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## Environmental Modelling &amp; Software

journal homepage: [www.elsevier.com/locate/envsoft](http://www.elsevier.com/locate/envsoft)Development of an open-source road traffic noise model for exposure assessment<sup>☆</sup>John Gulliver<sup>a,\*</sup>, David Morley<sup>a</sup>, Danielle Vienneau<sup>b,c</sup>, Federico Fabbri<sup>a</sup>, Margaret Bell<sup>c</sup>, Paul Goodman<sup>d</sup>, Sean Beevers<sup>e</sup>, David Dajnak<sup>e</sup>, Frank J Kelly<sup>e</sup>, Daniela Fecht<sup>a</sup><sup>a</sup> The UK Small Area Health Statistics Unit (SAHSU), MRC-PHE Centre for Environment & Health, Imperial College London, W2 1PG, London, UK<sup>b</sup> Department of Epidemiology and Public Health, Swiss Tropical and Public Health Institute, 4002 Basel, Switzerland<sup>c</sup> University of Basel, 4003 Basel, Switzerland<sup>d</sup> School of Engineering and Geosciences, Newcastle University, NE1 7RU, UK<sup>e</sup> Environmental Research Group, King's College London, SE1 9NH, UK

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## ABSTRACT

This paper describes the development of a model for assessing **TRA**ffic **N**oise **E**xposure (TRANEX) in an open-source geographic information system. Instead of using proprietary software we developed our own model for two main reasons: 1) so that the treatment of source geometry, traffic information (flows/speeds/spatially varying diurnal traffic profiles) and receptors matched as closely as possible to that of the air pollution modelling being undertaken in the TRAFFIC project, and 2) to optimize model performance for practical reasons of needing to implement a noise model with detailed source geometry, over a large geographical area, to produce noise estimates at up to several million address locations, with limited computing resources. To evaluate TRANEX, noise estimates were compared with noise measurements made in the British cities of Leicester and Norwich. High correlation was seen between modelled and measured L<sub>Aeq,1hr</sub> (Norwich:  $r = 0.85$ ,  $p = .000$ ; Leicester:  $r = 0.95$ ,  $p = .000$ ) with average model errors of 3.1 dB. TRANEX was used to estimate noise exposures (L<sub>Aeq,1hr</sub>, L<sub>Aeq,16hr</sub>, L<sub>night</sub>) for the resident population of London (2003–2010). Results suggest that 1.03 million (12%) people are exposed to daytime road traffic noise levels  $\geq 65$  dB(A) and 1.63 million (19%) people are exposed to night-time road traffic noise levels  $\geq 55$  dB(A). Differences in noise levels between 2010 and 2003 were on average relatively small: 0.25 dB (standard deviation: 0.89) and 0.26 dB (standard deviation: 0.87) for L<sub>Aeq,16hr</sub> and L<sub>night</sub>.

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## Software availability

The noise model (TRANEX) was implemented in R to call functions from PostgreSQL and GRASS GIS packages and can be obtained from the corresponding author or the following website: <http://www.sahsu.org/content/data-download>; first available in July 2014; TRANEX requires at least one standard desktop PC.

## 1. Introduction

There is growing concern on the effects of noise pollution on health (WHO, 2009). Environmental noise exposure is associated with annoyance (Babisch et al., 2013; Clark et al., 2012), sleep disturbance (WHO, 2011), cognitive ability in schoolchildren (Evans and Hygge, 2007; Clark et al., 2013), and health impacts, especially cardiovascular conditions and risk factors (Babisch et al., 2009; Hansell et al., 2013; Sorensen et al., 2012; Stansfeld et al., 2003). Exposure to environmental noise is ubiquitous and increasing in terms of road traffic noise and the reduction of the night-time quiet period (Hammer et al., 2014). Traffic-related noise is said to account for over 1 million healthy years of life lost annually to ill health and may lead to a disease burden that is second only in magnitude to that from air pollution (WHO-JRC, 2011).

<sup>☆</sup> Thematic Issue on Modelling Health Risks.

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Estimates of environmental noise exposures were required for a series of epidemiological analyses forming part of the 'Traffic and Health in London (TRAFFIC)' study (2011–2014) (<http://www.kcl.ac.uk/lsm/research/divisions/aes/research/ERG/research-projects/traffic/index.aspx>), funded by the Natural Environment Research Council (NERC) Environmental Exposure and Health Initiative (EEHI). The epidemiological analyses were designed to look at relationships of a range of air pollution metrics (e.g. particulate matter, nitrogen oxides, nitrogen dioxide, ozone) and noise levels with health outcomes in children and adults, including cardiovascular and respiratory mortality and hospital admissions, adverse birth outcomes (low birth weight and pre-term delivery), primary care data on diseases and consultations, and risk factors and vascular markers of diseases in children, over different periods between 2003 and 2010. In addition to confounders (e.g. smoking, deprivation) the epidemiological analyses of air pollution may control for noise levels and vice versa.

This paper describes the development of a **TRAFFIC Noise Exposure** model (TRANEX) and its implementation for exposure assessment in the TRAFFIC study. Instead of using proprietary software (e.g. CadnaA, SoundPLAN) we developed our own model for two main reasons: 1) so that the treatment of source geometry, traffic information (flows/speeds/spatially varying diurnal traffic profiles) and receptors matched as closely as possible to that of the air pollution modelling being undertaken in the TRAFFIC project, and 2) to optimize model performance for practical reasons of needing to implement a noise model with detailed source geometry, over a large geographical area, to produce noise estimates at up to several million address locations, with limited computing resources. We present an evaluation of the model using comparisons of estimated noise levels with noise level measurements from

the UK. We also describe the modelled noise exposures at postcode locations and for the resident population of London for an example year (2008) and changes in modelled noise exposures over the study period (2003–2010).

## 2. Materials and methods

As the model was developed primarily for application to London we adopted the Calculation of Road Traffic Noise method (CoRTN) (Department of Transport, 1988). The CoRTN method is used in the UK for strategic noise mapping (DEFRA, 2008; HMSO, 2006) and has been implemented as an optional noise calculation method in leading proprietary software such as SoundPLAN (<http://www.soundplan-uk.com>) and CadnaA (<http://www.datakustik.com/en/products/cadnaa>). The CoRTN method is also used as the UK primary noise calculation methodology for new road schemes (<http://www.dft.gov.uk/ha/standards/dmrb/vol11/section3/hd21311.pdf>). The study area (Fig. 1) is the area inside the M25 motorway that includes Greater London and the surrounding area, henceforth referred to as London.

### 2.1. The CoRTN method

Traffic noise estimates are calculated in CoRTN as one-hour, A-weighted  $L_{10}$  (dB) (i.e. the noise level that is exceeded 10% of the time), denoted as  $L_{A10,1hr}$  and  $L_{A10,18hr}$  for the period 06:00 until 0:00.

The CoRTN method includes the following terms:

$$L_{A10,1hr} = L_0 + \Delta_f + \Delta_g + \Delta_p + \Delta_d + \Delta_s + \Delta_c + \Delta_a + \Delta_r \quad (1)$$

where  $L_0$  is the basic noise level calculated at 3.5 m from the kerbside, at 0.5 m above ground level;  $\Delta_f$  is the correction for traffic speed and the percentage of heavy vehicles;  $\Delta_g$  is the adjustment for the gradient of a road section;  $\Delta_p$  is the road surface correction;  $\Delta_d$  is the slant distance between the road (source) and receptor;  $\Delta_s$  is the correction for shielding (i.e. barriers) between a road (source) and receptor;  $\Delta_c$  is ground cover attenuation;  $\Delta_a$  is the correction for the angle of view of the road;  $\Delta_r$  is the correction for reflections from buildings on the opposite side of the façade.

$$L_0 = 42.2 + 10 \log_{10} q \text{ dB(A)} \quad (2)$$

where  $q$  is the hourly traffic flow;

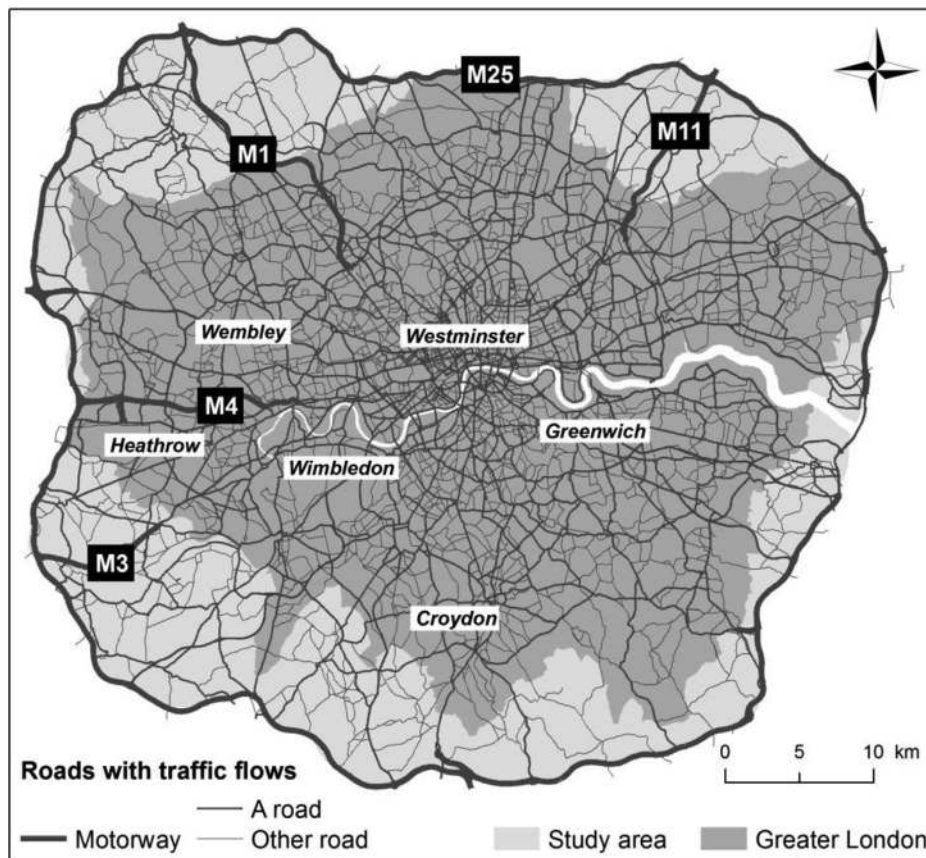


Fig. 1. Study area showing the road network used in TRANEX (source data: London Atmospheric Emissions Inventory (LAEI), 2010).

$$\Delta_f = 33 \log_{10}(v + 40 + 500/v) + 10 \log_{10}(1 + 5p/v) - 68.8 \text{ dB(A)} \quad (3)$$

$v$  is the average hourly traffic speed and  $p$  is the percentage of heavy vehicles on each road section;

$$p = 100f/q \quad (4)$$

$f$  is the hourly flow of heavy vehicles;

$$\Delta_g = 0.3 G \quad (5)$$

where  $G$  is the gradient of the road – only applicable to uphill flow on single carriageways;

$\Delta_p$ : a value of  $-1$  dB and is applicable to bituminous impervious road surfaces for roads with vehicle speed less than 75 km/h; pervious road surfaces have a value of  $-3.5$  dB;

$$\Delta_d = -10 \log_{10}(d'/13.5) \text{ dB(A)} \quad (6)$$

$d'$  is the shortest slant distance between a source and receptor;

$$d' = [(d + 3.5)^2 + h^2]^{0.5} \quad (7)$$

where  $d$  is the shortest distance between source and receptor;  $h$  is the difference in height above ground between the source and receptor (i.e. effective source position); the distance correction ( $\Delta_d$ ) is only applicable where  $d \geq 4$  m (i.e. beyond the distance from the kerbside where the basic noise level is calculated);  $d$  is given a value of 4 m where it is measured to be  $< 4$  m;

$\Delta_s$  is the correction for barriers between the source and receptor; effectively this is a lengthening of the shortest slant distance; where the path between the source and receptor is obstructed, the distance between the source and receptor is, for example, the sum of 1) the distance from the source to the top of a building (i.e. the diffracting edge) and 2) the distance from the top of a building to the receptor [further details are available from: <http://resource.npl.co.uk/acoustics/techguides/crtn/>];

$\Delta_c$  is the correction for ground cover correction:

$$\text{For } 0.75 \leq H < (d + 5)/6; \Delta_c = 5.2 I \log_{10}[(6H - 1.5)/(d + 3.5)] \quad (8)$$

$$\text{For } H < 0.75; \Delta_c = 5.2 I \log_{10}[3/(d + 3.5)] \quad (9)$$

$$\text{For } H \geq (d + 5)/6; \Delta_c = 0 \quad (10)$$

where  $H$  is the average height of propagation (m),  $d$  is the distance from the edge of the roadside to the receptor, and  $I$  is based on the different percentages of absorbent ground between the source and the receptor;

$$\Delta_a = 10 \log_{10}(\theta/180) \text{ dB(A)} \quad (11)$$

$\theta$  is the angle of the view of the road in degrees;

$$\Delta_r = 1.5(\theta_s/\theta)180^\circ \text{ dB(A)} \quad (12)$$

$\theta_s$  is the sum of angles by all the reflecting facades (i.e. individual buildings) on the opposite side of the road to the receptor.

The CoRTN method also includes further corrections for roads with low hourly flow ( $50 \leq q < 200$ ), and corrections for mixed ground cover.

Finally, the noise level from all sources ( $L_1, L_2, \dots, L_n$ ) can be combined using the following procedure:

$$L = 10 \log_{10} \left[ \sum_{i=1}^n 10^{L_i/10} \right] \text{ dB(A)} \quad (13)$$

where  $L$  is the predicted noise level from  $n$  noise sources.

Further information can be found in the CoRTN manual (Department of Transport, 1988) and other implementations of the method (e.g. Pamanikabud and Tansatcha, 2003).

## 2.2. Data

For implementation of the noise model in London we used the most detailed data sets available for traffic information (i.e. composition, speed, diurnal varying traffic profiles for different parts of London), land cover, road geography, building heights, and receptors (i.e. postcodes and addresses). Table 1 provides a list of data types, data sources, and their spatial resolution (i.e. accuracy).

Pre-processing of spatial data was undertaken in a geographic information system (GIS) (ArcGIS v 10.0, ESRI, Inc., Redlands, California). Information on buildings and land cover (Topographic Layer) and the Integrated Transport Network (ITN) form part of Ordnance Survey's 2009 version of MasterMap™ (MM) (see Table 1). We downloaded these data from Digimap® under the agreement for use in teaching and research in higher education. Although more recent updates are available we assumed this version to best reflect our study period.

The ITN provides detailed road network information including road type and information on one-way streets. Traffic source data (i.e. 10 m points along roads) are from the London Atmospheric Emissions Inventory (LAEI) (LAEI, 2010). Information on one-way streets and road tunnels in the ITN were linked to traffic source points. We used information from the ITN to exclude road tunnels from TRANEX.

Road traffic flows in the LAEI are represented using annual averaged daily traffic (AADT) data. The AADT data for each link has been calculated in accordance with that used in the LAEI 2008, and is described in Beevers et al. (2009). There are a total of 2028 manual classified count (MCC) sites within the LAEI area used to allocate traffic to the network – a total of ~63000 road links. Not all sites are counted each year, and of the 2028, 690 were counted in 2010. The MCC data are based upon only one day of observations, so to minimise the effect of specific local events introducing outliers into the dataset, the 2010 data has been added to a series of MCC data (extending back to 1999) and smoothed using a Local regrESSion (LOESS) smoothing function. Furthermore, as the MCC data only cover a 12-h weekday period (07:00 to 19:00), these data were then expanded to provide counts for each hour of each day in 2010 (including weekends and overnight hours), using hourly average automatic traffic count and automatic number plate recognition data. The resulting annual hourly dataset was then averaged by link to provide AADT estimates for cars, motorcycles, buses, light goods vehicles, taxis, and 6 types of rigid and articulated heavy goods vehicles. MCC sites with data from all years were used to calibrate the 2010 AADT to produce flows and speed estimates for other years (2003–2009).

Vehicle speeds for the major road network in the LAEI 2010 are based upon a combination of TrafficMaster GPS derived and Moving Car Observer (MCO) speeds. MCO speed is observed using a vehicle travelling at the average speed of the traffic, whereas the 'TrafficMaster' speed has been derived from a GPS-based vehicle tracking system using 2009/2010 observations, and averaged into overnight (22:00–06:00), AM (07:00–09:00), inter (10:00–15:00), PM (16:00–18:00) and evening (19:00–21:00) periods of the day. GPS speed was available for approximately 62% of the LAEI 2010 major road links with MCO data covering the remaining roads.

In order to obtain hourly traffic flows for 10 m traffic source points we combined information on traffic composition from the LAEI into two vehicle categories: light duty vehicles (LDV) and heavy vehicles (HV). From this we calculated hourly

**Table 1**  
Description of data used in TRANEX.

Variable	Data type	Provider	Source	Spatial resolution
Traffic flow	Point	King's College London	London Atmospheric Emissions Inventory (LAEI)	10 m traffic source points
Topographic Layer (including buildings and land cover)	Polygon	Digimap® ( <a href="http://www.digimap.edina.ac.uk">www.digimap.edina.ac.uk</a> )	Ordnance Survey (OS) MasterMap™	<1 m
Integrated Transport Network (ITN)	Line	Digimap® ( <a href="http://www.digimap.edina.ac.uk">www.digimap.edina.ac.uk</a> )	Ordnance Survey (OS) MasterMap™	<1 m
Building Heights	Polygon	Landmap ( <a href="http://www.landmap.ac.uk">www.landmap.ac.uk</a> )	LiDAR survey, high-resolution aerial photography	±0.5 m with 95% confidence limits
Land-Form PANORAMA Digital Terrain Model (DTM)	Regular grid	Digimap® ( <a href="http://www.digimap.edina.ac.uk">www.digimap.edina.ac.uk</a> )	Ordnance Survey (OS) contours	Scale: 1:50000; Horizontal resolution: 50 m Vertical resolution: 1 m
Postcodes	Point	King's College London	Ordnance Survey (OS)	<1 m



information on percentage of HV for the calculation of  $p$  in the CoRTN method (equation (4)). Average vehicle speed for each traffic source point also came from the LAEI.

Building height data (i.e. LiDAR) for all built-up areas within the M25 were downloaded from the Landmap website (<http://www.landmap.ac.uk>; accessed on 6th August, 2013). For some outlying areas close to the M25, building height data is not available because this data only covers urban areas. MM buildings were considered to better represent the buildings within our study period and to be of better spatial resolution than buildings from Landmap. We therefore assigned building heights to the nearest MM building within a 20 m radius of each building height location. MM buildings that could not be assigned a building height (e.g., no MM building within 20 m of building height data, missing building heights in Landmap) were assigned a default building height of 10 m if the footprint of a MM building was  $\geq 15 \text{ m}^2$ . Small buildings such as bus shelters, porches, garages etc. potentially cause problems in the definition of building facades and noise calculations (see Fig. 2). All buildings  $< 15 \text{ m}^2$  were therefore deleted (see Fig. 2). Building heights were converted into a  $0.5 \text{ m} \times 0.5 \text{ m}$  grid of buildings attributed with heights for viewshed analysis (i.e. for the reflections calculation).

For generation of receptors (i.e. address or postcode locations) a geometric centroid was created for each MM building. Each receptor was then moved to 1 m from the facade on the side of the building closest to the nearest road section with traffic information. Fig. 2 shows how this was achieved and also shows situations where this automated method of moving receptors to facades does not work.

Postcodes and address points were intersected with buildings and subsequently linked to receptors using a unique building identifier. Typically there are ~15 addresses associated with each postcode. Point locations for postcodes are the geometric centroids of the address locations associated with each postcode. Each postcode is attributed with a headcount using data from the 2011 census. There are 189531 postcodes, ~3 million address locations, and a population of 8613526 in the study area. In this study we only present results related to postcode

locations. Address locations are used for forthcoming individual-level health analyses.

### 2.3. Modifications to the CoRTN method

TRANEX broadly follows the CoRTN method with some modifications for the treatment of source geometry, the calculation of path distance, traffic on minor roads, road surfaces, tunnels, and gradients along roads. We also add in standard noise metrics ( $L_{Aeq,1hr}$ ,  $L_{Aeq,16hr}$ ,  $L_{night}$ ) as specified in the European Noise Directive (END; European Directive 2002/49/EC).

$L_{Aeq,1hr}$  is calculated from the following empirical relationship described in Abbott and Nelson (2002):

$$L_{Aeq,1hr} = 0.94 L_{10,1hr} + 0.77 \text{ dB(A)} \quad (14)$$

TRANEX then produces  $L_{Aeq,16hr}$  and  $L_{night}$  by averaging  $L_{Aeq,1hr}$  from the hours 07:00 – 22:00 and 23:00 – 06:00, respectively.

For minor roads we used a fixed value of 600 vehicles day<sup>-1</sup> based on the magnitude of manual counts undertaken during noise measurements, and MCC data made available by Norwich City Council and available in the LAEI. Counts were proportionally assigned to minor roads for each hour of the day using the diurnal traffic profile associated with the nearest main road in the LAEI.

The CoRTN method calculates the shortest path distance between each source and receptor along the line that bisects the angle subtended by each road section. In other words, the shortest path is taken as a line from the mid-point of each road section to each receptor. In TRANEX we use traffic information assigned to traffic source points. The shortest path is created from each of these points to receptors.

Fig. 3 shows the pre-processing steps to select traffic source points related to each receptor and the subsequent creation of ray-paths as the basis for calculating the propagation terms.

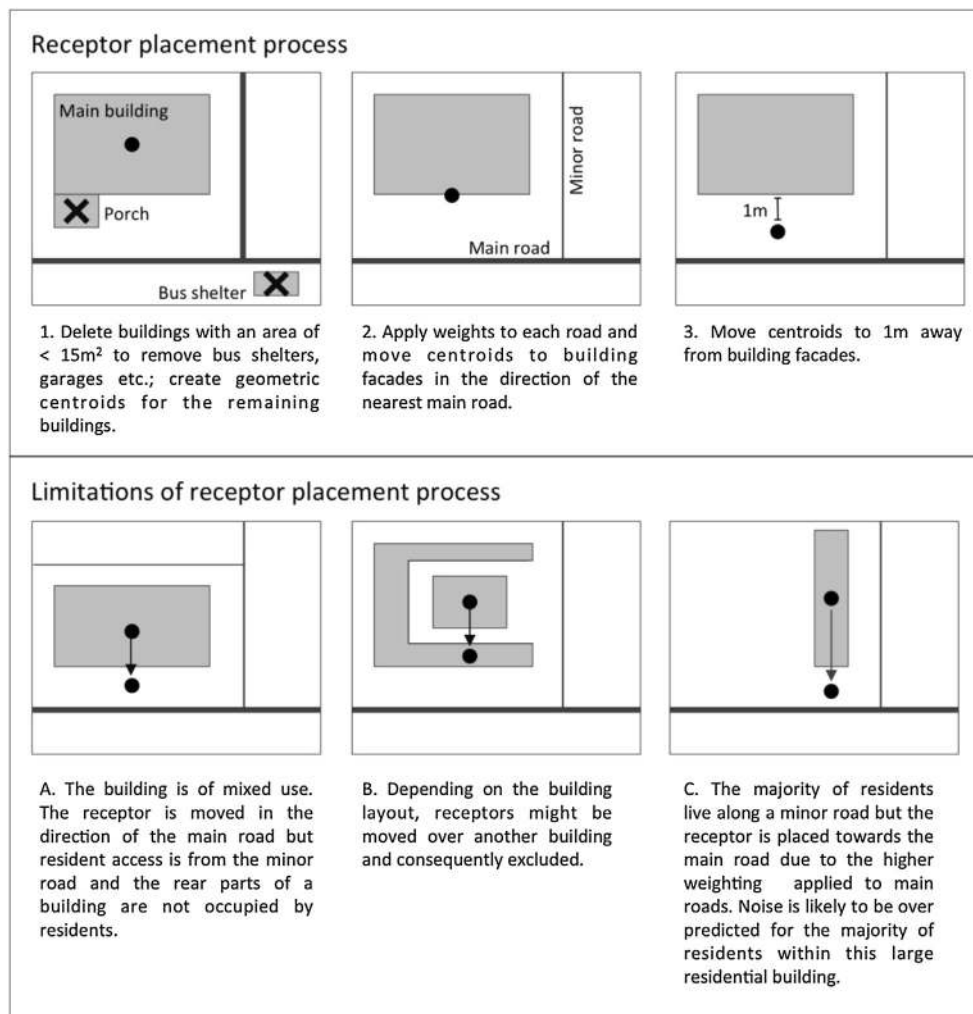


Fig. 2. Procedures used to generate receptors from building polygons and some of their limitations.

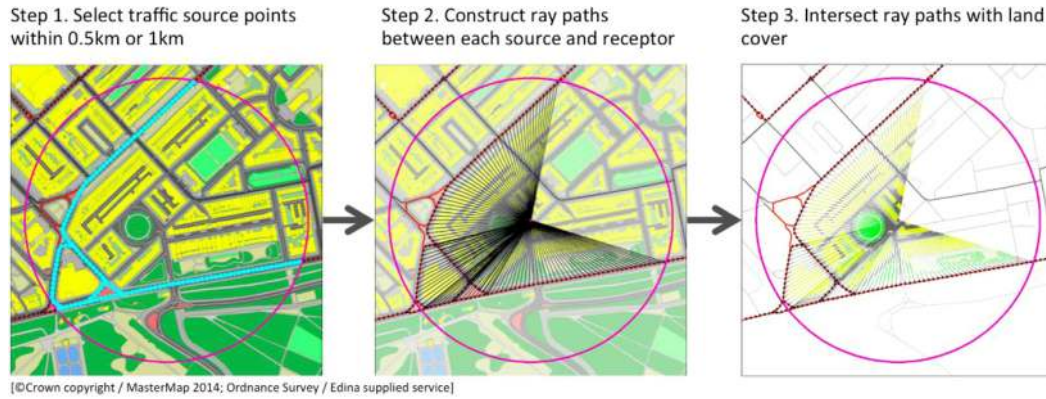


Fig. 3. Construction of ray paths for the distance, shielding and ground cover corrections.

A circular buffer of 500 m is created around each receptor and intersected with the traffic source points (Step 1; Fig. 3). If no traffic source points fall within the 500 m buffer, a second buffer with a radius of 1000 m is created and the operation is repeated. This is to ensure that the nearest main road is included in the noise calculation, which is especially important over open, flat terrain as noise from heavily trafficked roads at distances of ~1 km can sometimes be heard depending on

meteorology. A ray-path using straight-line geometry is created between the receptor and each traffic source point (Step 2; Fig. 3). Each ray-path is subsequently intersected with buildings and land cover for the corrections due to screening and ground cover (Step 3; Fig. 3).

In this study all receptors were given a height of 4 m above ground. For each receptor, the noise level is the combination (Equation (13)) of noise levels predicted

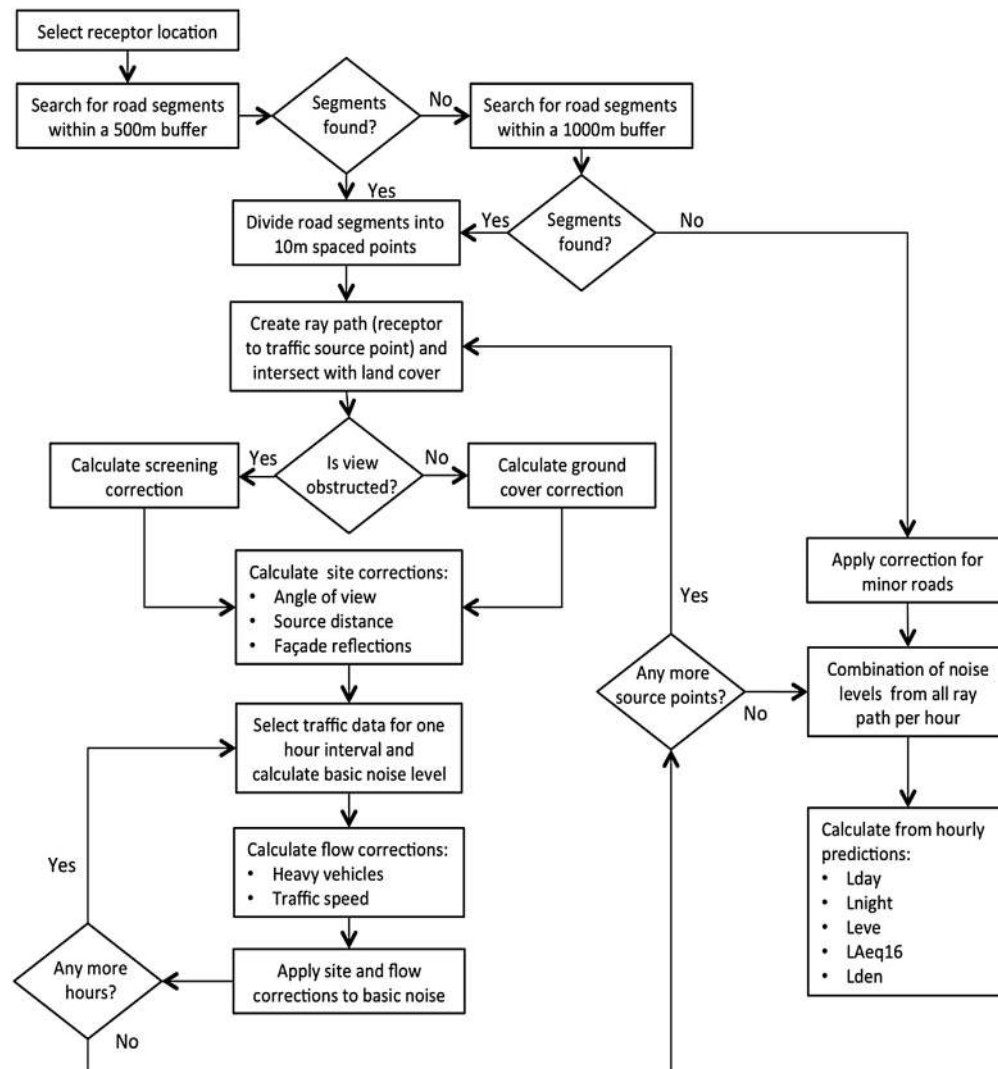


Fig. 4. Workflow applied in TRANEX.

for each pair of source-receptor points with the basic noise level adjusted for the propagation terms listed in Section 2.1. We were unable to characterise road surfaces in London so we treated all roads as bituminous impervious. We also were unable to determine the direction of flow on single carriageways so we did not include the CoRTN term for the gradient correction. Traffic in tunnels is excluded from TRANEX.

TRANEX was developed for exposure assessment (i.e. postcode/address locations), thus it is not directly usable for noise mapping (i.e. predicting over a regular grid of receptors). Fig. 4 shows the workflow of the CoRTN method applied in TRANEX including  $L_{Aeq}$  metrics and a fixed 'low flow' calculation for minor roads.

#### 2.4. Development of software

The modified CoRTN method has been implemented using open-source software. Calculations are carried out in a PostgreSQL<sup>1</sup> database with GIS functions provided by the PostGIS<sup>2</sup> extension. In terms of processing speed for spatial operations, PostGIS has greater performance than other common desktop GIS applications due to its use of efficient spatial indexing. This is of particular importance for this application of TRANEX which uses detailed land cover polygons on a city-wide scale precise to ~1 m as an input. As such, PostGIS provides an effective environment in which to handle large vector data sets. The CoRTN method also includes a correction based on the proximity of sound reflective surfaces (building façades). This is achieved via viewshed analysis of buildings within a 50 m radius of a receptor point. As viewsheds cannot be calculated by PostGIS, GRASS GIS<sup>3</sup> is used and the derived representation of visible building façades was imported into the PostgreSQL database. TRANEX is controlled by a script in the R software<sup>4</sup> using the PostgreSQL<sup>5</sup> and spgrass6<sup>6</sup> packages to call the database and viewshed functions, respectively.

TRANEX is implemented using two R scripts: 1) a pre-processor to generate receptors 1 m from the façade of each residential building using a set of rules for best placement of receptors, and 2) a script that contains the noise model which calls PostGIS and GRASS functions. On running the R script, TRANEX proceeds on a receptor point-by-point basis. The estimated noise metrics are stored both as an ArcGIS shapefile and within the PostgreSQL database.

#### 2.5. Model evaluation

While air pollution is routinely monitored in national networks, there is no routine monitoring for noise and data are generally not publicly available. To evaluate the performance of TRANEX, we utilised data on noise measurements collected as part of previous studies undertaken by the authors in the EU funded 5th Framework Program HEAVEN (Healthier Environment through the Abatement of Vehicle Emissions and Noise, in 2002) and HEARTS (Health Effects and Risks to Transport Systems, in 2005) projects in Leicester, UK, and data collected in 2014 to coincide with on-going air pollution monitoring being undertaken by the authors in Norwich, UK. Fig. 5 shows maps of the areas covering noise measurements used in this study.

The focus of this exercise was assessing the model performance in terms of spatial contrast in noise levels. In Leicester a total of 38, 30-minute noise measurements were taken using Casella sound level meters (2xCeL480 and 2xCeL593.100a instruments). Measurements were taken at both facade and non-facade locations, with heights 3.5–4 m above ground level. All instruments were calibrated before and after each survey day using a Casella CEL calibrator (reference pressure: 94 dB) to ensure that the instrument had not drifted by more than 1 dB(A) over that day. Noise measurements were made in HEAVEN between the hours of 10:00 and 15:00 during August 2002 and in HEARTS between the hours of 09:00 and 16:30 during February 2005 (Goodman, 2005; WHO, 2005).

In Norwich 35, 30-min noise level measurements were made using an Optimus CR:171B sound level meter, at 1.5 m above ground level, between the hours of 09:00 and 16:00, June 2014, next to residential properties. The microphone was placed at a height of 1.5 m to match the height of co-located air pollution monitoring. The noise sensor was calibrated at least three times per day using a CR:515 acoustic calibrator (reference pressure: 93.7 dB). All noise sensors had appropriate microphone shielding from the wind.

In Leicester we received traffic information from the Council's Airviro model (SMHI, 2014), used for local air quality management, which in turn received data from the cities' SCOOT (Split, Cycle, Offset, Optimisation Technique) (Imtech, 2013) system used for traffic control. In Norwich a version of the SATURN traffic model implemented by Norwich City Council was used to define composition, flows and speeds on main roads. Information from the traffic models and manual counts were used to produce time-varying information on flows, and in turn used to estimate noise levels for the different hours when noise measurements were made (e.g., 09:00 – 16:00). We used equivalent data to London on road geography, land cover

and building heights in Leicester and Norwich to run TRANEX for model evaluation. Noise model estimates were made with respect to the height above ground levels of each instrument's microphone in Leicester (3.5–4 m) and Norwich (1.5 m). Noise level estimates from TRANEX were then compared with short-term noise measurements made in the cities of Leicester and Norwich.

A series of performance statistics were used to evaluate models including: Spearman's rank correlation coefficient ( $r$ ), the coefficient of determination ( $r^2$ ) (i.e. the sum of the squares of the errors divided by the sum of the squared differences between measurements and the mean of all measurements), root mean square error (RMSE), the variance of measured and modelled noise levels, and 95% confidence intervals (CI) for the regression fit between modelled and measured noise levels. We used Spearman's correlation to reflect the skewed nature of noise measurements and also because for exposure assessment we are interested in relative ranking of exposures as well as model error. These statistical tests were chosen to cover the key elements of characterising and assessing performance of environmental models as described in Bennett et al. (2013).

#### 2.6. Exposure assessment

For each noise metric (e.g.  $L_{Aeq,1hr}$ ), we assumed exposures to be equal to modelled noise levels. Road traffic noise exposures were calculated for all 189531 postcodes in London for each year between 2003 and 2010. Exposure assessment of the population of London was undertaken by assigning population headcounts to noise exposures calculated for each postcode location.

### 3. Results

#### 3.1. Model evaluation

Results of comparing measured and modelled noise levels are shown in Table 2 and Fig. 6. Table 2 shows summary statistics from the comparison of measured and modelled noise estimates in Leicester and Norwich. Fig. 6 shows scatterplots of measured against modelled noise estimates in Leicester and Norwich. A high level of correlation was seen between measured and modelled noise levels (Leicester:  $r = 0.85$ ; Norwich:  $r = 0.95$ ). The average error in predicted noise levels was 2.6 dB(A) for Leicester and 3.5 dB(A) for Norwich. In Leicester and Norwich 63% and 34% of sites, respectively, have predicted noise levels within  $\pm 2$  dB(A) of measured noise levels. In both cities, modelled noise levels tend to over-predict measured noise levels as indicated by regression fit lines in Fig. 6, but the model under-predicts the variability in measured noise levels as indicated by the values of variance of measured ( $Var_O$ ) and modelled ( $Var_P$ ) noise levels in Table 2. Pooling sites from Leicester and Norwich yields an  $r = 0.90$  and an average model error of 3.1 dB(A). Overall the largest model errors relative to noise measurements are at sites where noise levels were measured <60 dB(A) and mostly are associated with low traffic flow in background areas.

#### 3.2. Modelled noise exposures in London

Table 3 shows summary statistics for modelled noise levels at 2008 postcode locations. Table 4 shows the number of postcode locations and number of people within (4 dB) bands of modelled noise exposures for  $L_{Aeq,16hr}$  and  $L_{night}$ .

For  $L_{Aeq,16hr}$  there is < 1 dB (i.e. median – min) variability across 50% of postcode locations (Table 3); 10% of the population have  $L_{Aeq,16hr}$  and  $L_{night}$  noise levels > 68.3 dB and > 63.5 dB, respectively. For  $L_{Aeq,16hr}$  and  $L_{night}$ , 74% and 70%, respectively, of the population have modelled road traffic noise exposures in the lowest 4 dB category of noise exposures (as shown in Table 4). Approximately 19% and 12% of the population are exposed to road traffic  $L_{Aeq,16hr}$  noise levels  $\geq 60$  dB and  $\geq 65$  dB, respectively. Approximately 19% and 12% of the population are exposed to road traffic  $L_{night}$  noise levels  $\geq 55$  dB and  $\geq 60$  dB, respectively.

TRANEX does not produce a continuous surface of noise level estimates (i.e. regular grid), but Fig. 7 shows the spatial variability

<sup>1</sup> <http://www.postgresql.org/>.

<sup>2</sup> <http://postgis.net/>.

<sup>3</sup> <http://grass.osgeo.org/>.

<sup>4</sup> <http://www.r-project.org/>.

<sup>5</sup> <http://cran.r-project.org/web/packages/RPostgreSQL/RPostgreSQL.pdf>.

<sup>6</sup> <http://cran.r-project.org/web/packages/spgrass6/spgrass6.pdf>.



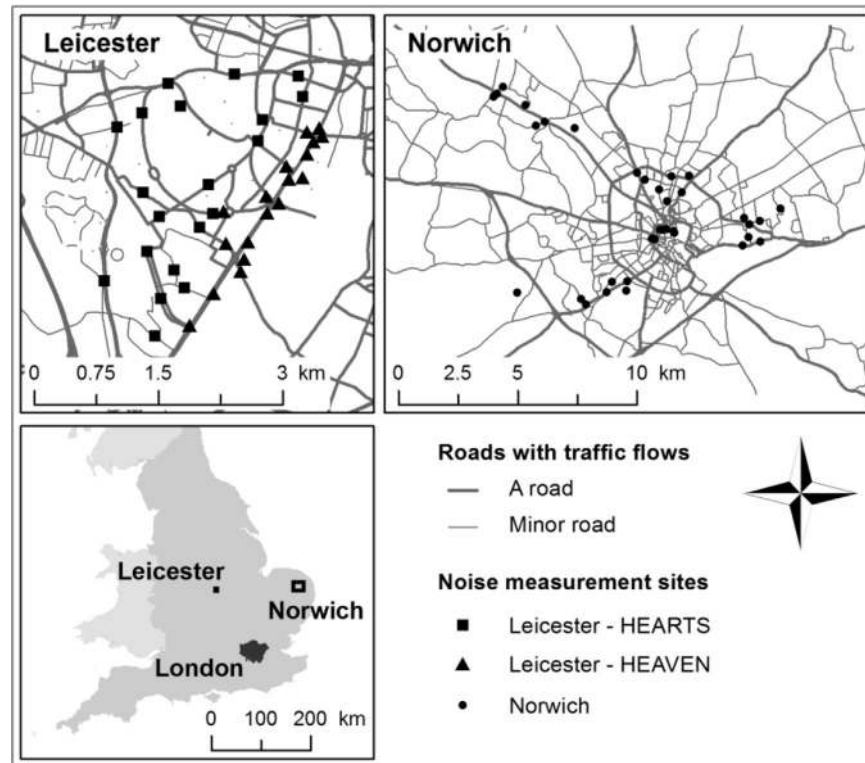


Fig. 5. Location of noise measurement sites in Leicester and Norwich.

in modelled road traffic noise exposures at postcode locations within London for 2008.

### 3.3. Changes in modelled noise exposures over time (2003–2010)

Differences over the study period (2003–2010) in noise exposures were calculated by subtracting values of  $L_{Aeq,16hr}$  and  $L_{night}$  predicted at postcode locations ( $n = 189531$ ) for 2003 from values predicted for 2010 (Table 5). Relatively large negative and positive changes were seen at a small number of postcodes. This may be due to traffic interventions (road closures, road building, traffic diversions etc.) between 2003 and 2010 (N.B. the comparison is for the same postcode locations). The average change for  $L_{Aeq,16hr}$  and  $L_{night}$  is  $< 0.3$  dB. Traffic flows over this period have generally increased but lower speeds due to traffic congestion may counteract the ability of traffic flows to raise noise levels. Approximately 54% of postcodes for both  $L_{Aeq,16hr}$  and  $L_{night}$  have an increase in modelled noise exposures between 2003 and 2010. The majority of postcode locations (96%) have changes in predicted  $L_{Aeq,16hr}$  and  $L_{night}$  noise exposures of  $< \pm 2$  dB between 2003 and 2010.

## 4. Discussion

We developed a traffic noise model (TRANEX) based on the CoRTN method for population exposure assessment in London. The model was developed in open-source GIS (via R). TRANEX was evaluated against short-term noise measurements made in Leicester and Norwich, UK. We undertook population exposure assessment using postcode locations in London for the period 2003–2010.

### 4.1. Performance of TRANEX

To date, we have not undertaken an evaluation study in London (i.e. where TRANEX was implemented for exposure assessment). The areas in Leicester and Norwich where noise measurements were made, however, have similar characteristics to many areas in London in terms of spatial contrasts in heavily trafficked roads, street canyons and open space. The study areas in Leicester and Norwich, for example, include several roads with  $>20,000$  AADT. One advantage of the noise measurements made in Leicester and Norwich for evaluating TRANEX is that they were not influenced by

Table 2

Summary statistics for the comparison of measured and modelled noise levels in Leicester and Norwich.

Location	N	Spearman's rho (r)	$r^2$	$Var_O$	$Var_P$	RMSE	Regression fit line		95% CI (lower, upper)
							$\beta$	Constant	
Leicester	38	0.95 <sup>a</sup>	0.81 <sup>a</sup>	35.5	26.4	2.6	1.09	−7.28	0.95, 1.22
Norwich	35	0.85 <sup>a</sup>	0.72 <sup>a</sup>	43.0	34.6	3.5	0.97	0.37	0.78, 1.17
All sites	73	0.90 <sup>a</sup>	0.80 <sup>a</sup>	45.9	37.3	3.1	1.02	−2.64	0.91, 1.12

$Var_O$  is the variance of the measured values (i.e. observations).

$Var_P$  is the variance of the modelled values (i.e. predictions).

<sup>a</sup>  $p = .000$ .



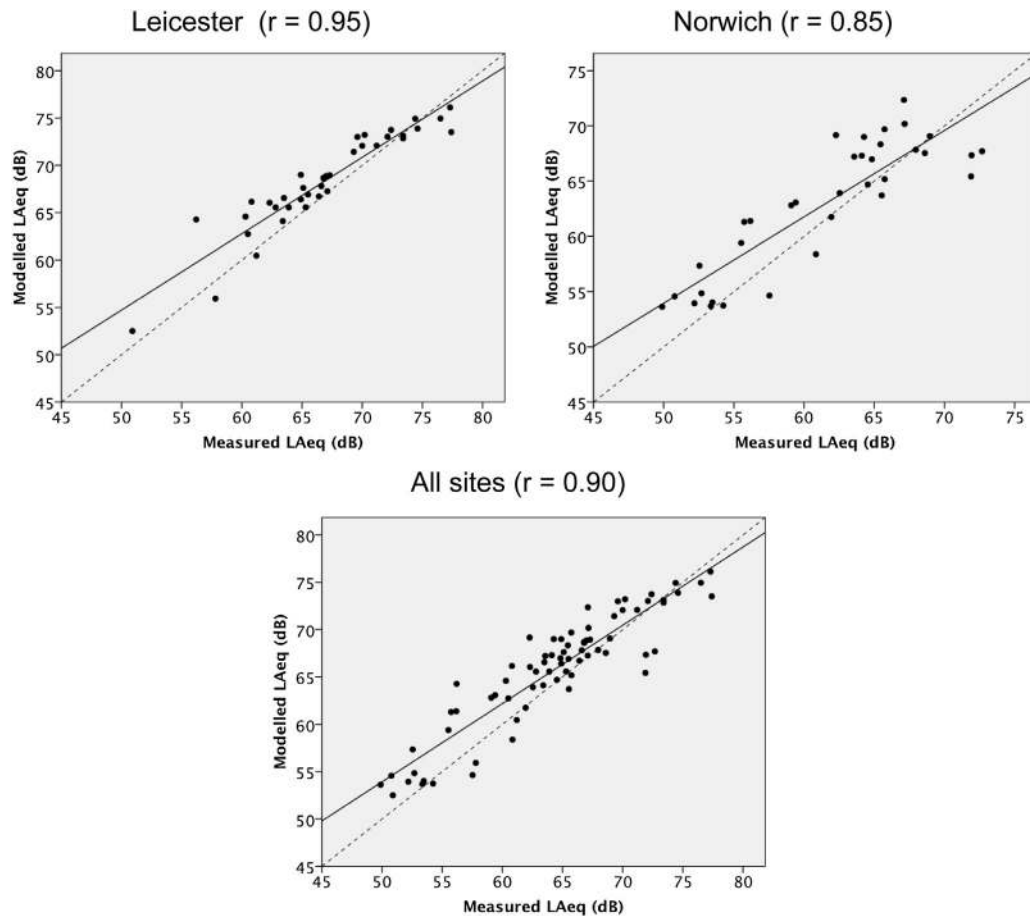


Fig. 6. Comparison of modelled and measured 30-min  $L_{Aeq}$  (dB) in Leicester, Norwich, and sites from both areas [regression fit line – solid line; 1-to-1 line – dashed line].

**Table 3**

Summary statistics for modelled noise levels (dB) at 2008 postcode locations ( $n = 189531$ ).

Noise metric	Min.	Max.	10th %ile	Median	90th %ile	Skewness
$L_{Aeq,16hr}$	54.8	82.6	54.9	55.6	68.3	1.39
$L_{night}$	49.2	78.4	49.3	50.1	63.5	1.35

noise from aircraft and railways. Taking all sites, the average error for our model was 3.1 dB(A) and the Spearman's correlation was 0.90 ( $p = .000$ ) Comparing modelled and measured hourly  $L_{Aeq}$  is a stringent test of models; it is likely that model errors would be

lower if compared with measurements over longer averaging times ( $L_{Aeq,16hr}$ ,  $L_{night}$ ). The better performance of TRANEX in Leicester compared to Norwich may be in part due to generally more representative traffic information in Leicester.

Noise model evaluations in the open literature, comparing estimated noise levels with noise measurements, are relatively scarce, and like the measurements presented in this study tend, by necessity, to be for short time periods when the focus is on assessing spatial contrasts in the performance of noise models. In Vancouver, Canada, Gan et al. (2012) compared measured (LDL 870 Environmental Noise Analyser) 5-min daytime (08:00–18:00) A-weighted noise levels with noise level predictions from CadnaA

**Table 4**

Cumulative modelled  $L_{Aeq,16hr}$  and  $L_{night}$  road traffic noise exposures for postcodes and the resident population of London in 2008.

Noise level (dB)	$L_{Aeq,16hr}$ Cumulative counts of (% in brackets)		$L_{night}$ Cumulative counts of (% in brackets)	
	Postcodes	People	Postcodes	People
48 – <51 <sup>a</sup>	–	–	112207 (59.20)	6032157 (70.03)
51 – <54 <sup>a</sup>	–	–	132,863 (70.10)	6,866,969 (79.72)
54 – <57	120,224 (63.43)	6,399,737 (74.30)	143,571 (75.75)	7,210,561 (83.71)
57 – <60	136,596 (72.07)	6,984,673 (81.09)	155,100 (81.83)	7,595,073 (88.18)
60 – <63	146,909 (77.51)	7,317,983 (84.96)	168,361 (88.83)	8,043,448 (93.38)
63 – <66	159,126 (83.96)	7,727,753 (89.72)	180,115 (95.03)	8,407,451 (97.61)
66 – <69	173,588 (91.59)	8,221,195 (95.45)	186,669 (98.49)	8,571,285 (99.51)
69 – <72	183,723 (96.94)	8,508,549 (98.78)	188,831 (99.63)	8,607,192 (99.93)
72 – <75	187,834 (99.10)	8,593,616 (99.77)	189,434 (99.95)	8,612,624 (99.99)
75 – <78	189,112 (99.78)	8,610,546 (99.97)	189,530 (100)	8,613,482 (100)
78 – <81	189,510 (99.99)	8,613,230 (100)	189,531 (100)	8,613,526 (100)
81 – <84 <sup>b</sup>	189,531 (100)	8,613,526 (100)	–	–

<sup>a</sup> Below the minimum (see Table 3) modelled noise level for  $L_{Aeq,16hr}$ .

<sup>b</sup> Above the maximum (see Table 3) modelled noise level for  $L_{night}$ .

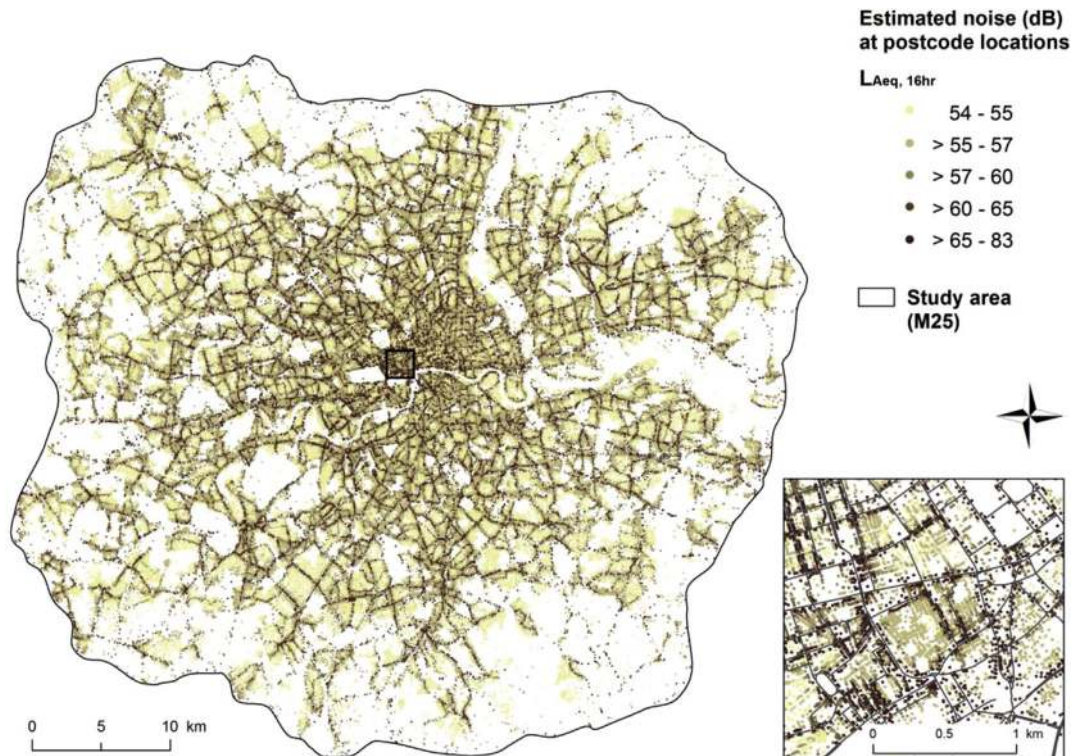


Fig. 7. Modelled  $L_{Aeq,16hr}$  (dB) noise exposures at postcode locations in London.

(using RLS-90; the standard method used in Germany) for 103 roadside locations. On average, measured 5-min noise levels were 6.3 dB higher than  $L_{day}$  but showed a good level of correlation ( $r = 0.62$ ). The underestimation in 5-min noise levels may be due in part to the different averaging periods for measured and modelled noise levels. Ko et al. (2011) compared modelled noise levels from the RLS-90 method in SoundPLAN 6.5 with daytime and night-time noise measurements made at 25 locations in Chungju, Korea (N.B. no details were given of the measurement instruments). Measured noise levels were in the range 65–77 dB. Overall the average error in predicted noise levels was 0.6 dB with an  $r^2$  of 0.50. Mioduszeewski et al. (2011) compared noise predictions from CadnaA with noise measurements at 25 locations for  $L_{day}$ ,  $L_{eve}$  and  $L_{night}$ . Differences between measured and modelled noise levels were in the range  $-3.1$ – $8.0$  dB; for  $L_{day}$  and  $L_{night}$  the range was  $-3.1$  to  $4.4$  dB (average =  $0.1$  dB) and  $0.8$ – $8.0$  dB (average =  $4.7$  dB), respectively. In Santiago, Chile, Suárez and Barros (2014) used CadnaA, applying different model options (RLS-90, the Swiss model STL96, the Nordic method SP48, and CoRTN) to predict  $L_{Aeq}$  noise levels for comparison with 15-min noise measurements made during the day (07:00 – 21:00) at 52 (roadside, suburban and rural) locations. Over 50% of differences between measured and modelled noise levels were less than 1 dB, with models tending to under-predict noise measurements. Errors in predicted noise levels were on average lower close to main roads (1.7 dB) than on local roads (3.1 dB). Lee et al. (2014) compared

measured and modelled noise levels in three cities in the United States. Noise measurements (10-min  $L_{eq}$ ) were collected between 09:00 and 17:00 h during weekdays using a 3 M SD-200 sound level meter in Atlanta (20 sites), Los Angeles (26 sites) and New York City (26 sites). Noise levels were estimated, for each of the 72 sites for the corresponding hour of the day when noise measurements were made, using the US Federal Highways Agency Traffic Noise Model (TNM). Noise levels were predicted using local traffic models in each city and then again from 10-min observed traffic counts made at the same time as noise measurements. TNM using traffic counts explained a high proportion of the variability in measured 10-min noise levels ( $R^2$ : 0.56–0.73) but model performance using modelled long-term traffic flows was overall poor ( $R^2$ : 0.08–0.42). TNM tended to under-estimate noise measurements, which may be because only the streets where noise measurements took place were included in the model. Based on comparison of our model evaluation with other studies we concluded that the model performance in our study is acceptable. Most importantly for exposure assessment, where relative ranking of exposures is important, model evaluation in this study showed a high level of (rank) correlation between noise levels estimates and noise measurements ( $r$ : 0.85–0.95).

#### 4.2. Modelled noise exposures in London

According to the World Health Organisation (WHO) community noise guidelines (2009), average outdoor noise levels in residential areas should not exceed 55 dB and 40 dB for  $L_{Aeq,16hr}$  and  $L_{night}$ . We modelled exposures of the resident population in London using 189531 postcode locations with a population of 8.61 million and presented results for 2008 as an example of our model output. For modelled  $L_{Aeq,16hr}$  and  $L_{night}$ , 19% and 100%, respectively, of the population have noise levels exceeding the WHO guidelines. The CoRTN method implemented in TRANEX predicts a minimum

**Table 5**  
Changes in predicted noise levels (dB) at postcode locations: subtracting 2003 values of  $L_{Aeq,16hr}$  and  $L_{night}$  from 2010 values.

Noise metric	Mean	Standard deviation	1st %ile	99th %ile	Minimum	Maximum
$L_{Aeq,16hr}$	0.25	0.89	−0.34	2.91	−12.52	21.91
$L_{night}$	0.26	0.97	−0.36	2.94	−12.42	21.56

night-time  $L_{Aeq,1hr}$  of 38.0 dB for a single minor road. The minimum modelled value of night-time  $L_{Aeq,1hr}$  in London was 42.4 dB because we combine the contribution of all sources up to 0.5 km or 1 km.

WHO also state that 20% of European Union populations are exposed to daytime levels exceeding 65 dB and 30% are exposed to night-time levels greater than 55 dB. For London, our results gave 12% (~1.03 million people) and 19% (~1.6 million people) of the population exposed to noise levels above these thresholds, respectively. Our estimates are based on road traffic noise alone and do not include incremental noise levels from aircraft and railways applicable to some of the resident population. A substantial number of people living in London are thus exposed to noise levels that are unacceptable during daytime and at night.

#### 4.3. Strengths and limitations

We have implemented the main aspects of the CoRTN in TRANEX. Our model does, however, have limitations. We have not included elevated road sections (e.g. flyovers, bridges). There is no information included in TRANEX on existing noise barriers. We have modelled noise propagation on a flat world – although London is relatively low-lying there are suburban areas with undulating terrain that will affect the propagation of noise levels between sources and receptors. We assumed minor roads to have a constant traffic flow of 600 vehicles  $\text{day}^{-1}$ . Notwithstanding that our results showed this to be a good approximation for noise levels on roads with low flows (i.e. ~50 vehicles  $\text{hour}^{-1}$  during the day-time), we may have under-estimated noise levels for some minor roads with higher flows (i.e. those roads that were not part in the LAEI). The LAEI does, however, include roads with relatively low flows (i.e. < 1000 vehicles  $\text{day}^{-1}$ ). Furthermore, we have applied the CoRTN method with a single value of average vehicle speed for each road link because at the time of this study we were limited to this information. Thus, our model is not ‘dynamic’ in terms of representing varying vehicle speeds along road links. Others (Guarnaccia, 2013; Iannone et al., 2013) have shown that noise levels are different around road intersections (acceleration/deceleration) than at mid-block (i.e. the free-flowing section of a road link) for the same volume of traffic, which means that we may have variable errors in modelled noise levels associated with changes in vehicle speeds along road links relative the average vehicle speeds that we have applied.

We have calculated noise levels at a single façade that is closest to the nearest main road for each dwelling. We decided to model noise at one point per building due to time constraints in modelling such a large number of locations. Thus, we may have misclassified exposures for other façades (i.e. rooms) within dwellings. Receptor placement is a pre-process to noise modelling and in a separate model script, which does not prohibit future applications by us, or others, in having a more detailed definition of receptors. An alternative method, for example, is to estimate noise levels at several points around each building and from them calculate the average (or median) noise level. This would, however, substantially increase the processing time for our model to estimate noise levels across London, and this was not feasible in the lifetime of this study. Noise estimates are universally made at 4 m above ground and this will misclassify noise levels to a varying degree for dwellings in high-rise accommodation. We were unable to include the gradient correction for uphill flow on single carriageways. Tunnel elements being excluded may lead to under-prediction of noise in the areas adjacent to tunnel mouths due to lack of propagation of retro-reflected sound from tunnel walls. As the CoRTN method produces estimates of noise levels in values of  $L_{10}$  we used the method by Abbott and Nelson (2002) to convert  $L_{10}$  to  $L_{eq}$ . Abbott and

Nelson (2002) showed that there was high correlation ( $r^2 = 0.90$ ) and relatively a small standard error of 2.1 dB (from comparison of 460 measurements of  $L_{eq,1hr}$  and predicted values of  $L_{10,1hr}$  in free-flowing traffic (i.e. as per the traffic model used in this study). It is expected that the magnitude of errors would be reduced for longer averaging periods such as those used in this study ( $L_{Aeq,16hr}$ ;  $L_{night}$ ). Indeed, Abbott and Nelson (2002) also showed that for 18-h averaging periods (06:00 – 24:00) comparison of measurements (1024 measurements at 76 sites) of  $L_{eq,18hr}$  and predicted values of  $L_{eq,18hr}$  yielded a  $R^2$  of 0.97 and the standard error was 0.85 dB. Finally, we estimated that 100% of people in London live in locations where the WHO community noise guideline of 40 dB for  $L_{night}$  is exceeded. The CoRTN method is, however, limited to a minimum noise value for  $L_{Aeq,1hr}$  of 38.0 dB during the quietest part of the night-time, which, with the data supplied to our model, resulted in a minimum value of 42.4 dB. By using the CoRTN method, we may have over-estimated night-time noise especially for people living in the quietest areas.

Despite these limitations, our model has a number of strengths. In particular, detailed information on traffic for ~63000 road links including varying flows and speeds for each year in the study period (2003–2010), and detailed information on land cover and heights of individual buildings within London. Through the implementation of the model in PostgreSQL, TRANEX offers excellent efficiency in terms of processing time for a large number of sources compared to other standard software platforms such as ArcGIS (~11 days processing time for 189531 postcodes on a 3.40 Ghz, 16 Gb RAM, 64 Bit, Intel i7-3770). TRANEX has been developed so that it is transferable to other cities. In the UK this means that it can be applied in most areas as long as there is sufficiently detailed information on traffic flows, composition and speeds.

#### 4.4. Future work

In consideration of other sources of environmental noise in the epidemiological studies, modelled values of noise levels from air and railways (not reported here) were provided by Department of Environment, Food and Rural Affairs (DEFRA) via permissions obtained from the rail industry and Civil Aviation Authority (CAA). By mid-2014 we had commenced running TRANEX for all ~3 million address point locations in London. Following the discussion on limitations of our current model, our aim is to make a number of improvements in future applications. We aim, for example, to develop a method to improve noise exposure estimation for dwellings on minor roads. We are currently considering a method that combines information on the order of connectivity between main roads and minor roads; e.g. a minor road connecting two main roads (i.e. 1st order) will likely have higher traffic flows than a minor road several orders “upstream” (e.g. dead-end roads/cul-de-sacs). This work would involve undertaking turning surveys between main roads and minor roads, and counting traffic along minor roads of different orders of connectivity to main roads. The work would also require a comprehensive series of noise measurements along different types of minor road to evaluate the approach. We also aim to improve estimation for address locations in high-rise accommodation by including terms in the model to calculate noise levels at receptors >4 m above ground level. The latter will depend on our ability to characterise the height of vertical address points.

Another area for improvement is to introduce ‘dynamic’ speed profiles on road links to better represent the acceleration/deceleration and free-flow phases of traffic. This would involve improvements to the traffic model that we have used in this study. Indeed, our model implementation using a series of points spaced along road links is ideal for applying variable speed information if it



becomes available. We also intend to look at including an “intelligent”, variable-sized buffer for selecting noise sources; for example, a fixed buffer size of 500 m may be too large when receptors are close to one or more main roads in a densely built up area, particularly in continuous street canyons (i.e. in this situation, noise from roads several hundred metres away will make negligible difference to incremental noise levels); for example, a 1000 m buffer may even be too small when a receptor is downwind of a major highway in open, flat terrain. We will also consider including atmospheric absorption and refraction and meteorological effects that are accounted for in other models (e.g. RLS-90, Nord 2000, HARMONOISE) and use wind direction to set the variable buffer for selecting noise sources. We intend, or invite others using our freely available software, to compare exposure estimates from our model with other models including those that are commercially available (e.g. SoundPlan, CadnaA etc.). We will compare noise levels from TRANEX with those from our implementation of the CNOSSOS-EU method (Kephapopoulos et al., 2014) (i.e. the standard method being adopted in the EU for noise assessments), which is currently in development, for different times of the day. Finally, we will undertake additional evaluation studies and make continuous noise measurements over longer periods (e.g. 24-hours) to allow comparison between noise measurements and the main noise metrics produced by TRANEX ( $L_{Aeq,16hr}$ ,  $L_{night}$ ).

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