfered with one another, which necessitated displaying them one by one in the virtual scene. This was a real step backward relative to this research's goal of displaying the air pollution data at different levels at and above the ground surface in the same view. Consequently, the development of the interface design continued further.

The next interface design reduced the large number of points in the 3D point shapes interface down to a number of 3D components that was slightly greater than the number of air pollution concentration bands. Instead of the 3D planar surfaces used in the previous interface design, Geomagic Studio version 10 was used to wrap a 3D volumetric mesh around the set of points relevant to each air pollution concentration band. This was accomplished by connecting the points of every set with a series of triangles to form an external 3D surface and internal 3D webs, creating a 3D volumetric cloud for every set of points.

For a set of points relevant to a certain air pollution concentration band, but with the points located in spatially separate groups, a separate 3D volumetric mesh was wrapped around each group of points. This prevented covering the in-between spaces, which contained points belonging to different air pollution concentration bands. Therefore, the volumetric clouds of these groups of points did not interfere with the volumetric clouds of the group(s) of points belonging to other air pollution concentration bands in the in-between spaces, which resolved the interference issue identified in the previous interface design. Therefore, this development enabled a display of the 3D volumetric clouds relevant to all air pollution concentration bands in one view.

Geomagic Studio was used to convert every volumetric cloud into polygons, and then to optimize the converted volumetric cloud by reducing the number of polygons so that the cloud would not overburden the virtual scene. However, this optimum number of polygons was large enough to preserve the 3D form of the volumetric cloud.

There was a difficulty when wrapping a 3D volumetric mesh around a group of points that totally surrounded another group of points belonging to a different air pollution concentration band. The external volumetric cloud interfered with the internal volumetric cloud. To resolve this difficulty, Geomagic Studio was used to trim the external volumetric cloud by subtracting the internal cloud. This gave the external volumetric cloud its correct hollow core shape, and hence it did not interfere anymore with the internal volumetric cloud. The optimized 3D volumetric clouds for all the air pollution concentration bands were exported from Geomagic Studio in DXF format for the integration with the Dunkirk AQMA 3D city model in the 3D Analyst of ArcGIS 9.2.

Getting the correct visual impact of the clouds was found to be very important to enhance the understanding of the pollution dispersion. Considerable research went into identifying the correct color, color shades, and transparency of the clouds. The volumetric clouds in the 3D Analyst of ArcGIS 9.2 were assigned a monochromatic color scheme of four shades of the color gray, to reflect the hierarchy of NO_2 concentration bands. The darker the cloud color, the higher was the NO_2 concentration of this cloud. In addition, the 3D volumetric clouds were assigned a 50% degree of transparency to not obscure parts of the virtual scene located behind and underneath. The transparency of these 3D volumetric clouds maintained a good degree of location recognition and orientation while navigating the virtual scene. Fig. 1 displays a flowchart for this 3D volumetric clouds air pollution visualization method. Figs. 7 and 8 are screenshots of the virtual scene showing before and after the proposed implementation of NET Phase 2, respectively, using the 3D volumetric clouds with the four shades of the gray color scheme. This achieved the aim, mentioned in the "Research Aim and Objectives" section, of utilizing people's everyday perceptions of gray clouds representing poor weather to try to create an intuitive visualization of air pollution.

Air Quality Visualization as a Design Tool for Alternative Traffic Scenarios

As predicted in Fig. 8, the current proposed design of NET Phase 2 will not eliminate the exceedance of the permissible annual mean NO_2 concentration (40 $\mu g/m^3$) in the Dunkirk AQMA. Therefore, to eliminate such an exceedance, a number of alternatives for the 2021 traffic scenario with NET Phase 2 were developed. The alternative traffic scenarios effectively assumed the development of further (unspecified) transport measures to reduce the traffic, and hence to further improve the predicted 2021 air quality, in the Dunkirk AQMA. Various amendments to the original 2021 forecast traffic flows and speeds were tried, resulting in eight alternative traffic scenarios.

The 3D volumetric clouds interface was applied to visualize the predicted air quality benefits after each amendment to the original 2021 forecast traffic flows and speeds, which enabled the identification of these eight alternatives. For each alternative traffic scenario, it was decided to color the roads in the 3D air pollution dispersion interface according to the reduction factors applied to their original 2021 forecast traffic flows with NET Phase 2. As an example, Fig. 9 displays a screenshot of the 3D air pollution dispersion and the different reduction levels from the original 2021 forecast traffic flows with NET Phase 2 for one of the alternative traffic scenarios. This may help transport planners to identify the transport measures that can be applied to amend the design of a proposed urban transport scheme to achieve specific future air quality benefits.

Application of the Developed Interface to Two Other Urban Transport Schemes

Air Pollution Dispersion Modeling in Nottingham City Centre

The air pollution dispersion model was further applied to the areas affected by the Turning Point East and Broadmarsh Shopping Centre Extension transport schemes in Nottingham City Centre. The roads directly affected by the implementation of the Turning Point East and the Broadmarsh Shopping Centre Extension transport schemes partially coincide with the Nottingham City Centre AQMA, and the two continuous air quality monitoring stations in the city center [the Automatic Urban and Rural Network (AURN) and the Carter Gate monitoring stations] are nearby. Therefore, the initial boundary of the air pollution model application area was drawn so that it contained the roads directly affected by the two transport schemes, the Nottingham City Centre AQMA, and the locations of the two continuous air quality monitoring stations, as shown by the initial model area in Fig. 10. Hence, the air pollution model would be validated against air pollution monitoring data measured within

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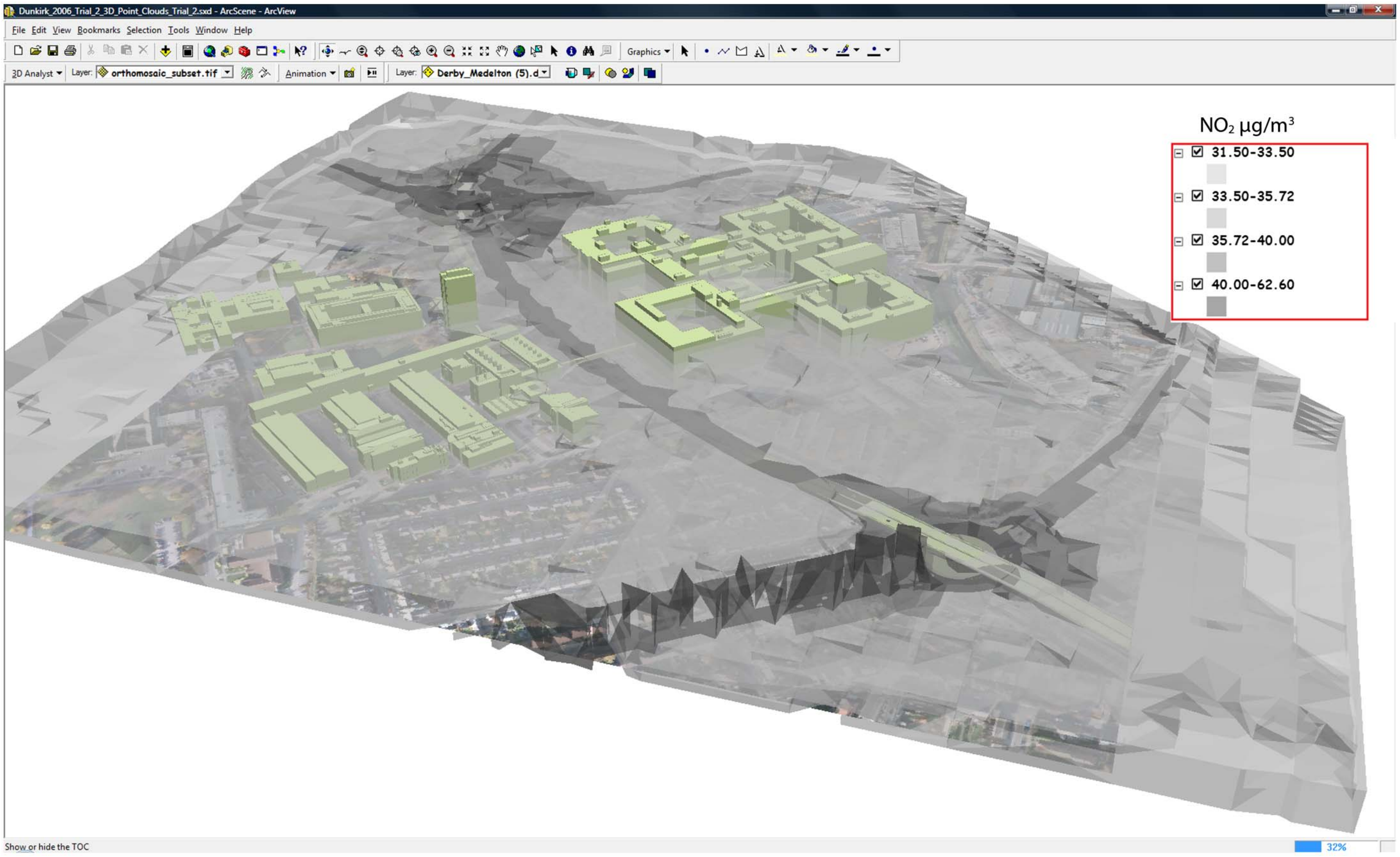

Fig. 7. 2006 NO_2 volumetric clouds in Dunkirk AQMA

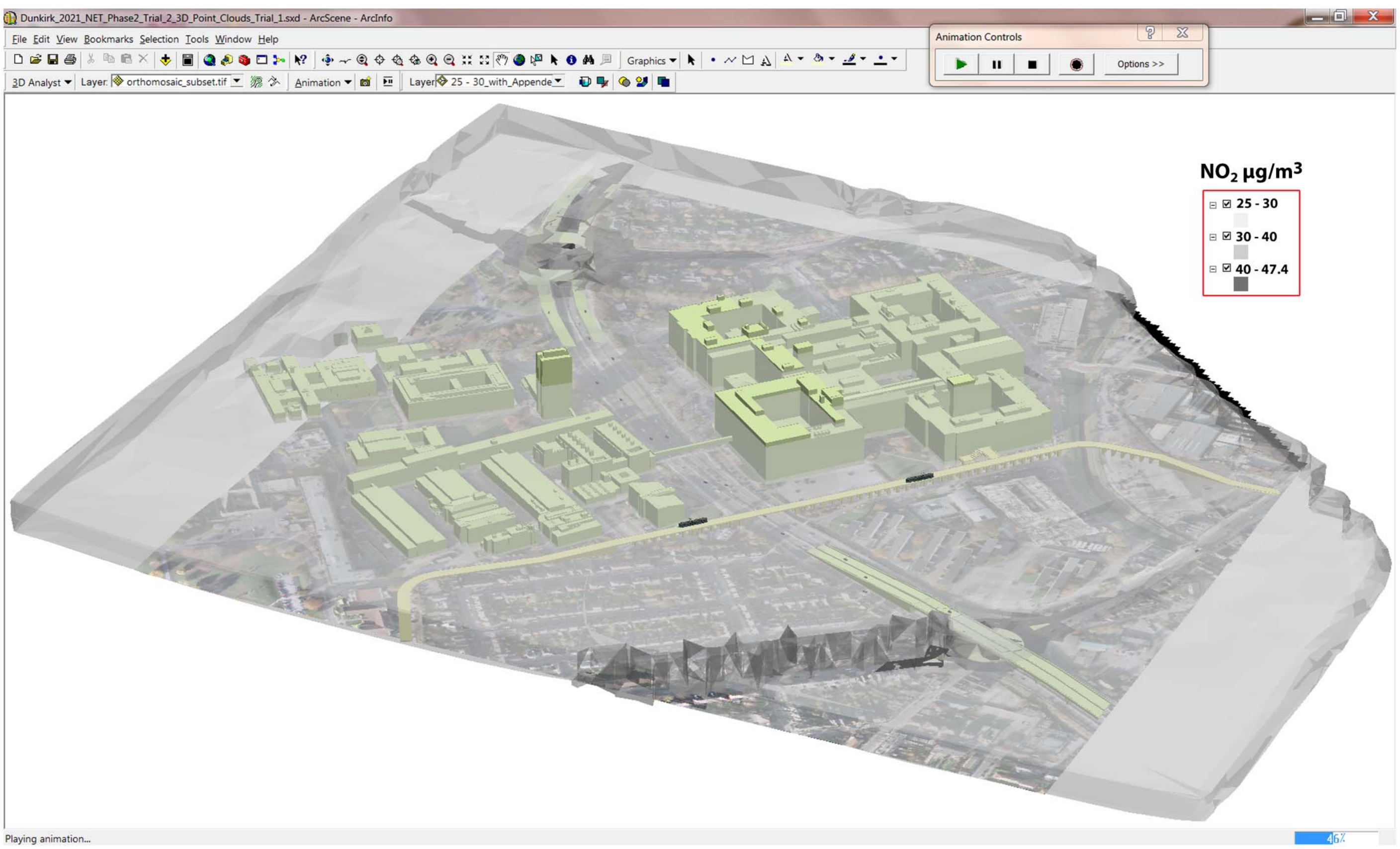

Fig. 8. 2021 (with NET Phase 2) NO_2 volumetric clouds in Dunkirk AQMA

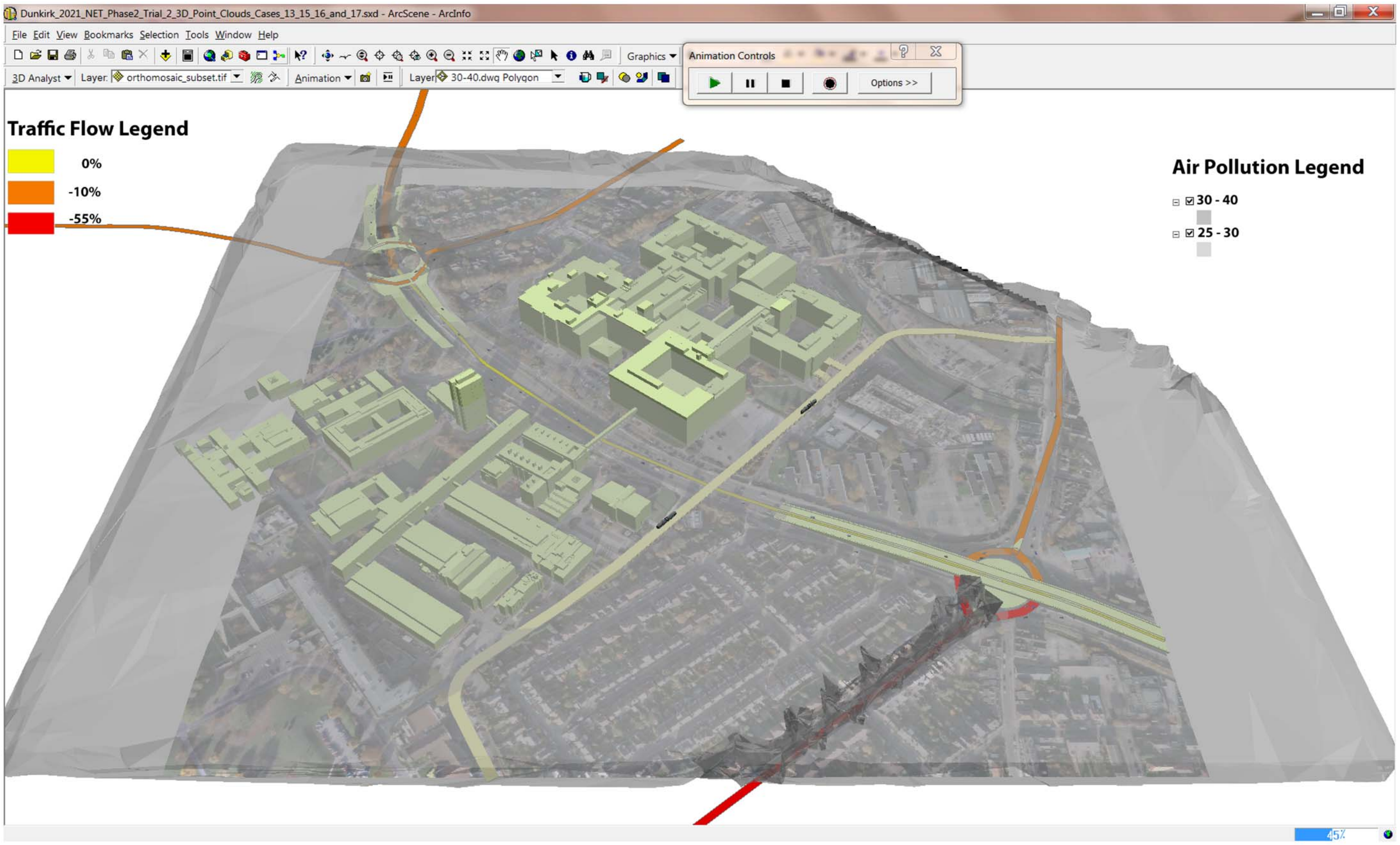

Fig. 9. 3D volumetric clouds interface for an alternative 2021 NET Phase 2 traffic scenario

the model application area (Department for Environment, Food and Rural Affairs 2009).

To get precise air quality predictions inside the initial model application area, the traffic emission contributions of the road segments located within 200 m from this area had to be considered in the air pollution model [Design Manual for Roads and Bridges (DMRB) 2007]. Therefore, the final boundary of the air pollution model application area was drawn so that it included the initial model application area and the 200-m buffer zone around this area, as shown by the final model area in Fig. 10.

The ADMS-Roads version 2.3 was used to output NO_2 concentrations at an intelligent grid covering the model application area, which was designed as discussed in the "Air Pollution Dispersion Modeling in Dunkirk AQMA" section. The modeling year for the air pollution base case scenario model was 2006, which was validated against 2006 NO_2 measurements. The validated air pollution model was configured to output NO_2 concentrations at a height step of 6 m (as discussed in the "Air Pollution Dispersion Modeling in Dunkirk AQMA" section). A study of NO_2 decay with height was conducted at the AURN and Carter Gate monitoring stations. The results suggested a height limit of 40 m above the ground surface at the AURN monitoring station, and a 20-m height limit above the ground surface at the Carter Gate monitoring station. Therefore, an average height limit of 30 m was selected for the entire air pollution model application area. This was because the large savings in the model run time, because of the reduction in the height limit from 40 to 30 m, significantly outweighed the small rise in NO_2 concentrations at the AURN monitoring station ($0.2\ \mu g/m^3$).

The 2006 NO_2 concentrations exceeding the permissible annual mean NO_2 concentration ($40\ \mu g/m^3$) existed at the ground level and disappeared at 6 m above the ground surface. This led to an unrealistic representation of these concentrations as a 2D planar surface draped on the ground surface rather than a 3D volumetric cloud. This gave a wrong perception of the true vertical and horizontal spatial extensions of these high NO_2 concentrations that are potentially highly important for air pollution exposure-related transport scheme design. Therefore, a specific investigation was undertaken to identify the height limit of the cloud representing these high NO_2 concentrations. The investigation resulted in a 4-m height limit for the cloud that represented annual mean NO_2 concentrations exceeding $40\ \mu g/m^3$.

To construct the 3D point cloud for these NO_2 exceedances, the ground-level receptor points at which the NO_2 concentration exceeded $40\ \mu g/m^3$ were first isolated from the rest of the air pollution output grid points. Then, these points were repeated at 1, 2, 2.5, 3, and 4 m above the ground surface. The resulting set of receptor points above the ground surface was too large to be defined in the air pollution model interface to calculate NO_2 concentrations at these points. Moreover, it was impossible to create a grid from this large set of points that had an irregular horizontal distribution and had to be defined at multiple heights above the ground surface. Hence, another technique was used to read the three coordinates and attributes of each of these receptor points: name, x, y, and height above the ground surface, from an external comma-delimited text file to define an output receptor point on the fly during the air pollution model run time. Using 2014 as a year that was expected to be after the implementation of both the Turning Point East and Broadmarsh Extension schemes, the validated air pollution model was configured to predict annual mean NO_2 concentrations for the 2014 Nottingham City Centre traffic scenario, with the proposed urban transport schemes.

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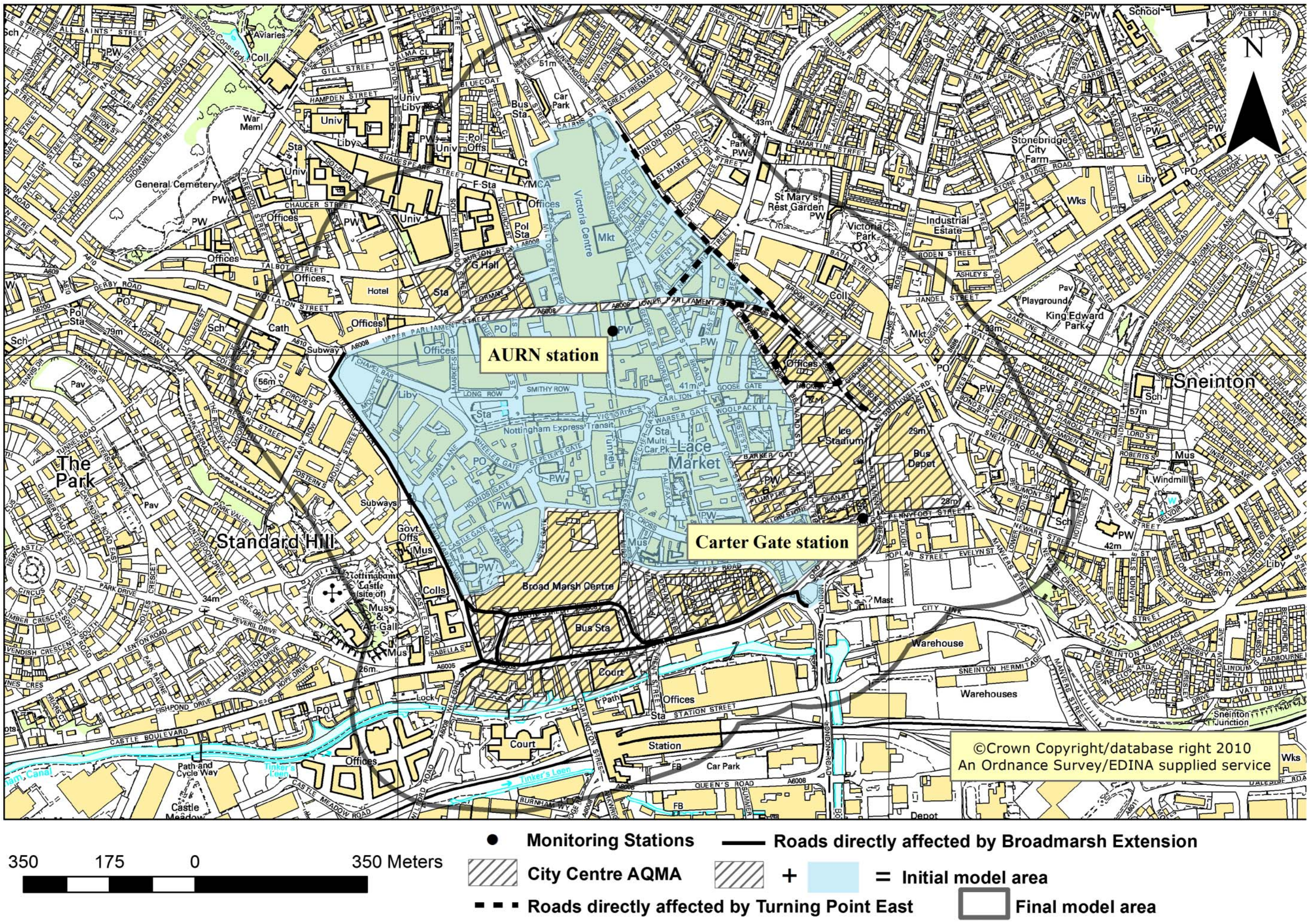

Fig. 10. Air pollution model application area in Nottingham City Centre

Nottingham City Centre 3D City Model

The DTM data for the air pollution model application area in Nottingham City Centre was downloaded from EDINA Digimap in the form of 3D topographic point data (EDINA 2009). The functionality of the 3D Analyst of ArcGIS 9.2 was used to get these 3D points connected with a series of edges to form a network of triangles called a triangular irregular network (TIN) that was used to represent the terrain surface morphology in the 3D digital city model.

Orthoimages of Nottingham City were provided by Blom Aerofilms Ltd for this research project, each with 10-cm resolution and 250,000 m^2 coverage. The orthoimages relevant to the air pollution model application area were merged together into a single large orthoimage. The large orthoimage was draped onto the TIN for a more realistic view of the terrain, which may assist the orientation of the viewer in the 3D digital city model.

A 2D shape file for the footprint of buildings located in the entire Nottingham urban area was downloaded from the University of Manchester Landmap Service (Landmap 2009). The shape file was clipped with the polygon shape file of the air pollution model application area to remove the buildings located outside this area. The resulting shape file was configured so that the buildings obtained their base heights from the TIN. Then, the 3D Analyst of ArcGIS 9.2 was used to extrude the buildings vertically above the TIN surface according to a height attribute in the buildings shape file. However, this strategy unrealistically represented the elevated structures located inside the air pollution model application area as walls. Therefore, the 2D polygons of these elevated structures were isolated and exported to AutoCAD Civil 3D where they were designed as realistic 3D elevated structures.

The integration between AutoCAD Civil 3D and the 3D Analyst of ArcGIS 9.2 enabled the update of the 3D city model to represent changes in Nottingham City Centre's built environment, which would be expected because of the implementation of the Turning Point East and Broadmarsh Extension schemes. Therefore, an intuitive visual distinction could be achieved between the 3D air pollution dispersion interfaces with and without these transport schemes. The discussions with Nottingham City Council confirmed that the implementation of the Turning Point East scheme would not involve any modifications to Nottingham City Centre's built environment because the scheme would only involve changing the operation of certain roads. However, it was confirmed that the implementation of the Broadmarsh Extension scheme would involve changing the road network and the demolition of existing buildings to extend the Broadmarsh Shopping Centre to four proposed new blocks.

The average heights of these new blocks were provided by the Nottingham City Council. The 2D footprints were used along with the average heights to create 3D models for the new blocks in AutoCAD Civil 3D. Existing blocks in the 3D city model were imported into AutoCAD Civil 3D, where existing blocks interfering with the four new blocks were deleted. The remaining existing blocks and the new blocks were exported to the 3D city model to

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represent the built environment in Nottingham City Centre after the extension of the Broadmarsh Shopping Centre. The color of the four new blocks was different from the color of the remaining blocks to distinguish intuitively between the present (existing) blocks and the future blocks of the Broadmarsh Shopping Centre.

Nottingham City Centre 3D Air Pollution Dispersion Interface

The methodology developed in the "3D Air Pollution Dispersion Interface Design and Development" section was used to represent the calculated NO_2 concentrations, at and above the ground surface in Nottingham City Centre, as 3D volumetric clouds. Figs. 11 and 12 are screenshots of the virtual scene before and after the proposed implementation of the Turning Point East and Broadmarsh Extension schemes, respectively, using the 3D volumetric clouds with the four shades of gray color scheme. As indicated by the comparison between Figs. 11 and 12, the proposed implementation of the Turning Point East and Broadmarsh Extension transport schemes may significantly improve the air quality and eliminate the exceedance of the permissible annual mean NO_2 concentration (40 $\mu g/m^3$) in Nottingham City Centre.

Discussion

The selection of NO_2 to model before and after the implementation of NET Phase 2 running through the Dunkirk AQMA was helpful to validate the ability of the visualization method to facilitate the understanding of the air quality impact of this proposed transport scheme. Because NO_2 is mainly a traffic-related air pollutant, the modeling of NO_2 was also helpful to validate the transferability of the visualization method to the Turning Point East and Broadmarsh Extension transport schemes in Nottingham City Centre.

A 31×31 regular size for the air pollution intelligent output grid was suitable to optimize the overall air pollution model performance as much as possible, considering both the air pollution model run time and the output data resolution, in both the Dunkirk AQMA and Nottingham City Centre. The automatic generation of the additional grid points whose number and location depend on the relative emissions from each pair of intersecting roads was disabled using a special customization text file in ADMS-Roads (*.igp file). This facilitated a direct comparison between before and after the implementation of urban transport schemes while capturing the rapidly changing gradient of NO_2 concentrations close to the main roads in the air pollution model application area.

The height limit and step determination was suitable for capturing the vertical dispersion of NO_2 concentrations above the ground surface, which is necessary to attain a true 3D visualization of NO_2 dispersion in the 3D city model. However, the height limit and step was determined using only one or two locations in the air pollution model application area. Using two different locations in Nottingham City Centre showed that the height limit may change from one location to another in the model application area.

The selected LOD to represent the 3D landmarks of the Dunkirk AQMA in its 3D city model was suitable to achieve smooth navigation while maintaining a good level of location recognition and orientation in the 3D city model. In addition, the virtual traffic animation and the representation of road network features in the 3D city model both improved the location recognition and orientation and compensated for the absence of 3D residential buildings; were these residential buildings represented in the 3D city model, they would partially obscure the visualization of the air pollution. However, it has not been feasible to increase the number of displayed virtual vehicles in the 3D city model to properly simulate the actual traffic conditions in the Dunkirk AQMA so that the observer can intuitively fully understand the relationship between the traffic and the displayed air pollution. Such an increase in the number of displayed virtual vehicles in the 3D city model overburdened the model and impeded smooth navigation through the virtual scene.

In terms of maintaining a good level of location recognition and orientation, the representation of the 3D models of all the buildings in the Nottingham City Centre 3D city model was helpful to compensate for the availability of these models with only a low LOD. The low LOD of these models allowed the representation of all the buildings in the 3D city model without impeding smooth navigation through the virtual scene.

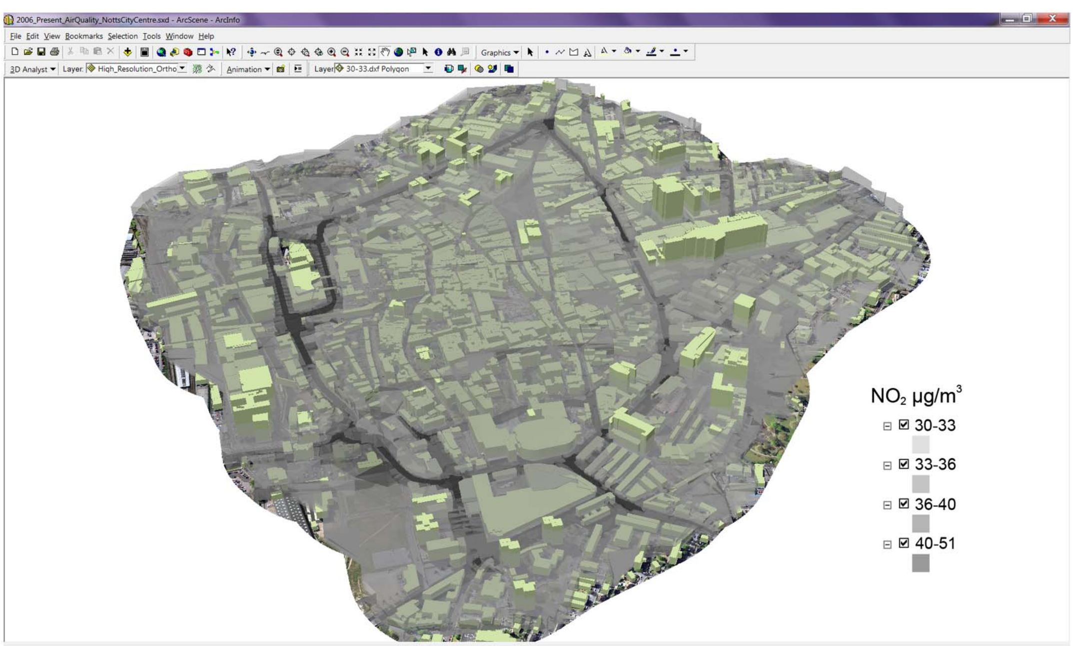

Fig. 11. 2006 NO_2 volumetric clouds in Nottingham City Centre

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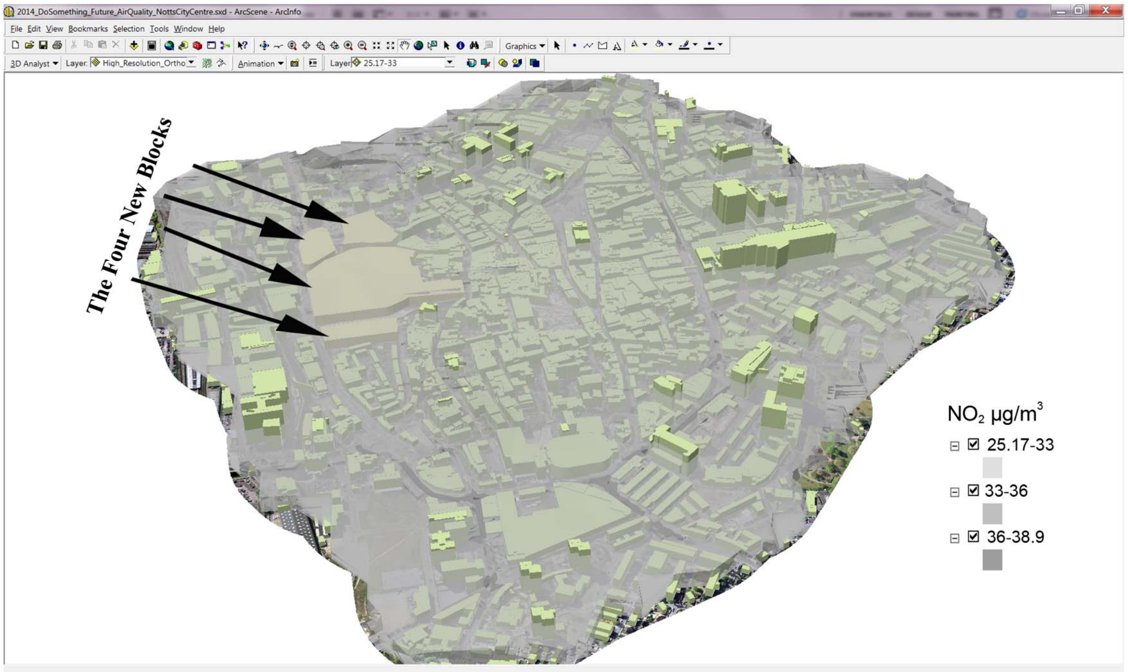

Fig. 12. 2014 (with the proposed transport schemes) NO_2 volumetric clouds in Nottingham City Centre

The representation of the NET Phase 2 infrastructure in the Dunkirk AQMA 3D city model, requiring real integration of computer-aided design (CAD) and virtual reality, which was identified as a challenge by Whyte et al. (2000), has been achieved so as to create a contrast between present and future infrastructure in the Dunkirk AQMA. This concept of updating the 3D city model to represent future changes in the built environment that would accompany the implementation of proposed transport schemes was also helpful to create an intuitive visual distinction between before and after the implementation of the Turning Point East and Broadmarsh Extension schemes in Nottingham City Centre. However, the animation of the virtual tram object over the curved parts of the NET Phase 2 viaduct is not fully realistic. Because the virtual tram is a long object without hinges, it looks like the virtual tram partially leaves the track when traversing the curved parts of the NET Phase 2 viaduct.

The 3D point shapes interfaces, shown in Figs. 3 and 4, displayed NO_2 concentrations at and above the ground surface in a single 3D virtual scene, which was identified as a challenge ahead by Wang et al. (2008). The large number of points in the 3D point shapes interfaces was found not to be particularly intuitively meaningful, so the research was progressed to the 3D visualization of NO_2 concentrations at and above the ground surface as a much smaller number of 3D planar surfaces, as shown in Figs. 5 and 6. However, these surfaces interfered with one another when displayed together in the virtual scene, so the research was progressed further to the representation of the NO_2 concentrations by 3D volumetric clouds, as shown in Figs. 7 and 8, which given the analogy with weather clouds mentioned in the "Research Aim and Objectives" section, provides a good, intuitive visualization of air pollution.

The 3D volumetric clouds interface was helpful as a design tool in developing the alternative traffic scenarios that could maximize the air quality benefits of NET Phase 2 in the Dunkirk AQMA. Coloring the roads in the 3D air pollution dispersion interfaces for the developed alternative traffic scenarios was helpful to simplify the visualization of all the different reductions to the original forecast traffic flows considered for the same future traffic scenario (see Fig. 9). This further increased the information retention and reduced the comprehension time of the 3D air pollution dispersion interfaces for these traffic scenarios.

The 3D volumetric clouds interface was found applicable to visualize NO_2 dispersion at and above the ground surface in the 3D city model of Nottingham City Centre (see Figs. 11 and 12). However, because the base elevations of 3D points, which were wrapped with a 3D volumetric mesh to create each 3D volumetric cloud, were interpolated from the DTM, the low resolution DTM of the Nottingham City Centre 3D city model resulted in assigning some of these points, located at the same height above the ground surface, the same total elevation. This excluded these points from the wrapped volumetric cloud because Geomagic Studio version 10 does not support wrapping 3D volumetric meshes around planar point sets. A specific investigation and the development of additional output receptor grid points, described in the "Air Pollution Dispersion Modeling in Nottingham City Centre" section, were needed to give the 3D volumetric clouds representing the critical NO_2 concentrations (exceeding 40 $\mu g/m^3$) realistic vertical and horizontal shapes in the Nottingham City Centre 3D air pollution dispersion interface.

Conclusions and Recommendations

A new approach has been developed to allow 3D visualization of air pollution in a virtual reality environment, overcoming computational challenges identified by current 3D visualization approaches. Benefits have been identified in understanding the pollution dispersion and the air quality impact of proposed urban transport schemes. This has allowed the visualization process to be used in the development of future traffic scenarios that could be used to alter the design of a proposed transport scheme to achieve specific air quality benefits. Further work is needed to overcome the challenges identified in the "Discussion" section and to test the 3D

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volumetric clouds interface on a wider range of potential users, from lay people to professionals.

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