Predicting the Impact of Intercity Transportation Connections on Spatial Environmental Noise Pollution in Greater Khartoum, 2009

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The traffic noise of public transportation vehicles is part of the general environment problem in urban areas, and controlling traffic noise has become a serious issue for communities. To ensure a high-quality environment, methods for predicting noise emissions are used. This study is based on data for minibuses (MB) with a passenger capacity of 15–25 persons, provided by the Department of Public Transportation and Petroleum of Khartoum Town in 2009, and on fieldwork conducted in June 2009. Josse's mathematical model for noise prediction is used to examine the influence of intercity transportation connections on levels of noise pollution in Greater Khartoum, which consists of the towns of Khartoum, Omdurman, and Khartoum North. The author contends that because of intercity transportation connections, there are significant geographic differences within the transportation network of Greater Khartoum on levels of noise pollution. Results indicate that MB contribute 69.6 dB on average to the total noise level. These values put Greater Khartoum above the mid-point of the scale typically used to compare levels of noise pollution. This noise level also exceeds the 45 dB recommended as safe for a city by the World Health Organization. Mean noise levels in Khartoum, Omdurman, and Khartoum North were 68.6 dB, 72.5 dB, and 67.7 dB respectively; the calculated F*-ratio is 1.79, less than the critical value of 4.46, suggesting that the difference is not statistically significant. However, intercity transportation connections have spawned new transportation lines and changed the existing noise levels on all transportation axes in the three towns. The author proposes a plan to curb noise levels caused by MB in Greater Khartoum.*

Key words: noise pollution, transportation axes, intercity connections, minibuses, spatial differences, Josse's prediction model

La pollution sonore créée par les véhicules de transport public est un élément constitutif de la question environnementale générale dans les zones urbaines ; la contrôler est un enjeu majeur pour les communautés concernées. Pour assurer un environnement de bonne qualité, on utilise des méthodes de simulation des émissions sonores. Cette étude est basée sur des données pour des minibus (MB) d'une capacité de 15 à 25 passagers ; elles ont été fournies par le Ministère des Transports publics et des Hydrocarbures de la Ville de Khartoum en 2009, complétées par une enquête de terrain effectuée en juin 2009. Le modèle mathématique de Josse pour le calcul de la pollution sonore est utilisé pour étudier l'influence des connections interurbaines sur les niveaux de pollution sonore dans le Grand

Khartoum, qui comprend les villes de Khartoum, Omdurman, et Khartoum Nord. L'auteur affirme que ces connections entraînent d'importantes disparités géographiques de niveaux de pollution sonore au sein du réseau de transport du Grand Khartoum. Les résultats indiquent que les minibus contribuent en moyenne à 69,6 dB du bruit total. Ces valeurs placent le Grand Khartoum au-dessus de la moitié des valeurs généralement utilisées pour comparer des niveaux de pollution sonore. Ce niveau de bruit dépasse également le seuil de précaution de 45 dB recommandé par l'Organisation mondiale de la santé. Les niveaux moyens de bruit à Khartoum, Omdurman et Khartoum Nord étaient respectivement de 68,6 dB, 72,5 dB et 67,7 dB; le test du F a été de 1,79, inférieur au seuil critique de 4,46, ce qui suggère que la différence n'est pas statistiquement significative. Cependant, les connections interurbaines ont créé de nouvelles lignes de transport et modifié les niveaux de bruit existants sur l'ensemble des axes routiers des trois villes. En conclusion, l'auteur propose un plan pour réduire les niveaux de bruit produits par les minibus dans le Grand Khartoum.

Mots-clés: pollution sonore, axes routiers, connections entre villes, minibus, différences spatiales, modèle de simulation de Josse

Introduction

Sound is small vibrations that affect air pressure at different frequencies (measured in hertz, Hz). This pressure fluctuates around atmospheric pressure at different amplitudes, using air as a medium to travel. Audible sound has a range of 20–20 000 Hz per second. Generally, sound sources are many in a given environment, and they are usually found in combination (Priyadarsh 2011). Sound can be a source of pollution; noise pollution is one of the easiest forms of pollution to understand (PCCD 2011). *Wikipedia* (2011) and the *Gale Encyclopedia of US History* ("Noise pollution" n.d.) define noise pollution as "a displeasing human-, animal- or machine- created sound that disturbs the activity of human or animal life"; "Usually 80 db is the level at which sound becomes physically painful" (iloveindia.com 2011). The World Health Organization (WHO) has fixed 45 dB as the safe noise level for a city (ILO 2009). In addition, the WHO has proposed 30 dB(A) as a constant noise limit for sleeping and 45 dB for individual noise events (Williams 2009).

The WHO ranks noise pollution third (after air and water pollution) as the most challenging to human health (ILO 2009). People in urban areas are more exposed to noise caused by motor vehicles relative to other types of noise, making traffic noise pollution a worldwide problem (Al-Mutairi et al. 2009). There are wide differences in noise levels worldwide. In Europe, half of urban centres suffer from noise pollution, and in 19 EU countries noise levels averaged 55 dB or more in urban centres with 250 000 people (Expatica 2011). Further, "over 210 million people in Europe are exposed to traffic noise levels exceeding the threshold at which the World Health Organization has found noise becomes a serious problem for people" (Mitchell 2009). Throughout the European Union, higher noise levels affect 20 % of the population (WHO 1997; EU 2011), at the high cost of €40 billion; 30 % of British people are affected by noise pollution (Environmental Protection UK 2007). Similarly, the majority of Americans are exposed to higher levels of noise pollution (Miller 1999), as are Australians (Australian Academy of Science 2011), and noise pollution is rapidly increasing in Third World countries (Vaziri 2006). However, this study is the first to address noise pollution in Sudan.

Accelerating world population growth has produced serious problems including lack of privacy, reduced personal space, and noise (Gradua Networks 2011). The world's urban population increased 12-fold between 1950 and 1998 and is projected to equal the current world population by 2025, particularly in the developing world (WBCSD 2004).

Rapid growth in the number of urban automobiles will certainly increase noise pollution (Huang et al. 2009). As a result of "the impact of urbanization and the expansion of urban land use … a large city of 5 million inhabitants may stretch over 100 km and may use an amount of land exceeding 5 000 km^2 to be supported with a vast and complex transport system" (Rodrigue 2011). In addition, increasing energy usage has exacerbated noise pollution (bcb 2011), as do poor urban planning and increases in the density of residential and commercial buildings (Buzzle.com 2011). However, levels of noise pollution are also influenced by many traffic parameters such as road surface, tires, driving behaviour, number and types of vehicles, and infrastructure (Shukla et al. 2009), as well as by traffic volumes (Mitchell 2009).

People's health can also seriously be affected by traffic noise (Mitchell 2009), as well as their behaviour (Wikipedia 2011). Such impacts are multi-faceted and inter-related (iloveindia.com 2011), including many symptoms of psychological disorders (Wikipedia 2011; Buzzle.com 2011). Exposure to noise can have both short-term effects and long-term effects (Shukla et al. 2009), including immediate annoyance and, over time, temporary or permanent loss of hearing (Wikipedia 2011). Because of the sensitivity of human hearing, it is estimated that prolonged exposure to noise at 50–95 dB can damage hearing, and at the least will be annoying (Williams 2009), and noise is considered potentially hazardous when levels exceed 85 dB over eight hours' exposure per day (ILO 2009). "When people are crowded into a small place noise can have an effect on a person's behavior and attitude" (Gradua Networks 2011). The WHO (1995) distinguishes the adverse effects of noise pollution on human health into seven categories, noting that "lack of concentration followed by irritation, fatigue and headache" are most commonly manifested (Joshi et al. 2003). the WHO has also estimated that noise pollution contributes to premature deaths from accidents and accounts for 3 % of deaths from ischemic heart disease among Europeans (Highfield 2011). In Canada, there is an inverse relationship between noise levels due to traffic density and number of frog species, and in the Amazon, terrestrial insectivores, which use sound in hunting their prey, have been found to avoid locations of road construction (Daily Planet Media 2007).

This article discusses the impact of intercity transportation connections on environmental noise pollution in Greater Khartoum, using Josse's (1972) model for predicting noise levels in cities that do not have empirical traffic-noise data. I first outline the research methodology by explaining why Josse's model was used rather than other models, then review the results of applying this model in each of the three towns in Greater Khartoum and showing the contribution of intercity transportation connections to changing levels of noise pollution in each of the three towns. Results are then discussed, conclusions are drawn, and a plan is proposed for curbing noise pollution in Greater Khartoum.

Background: Noise-Prediction Models

There are numerous models for predicting the contribution of public transportation vehicles to the total level of noise pollution in urban areas. These mathematical models are used to determine equivalent noise level (Leq), considered the most representative physical variable quantifying noise emissions. The Leq corresponds to the sound pressure of a stationary noise source emitting the same acoustic (audio) energy as the actual non-stationary source. The equivalent continuous noise level in A-weighted decibels (dB(A)) is widely recognized as a stable descriptor of motor-vehicle noise levels (Tarulescu 2007), recommended by many national and international regulatory agencies as a suitable index for use in assessing motor-vehicle noise. Leq is known to correlate well with known effects of environmental noise on the individual and the public. The physical parameters to which Leq is correlated include traffic intensity, type of road surface, type of urban area, height of buildings, and road width.

Mathematical models for predicting traffic noise usually extract the functional relationship between the parameter of noise emission, Leq, and measurable parameters of traffic and roads. The classical functional relationships have based on data measured through semi-empirical models, typically regression analysis. Although these correlations are nonlinear, they do not provide a very accurate approximation of the trend followed by sound pressure level according to a certain number of physical parameters, because any model itself includes the flow and composition of road traffic, which may be different from those examined in urban areas. Of all the mathematical models available in the literature, those that present this feature are proposed by Josse (1972), Burgess (1977), and Fagotti and Poggi (1995). These functional relationships are essentially based on regression techniques:

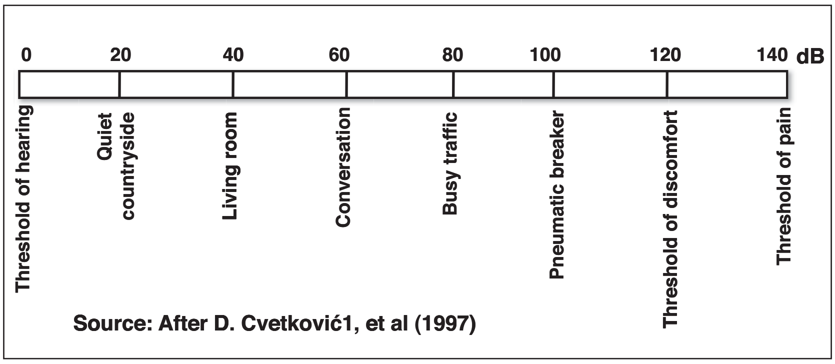
$$Leq = 55.5 + 10.2 \log Q + 0.3p - 19.3 \log (L / 2) \text{ (Burgess 1977)}$$

$$Leq = 38.8 + 15 \log Q - 10 \log L \text{ (Josse 1972)}$$

$$Leq = 10 \log (Nc + Nm + 8Nhv + 88Nb) + 33.5 \text{ (Fagotti and Poggi 1995)}$$

Here p is the percentage of heavy vehicles, L is road width, Q is the total number of vehicles per hour, Nc is the number of light vehicles per hour, Nm is the number of motorcycles per hour, Nhv is the number of heavy vehicles per hour, and Nb is the number of buses per hour. The total number of vehicle per hour, Q, is expressed as the equivalent number of cars and obtained under the assumption that one heavy vehicle is equivalent to six light vehicles and one motorcycle to three light vehicles.

FIGURE 1



Typical examples of levels of noise pollution (after Cvetković, Praščević, et al. 1997)

Cvetković, Praščević, et al. (1997) document typical examples of noise levels in 20-dB intervals, ranging from 0 to 140 dB (see Figure 1). For example, 0–20 dB is the noise level of quiet countryside; 40–60 dB, of conversation; 60–80 dB, busy traffic; 100–120 dB is the threshold of discomfort, and 120–40 dB the threshold of pain.

Data and Methodology

Greater Khartoum consists of Khartoum, Omdurman, and Khartoum North towns. The history of Khartoum town began under Turko-

Egyptian rule in the 19th century; in the early 20th century, Anglo-Egyptian rule re-established it as the capital of the Sudan (Walsh et al. 1994). Khartoum began as a narrow strip limited to the south by the railway station, to the east and north by the Blue Nile, and to the west by the White Nile. Old native villages spread to the south of the railway station. Omdurman, surrounded by the desert to the west and south, the Sabalouqa mountains to the north, and the Nile to the east, developed in a narrow strip along the Nile, centred on the Imam Mahadi Tomb (Abu Saliem 1970). Khartoum North began on the fringe of the right bank of the Blue Nile, in a small strip centred on certain government departments

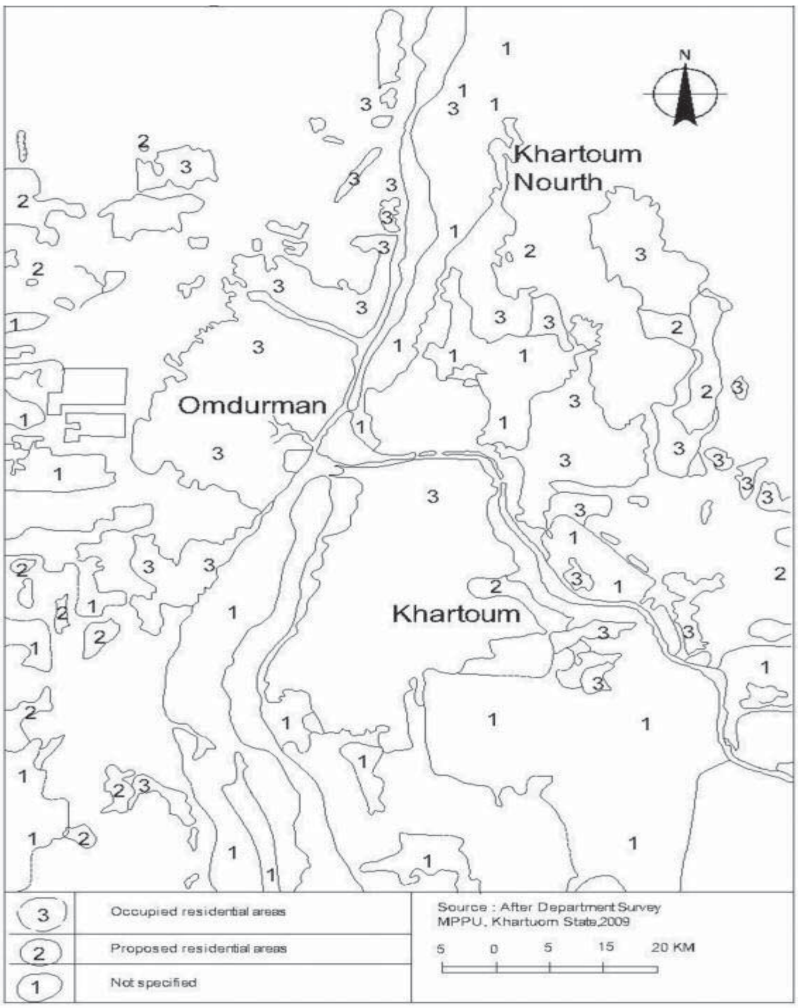


FIGURE 2
Greater Khartoum in 2008

(Gleichen 1905). Old villages were distributed along the Nile and the Blue Nile. Over time, Greater Khartoum grew through new residential urban plans and unofficial land sales by the native population (see Figure 2).

The occupied areas of Greater Khartoum are indicated by (3) in Figure 2; proposed residential areas are indicated by (2). These proposed residential areas appear very small relative to the occupied areas, which may be because the majority of urban plans proposed have been executed, becoming part of the urban area shown in Figure 2, or because of the new government policy to halt further allocation of urban land to individuals. Huge areas are given to public and private companies to invest in housing as part of the new investment trend in urban land use. These companies, in turn, sell urban land to individuals at higher prices. Some areas in Figure 2 are indicated as "not specified" (1); this category includes land allocated to miscellaneous agricultural and military uses, as well as areas occupied by squatter settlements, according to our 2009 fieldwork.

Data on the number of minibus (MB) and transportation lines, confined to the year 2009, were collected from the Department of Public Transportation and Petroleum in Khartoum town. These data relate to MB with a passenger capacity of 15–25 persons, which are the main form of public transportation in Khartoum town and operate for long hours each day. No field measurements of noise levels were collected, since the prediction models usually do not require this for cities that do not have empirical data on traffic-noise levels.

Our fieldwork, conducted in June 2009, first distinguished transportation network components: central bus stations, first-order transportation stations, transportation lines, and transportation axes. There is only one *central bus station* for MB convergence and divergence in each of the three towns; these are located at the heart of each city. *First-order transportation stations*, located on the main transportation axes, have developed with the expansion and growth of Greater Khartoum. They are central markets for their neighbourhoods and nuclei for the future emergence of new central bus stations. A *transportation line* is a line connecting a central or first-order bus station with one destination; a *transportation axis* contains many transportation lines, which are progressively reduced with distance up to the final destination.

No sampling procedure was used in choosing either main transportation axes connecting parts of each town together or transportation lines connecting first-order transportation lines together or with central bus stations; the entire network of main transportation axes and lines in each community is taken into consideration. In Khartoum town, there are four main axes; Omdurman has five, and Khartoum North has two.

Five axes connect the Khartoum central station with Omdurman, four connect the Khartoum central station with Khartoum north, and two connect the Khartoum North central station with Omdurman. Sequential numbers were assigned to axes and transportation lines, first to those operating within each town, then those connecting the three towns, and finally those connecting first-order transportation stations together.

Road width was estimated by travelling on the transportation network and based on data provided by the Road Authority of Khartoum town in 2009. Based on observation and interviews with some MB drivers, it was estimated that on average, the MB made 20 round-trip journeys per 12-hour working day.

Prediction models for noise pollution proposed by Burgess (1977) and Fagotti and Poggi (1995) require miscellaneous data on the percentage of heavy vehicles, the total number of vehicles per hour, and the number of light vehicles, motorcycles, heavy vehicles, and buses per hour; these models are designed primarily for the developed world, where sophisticated data are available to feed into them. Such data are difficult to obtain in the developing world, including Sudan; we therefore chose to use the mathematical model for noise-level prediction proposed by Josse (1972), which requires data only on number of vehicles per hour (which can be estimated through simple fieldwork) and road width (easy to access in official Transportation Authority records). The less demanding data requirement does not reduce the performance and reliability of Josse's model for application in the developing world. Josse's model states:

$$Leq = 38.8 + 15\log Q - 10\log L$$

Where Q is the total number of vehicles per hour and L is the road width.

The value of Q is obtained by multiplying the total number of MB by the total number of journeys per day, expressed mathematically as ($n \times 20/12$). Equivalent noise level (Leq) is the predicted noise level in dB.

The typical examples of noise levels described by Cvetković Praščević, et al. (1997) and illustrated in Figure 1 were used as a reference guide to categorize our fieldwork results for Greater Khartoum. Predicted values for noise levels were calculated for each town by transportation axes and lines. The values showing the impact of intercity transportation connections on predicted noise levels were obtained by subtracting these values from the values calculated for pre-intercity transportation connections.

Mean, median, range, standard deviation, relative variability, coefficient of variation, and analysis of variance (ANOVA) were calculated in order to depict the general situation and the statistically significant differences in noise levels within Greater Khartoum. For the ANOVA, level of significance was set at $p = 0.05$; the null hypotheses (that there are no statistically significant differences in levels of noise pollution between and within the three towns) is rejected if the calculated F-value is greater than the critical value of F for the chosen level of significance.

Results

The Transportation Network of Greater Khartoum

The transportation network of Greater Khartoum coincides with its history. Each town has a central bus station, from which emerge major transportation axes, as illustrated by names and axis numbers in Table 1 and Figure 3. Thanks to rapid urban growth in Greater Khartoum, first-order transportation stations are as important as central bus stations. In Khartoum these stations are Klakla Lafa, Suq Shabi, Suq Mrkazi, and Mina Bari; in Omdurman, Suq Shabi and Suq Libya; and in Khartoum North, Suq Mrkazi and Kuku (see Figures 3 and 4). Small focal points have developed on these main transportation axes, such Mayou, Soba, and Jebel Awlia (see Figures 3 and 4).

In Greater Khartoum, there are 124 transportation lines and 8 228 MB (locally called *Hafilat*) operating over 329 km with a mean road width of 3.5 m per direction (7 m total). In Khartoum town, there are 38 transportation lines and 2 116 MB operating over 4 major transportation axes (numbers 1–4 in Table 1 and Figure 3), with a total road length of 93 km. Axis 1 goes south to Jebel Awlia, and axis 2 south-east to Mayuo. Axis 3 goes east to Buri suburb and then turns south to Mujahedien. Axis 4 goes south-east to Soba. In Omdurman there are 53 transportation lines and 5 179 MB operating over five major axes (numbers 5–9 in Table 1 and Figure 3), with a total road length of 134 km. Axis 5 goes west and south-west to Um Beddah; axis 6 goes south to Muradah, Muhandesien, and el Salha up to Gumoia. Axis 7 goes north to Karary, and axis 8 north-east to Gamier. Axis 9 goes north-west to El Thwrat. From Khartoum North (Bahri) central station emerge 17 transportation lines with 761 MB operating over 57 km of road to serve 2 major axes (numbers 10 and 11 in Table 1 and Figure 3). Axis 10 goes north to el Gaily, while axis 11 goes north-east to Haj Yousif.

Intercity Transportation Connections by Central Station

The three towns are connected from Khartoum's central station (see Table 2 and Figure 3) by means of 4 248 MB making a total of 6 140 journeys per day over roads with a mean width of 3.5 m. From Khartoum Central Station emerge five axes (numbered 12–16 in Table 2 and Figure 3) serving Omdurman, with 2 210 MB connecting to the internal trans-

TABLE 1
Transportation axes in Greater Khartoum, 2009

Towns and transportation axes (with sequential numbers)	Total mean road width (m)	No. MB	Q = *n* × 20/12	mean (Leq) (dB)
Khartoum				
(1) City centre to Jebel Awlia	8.0	442	736.6[1000]	69.4
(2) City centre to Mayuo	8.0	812	1 353.3	73.4
(3) City centre to Buri suburb and Mujahedien	8.0	572	953.3[1000]	71.2
(4) City centre to Soba	8.0	110	183.3	60.4
Total		2 116	3 526.6	68.6
Omdurman				
(5) City centre to Um Beddah	8.0	1 780	2 966.6	78.5
(6) City centre to el Salha and Gumoia	8.0	925	1 541.6	74.3
(7) City centre to Karary	8.0	803	1 338.3	73.4
(8) City centre to Gamier area	6.0	69	115	58.6
(9) City centre to El Thwrat	8.0	1 602	2 670	77.9
Total		5 179	8 631.6	72.5
Khartoum North				
(10) City centre to El Gaily	8.0	562	936.6	71.1
(11) City centre to Haj Yousif	8.0	199	331.6	64.3
Total		761	1 268.3	67.7

portation network there. Transportation line 12 connects the two city centres; axis 13 goes to southern Omdurman, while axis 14 goes to western Omdurman, where it joins axis 5 and crosses axis 6 to boost axis 13. Axes 15 and 16 meet in central Omdurman to join axes 7–9, then travel to the northern and north-western parts of the town. Khartoum Central Station connects to Khartoum North via four axes (numbered 17–20 in Table 2 and Figure 3), which together add 956 MB to the internal transportation network there. Axis 17 connects the two city centres; Axis 18 goes eastward to connect with axes 20 and 11 in Kuku. Axis 19 goes

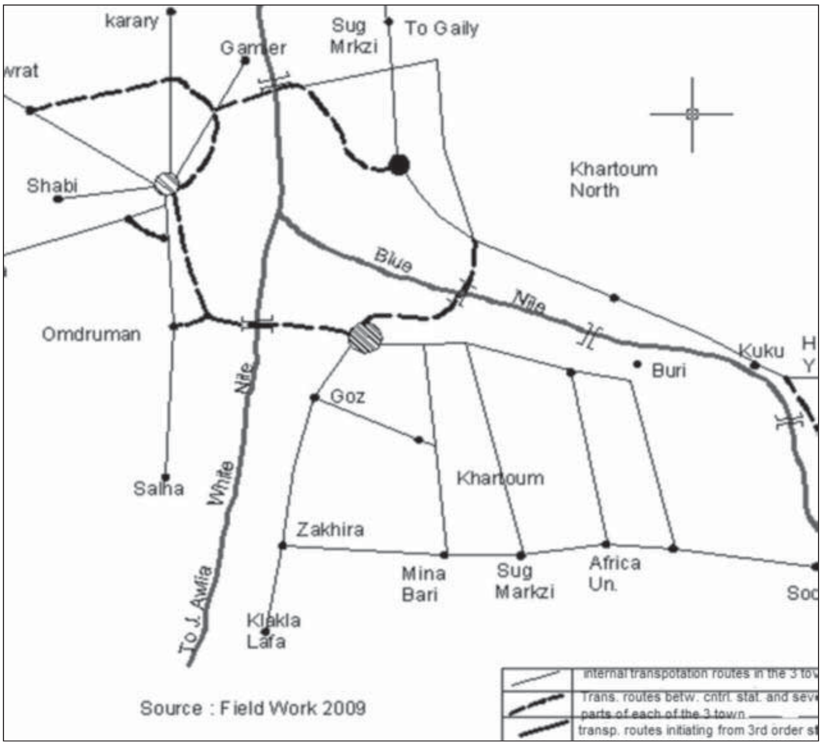


FIGURE 3
Transportation network for Greater Khartoum

north, crossing axis 10 at Khartoum North Central Station, while axis 20 goes south-east to connect with axis 19 in Kuku. Axis 20 has two first-order transportation stations, one at Kuku and the other connecting with Munshia Bridge (see Figure 3). In addition, Khartoum North and Omdurman are connected by two transportation axes (labelled 21 and 22 in Table 2 and Figure 3). Axis 21 links the two central stations and, at Shambat Bridge, joins with all transportation axes and lines going to and coming from Omdurman (see Figure 3). It also crosses axes 8, 15, 16, 24, 25, and 34. Axis 22 goes to El Thwrat, accompanying axes 21 and 16 to their final destination.

Intercity Transportation Connections by First-Order Transportation Station

First-order transportation stations serve intercity connections with 1 040 MB making 1 963 journeys per day (see Table 3 and Figure 4), equalling 25 % of all MB journeys per day in Greater Khartoum. Many

TABLE 2

Transportation connections between Khartoum Central Station and Omdurman and Khartoum North, 2009

Connections (with sequential numbers)	Total mean road width (m)	No. MB	Final destination (station name)	Q = $n \times 20/12$
Khartoum Central to Omdurman				
(12) Central	8.0	436	Omdurman Central Station	726
(13) Southern	6.0	427	Gamoui	710
(14) Western	8.0	456	Muialih	760
(15) Northern	8.0	285	Kulia Harbia	475
(16) North-western	8.0	606	Sabrien	1010
Total		2 210		3 581
Khartoum Central to Khartoum North				
(17) Central	8.0	120	Bahri Central Station	200
(18) Eastern	8.0	181	Haj Yousif Wihda	301
(19) Northern	8.0	465	Kadaro	775
(20) South-eastern	8.0	192	Eisailat	320
Total		956		1 596
Khartoum North Central to Omdurman				
(21) Omdurman Central	8.0	150	Shouhada	250
(22) El Thwrat	8.0	50	Sabrien	83
Total		200		333
Grand total		3 208		4 177

transportation lines connect these stations with central bus stations and other transportation stations in Greater Khartoum (see Figure 4). Khartoum North Central Station is connected to Suq Shabi Khartoum by 23 MB; at the University of Khartoum underpass, near the Blue Nile Bridge (see Figures 3 and 4), the route connects to axes 17, 18, 19, and 20. At Suq Shabi Khartoum, this transportation line meets axis 2 and transportation lines to and from Omdurman. Similarly, Khartoum North Central Station is connected with Mina Bari by 113 MB; this route meets the axis going to Mayou and Klakla Lafa to join axis 1 there. From Mina Bari emerge two transportation lines reaching Hilal Stadium Omdurman and El Thwrat. The transportation line reaching Suq Shabi Omdurman meets axis 5 and axis 14; it also crosses axes 6–9 in Omdurman. The line that goes to El Thwrat boosts all axes coming from Khartoum Central Station. Two transportation lines also depart from Suq Shabi Omdurman, travelling to Mina Bari and Suq Mrkazi Bahri. The first line meets axes 2 and 5 and crosses axis 1; the second connects with axes 5 and 3 and crosses axis 11. In addition, Suq Shabi Khartoum connects with Suq Libya, and this line meets axis 1. From Mina Bari, another five lines originate to connect with first-order transportation stations in

TABLE 3
Transportation lines between first-order transportation stations in Greater Khartoum, 2009

Name of transportation line (origin–destination), with sequential number	No. MB	Total mean road width (m)	Q = *n* × 20/12
(23) Shabi Omdurman–Mina Bari	210	8.0	350
(24) Shabi Omdurman–Suq Mrkazi Bahri	100	8.0	166
(25) Shabi Omdurman–Bahri	41	8.0	68
(26) Shabi Khartoum–Suq Libya	67	8.0	111
(27) Shabi Khartoum–Bahri	23	8.0	38
(28) Mina Bari–Suq Mrkazi Bahri	100	8.0	166
(29) Mina Bari–Suq Libya	25	8.0	41
(30) Mina Bari–El Thwrat	38	8.0	63
(31) Mina Bari–Hilal Stadium	132	8.0	220
(32) Mina Bari–Klakla Lafa	200	7.0	333
(33) Mina Bari–Haj Yousif	70	7.0	116
(34) Haj Yousif–Suq Libya	150	8.0	250
(35) Klakla Lafa–Suq Libya	25	8.0	41
Grand total	1 040		1 963

Omdurman and Khartoum North. The transportation line connecting Mina Bari with Suq Mrkazi Bahri meets axes 17–20 at the University of Khartoum underpass. Mina Bari is also connected directly with Suq Libya; this line meets axes 1, 6, 5, and 12–16 at Ingaz Bridge (see Figure 3). The two transportation lines that reach El Thwrat and Hilal Stadium use 170 MB and connect with axes 12–16 at Ingaz Bridge, thereafter bifurcating into northbound and north-west-bound transportation lines. Moreover, a line connects Mina Bari with Klakla Lafa to meet axis 1 at Zakhera (see Figure 3). Klakla Lafa is also connected directly with Suq Libya, and consequently connects axes 11 and 5 there. Transportation line 33 links Mina Bari and Haj Yousif and meets axes 17–20 at the University of Khartoum underpass; it also meets axis 11 and lines 34 and 35 at Kuku (see Table 3).

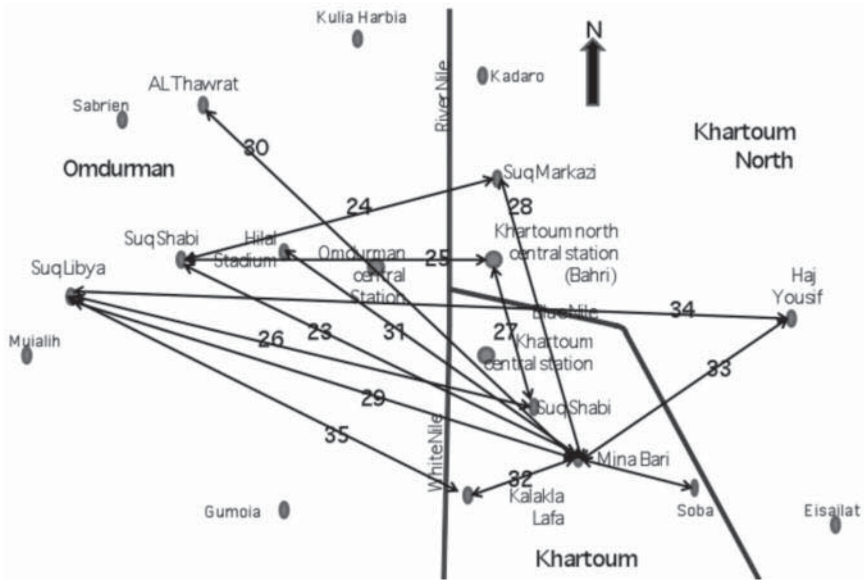


FIGURE 4
Sketching transportation lines linking first-order transportation stations in Greater Khartoum

Geography of Noise Pollution by Town in Greater Khartoum

Minibuses contribute a mean of 69.6 dB to the total noise level in Greater Khartoum. This value places Greater Khartoum almost in the category of "busy traffic," according to the typical examples of noise levels shown in Figure 1, and exceeds the safe urban noise level of 45 dB recommended by the WHO. Omdurman has the highest MB noise level, at 72.5 dB, followed by Khartoum (68.6 dB) and Khartoum North (67.7 dB; see Table 1). In Khartoum town, if axes are ranked by noise level, axis 2 is highest, followed by axes 3, 1, and 4; in Omdurman, the ranking is axis 9, 5, 6, 7, and 8; and in Khartoum North axis 10 has the highest noise level, followed by axis 11 (see Table 1).

Table 4 summarizes results for the description of noise levels by transportation axis in the three towns. By mean and median noise-level values, Omdurman ranks first, then Khartoum and Khartoum North. The tendency of values to cluster around the mean or the median do not differ among towns. Measures of dispersion (range, SD, relative variability, and coefficient of variation) given in Table 4 relate to differences between the mean and median noise-level values within each town. The range values are quite large in Khartoum and Omdurman (13 and 19.9, respectively) but small in Khartoum North (6.8). Although the means and standard deviations shown in Table 4 suggest minor differences

TABLE 4
Summary of results for description of noise-level data in the three towns of Greater Khartoum, 2009

	Khartoum	Omdurman	Khartoum North
Mean (dB)	68.6	72.5	67.7
Standard deviation (dB)	5.7	8.1	4.8
Maximum	73.40	78.50	71.10
Minimum	60.40	58.60	64.30
Range	13	19.9	6.8
Median	70.3	74.4	67.7
Relative variability	<0.06	0.06	<0.06
Coefficient of variation	8.3%	11.1%	7.0%

between the three towns, the differences in range values indicate a wide dispersion of the values of noise levels within and between the transportation axes in each of the three towns.

Combining measures of central tendency (e.g., mean and median) and measures of dispersion in the variability index allows us to consider the dispersion of distribution of noise levels by axis in relation to the average value in Greater Khartoum. In Table 4, the values of relative variability and coefficient of variation show steady differences between the three towns. These values could lead us to conclude that there is an uneven distribution (i.e., differences) of levels of noise pollution in Greater Khartoum. But does this uneven distribution achieve statistical significance? Table 5 shows the analysis of variance conducted to answer this question (significant at $p = 0.05$). The calculated value of the F-ratio is found to be 1.79, less than the critical value of 4.46. We must therefore conclude that there are no significant differences between the three towns in terms of levels of noise pollution.

The Impact of Intercity Transportation Connections on Noise Pollution

Traffic noise levels attributable to road-network additions in areas of Greater Khartoum are illustrated in Tables 6a–6c. Intercity transportation connections between Khartoum and the towns of Omdurman and Khartoum North (Table 6a) have led to the appearance of the new transportation line linking Khartoum central station with Ingaz Bridge (Figure 3), which includes axes and transportation lines numbered 12–16, 23, 26, 29–31, and 35 (Tables 2 and 3, Figures 3 and 4). The predicted noise on this line is 81.29 dB—the highest level recorded in Greater Khartoum. Intercity transportation connections have also added 5 dB to the portion of axis 1 between Khartoum Central Station and Goz (see Figure 3) as a result of the influence of transportation lines 23, 26, 29–31, and 35 (see Figure 4) and 2.8 dB to the portion between

TABLE 5

Analysis of variance (ANOVA; significant at $p = 0.05$) for noise-level data in Greater Khartoum's three towns

Khartoum (A)	Omdurman (B)	Khartoum North	Khartoum		Omdurman		Khartoum North	
x	x	x	$x - \bar{x}$	$(x - \bar{x})^2$	$x - x$	$(x - \bar{x})^2$	$x - \bar{x}$	$(x - \bar{x})^2$
69.4	78.5	71.1	0.8	0.64	6	36	3.4	11.56
73.4	74.3	64.3	4.8	23.04	1.8	3.24	-3.4	11.56
71.2	73.4		2.6	6.76	0.9	0.81		
60.4	58.6		-8.2	67.24	-13.9	193.2		
	77.9				5.4	29.16		
274.4	**362.7**	**135.4**		**97.68**		**262.42**		**23.12**

$n = 4$	$n = 5$	$n = 2$	Within-group ANOVA = 47.90
$\bar{x} = 68.6$	$\bar{x} = 72.5$	$\bar{x} = 67.7$	Between-group ANOVA statistics: Grand mean = 69.6; Khartoum $\bar{x}$ = ?????; Omdurman $\bar{x}$ = 42.05; Khartoum North: $\bar{x}$ = 7.22 Estimate between-groups ANOVA = 26.63, F (47.90,26.63) = 1.79; significant level set at p = 0.05; critical value = 4.46 1 degrees of freedom for between-groups estimate of variance = 8 2 degrees of freedom for within-group estimate of variance = 2

Goz and Klakla Lafa by means of transportation lines 35 and 32 (see Figure 4). These new additions raise noise levels to 74.4 dB and 72.2 dB, respectively, for these two portions of axis 1.

Transportation connections between Khartoum and Omdurman are represented by the transportation line linking Goz and Suq Shabi Khartoum (see Figure 4), which contributes 69.9 dB. Because some transportation lines first reach Suq Shabi Khartoum, then continue to Mina Bari, they add 1.4 dB to the line Suq Shabi Khartoum–Mina Bari on axis 2, raising the noise level by 0.6 dB, from 73.4to 74.8 dB. The portion of axis 2 between Khartoum Central Station and Khartoum Hospital also grew by 1.8 dB thanks to intercity transportation connections between Khartoum and Khartoum North on axes 18, 20, and 28 (see Figure 3). Because axis 3 meets axes and transportation lines 17–20, 27, and 28, bound for Khartoum North, at the University of Khartoum underpass (see Figures 3 and 4), we find that the portion between Khartoum Hospital and the underpass (inlet to the Blue Nile Bridge) has risen by 6.7 dB, to record a new noise level of 77.9 dB instead of 71.2 dB. The noise level has also changed on axis 4 from 60.4 dB to 66.5 dB with the addition of 6.1 dB from transportation lines 28 and 33 (see Figure 4) linking Mina

TABLE 6a

Levels of noise pollution (in dB) in Khartoum attributable to transportation connections with Omdurman and Khartoum North, 2009

Khartoum Town	Axes and lines by number	No. of MB operating locally	Leq (dB)	Total No. of MB (operating locally + connecting)	current Leq (dB)	Difference (dB)
Khartoum central–Ingaz bridge	12, 13, 14, 15, 16, 23, 26, 29, 30, 31, 35	2 709	–	–	–	–
Axis 1a: Khartoum Central–Goz crossing	23, 26, 29, 30, 31, 35	497	69.4	939	74.4	5.0
Axis 1b: Goz crossing–Klakla Lafa	32, 35	225	69.4	667	72.2	2.8
Axis 1c: Goz crossing–Suq Shabi Khartoum	23, 26, 29, 30, 31	472	–	–	–	–
Axis 2a: Khartoum Central–Khartoum Hospital	18, 20, 28,	473	77.41	1 967	79.2	1.8
Axis 2b: Suq Shabi Khartoum –Mina Bari	29, 30, 31	195	73.4	1 007	74.8	1.4
Axis 3: Khartoum Hospital–University of Khartoum underpass	17, 18, 19, 20, 27, 28	1 079	71.2	1 615	77.9	6.7
Axis 4	28, 33	170	60.4	280	66.5	6.1

Bari, Suq Mrkazi Bahri, and Haj Yousif (see Figure 4).

Table 6a near here please

Intercity transportation connections between Omdurman, Khartoum, and Khartoum North (Table 6b) have produced new transportation axes and lines. The new transportation line connecting Ingaz bridge with Omdurman locality headquarters (HQ) on axis 12 (see Figure

TABLE 6b
Levels of noise pollution in Omdurman attributable to transportation connections with Khartoum and Khartoum North, 2009

Omdurman Town	Axes and lines by number	No. of MB operating locally	Leq (dB)	Total No. of MB (operating locally + connecting)	current Leq (dB)	Difference (dB)
A: Ingaz bridge–Omdurman locality HQ	12, 15, 16, 30, 31	1 497	–	–	–	–
B: Ingaz bridge–Muhandiesin (crossing axis 6)	13, 14, 23, 26, 29, 35	1 210	–	–	–	–
C: Muhandiesin–Omdurman Central	14, 13, 23, 26, 29, 35	1 210	74.3	2 135	79.7	5.4
Axis 5	13, 26, 29, 34, 35	694	78.5	2 474	80.7	2.2
Axis 7	15	285	73.4	1 088	75.3	1.9
Axis 8	21	285	58.6	354	68.0	9.4
Axis 9	16, 22, 30	694	77.9	2 296	80.2	2.3
Azhari crossing	21, 22, 24, 25, 30, 31, 8, 21, 15, 16	1 621	–	–		77.94

3) recorded 77.42 dB thanks to transportation axes and lines 12, 15, 16, 30, and 31 (see Tables 2 and 3, Figures 3 and 4). Further, the new transportation line between Ingaz bridge and Muhandiesin on axis 6 (see Figure 3) recorded 76.04 dB due to the addition of noise from transportation axes and lines 13, 14, 23, 26, 29, and 35 (see Tables 2 and 3, Figures 3 and 4). Muhandiesin–Omdurman Central has risen by 5.4 dB due to the influence of transportation axes and lines 14, 13, 23, 26, 29, and 35 (see Figures 3 and 4), and transportation axes and lines 14, 13, 23, 26, 29, 35 (Figures 3 and 4) have added 2.2 dB to axis 5 (see Table 6b). Axis 8 has accepted 9.4 dB more as a result of axis 21 (see Figure 3); similarly, Axis 9 has added 2.3 dB due to the influence of axes 16 and 22 (see Figure 3) and transportation line 30 (see Figure 4), to be ranked the second noisiest in Greater Khartoum after Khartoum Central Station–Ingaz Bridge (see Figure 3). Because the Alazhari roundabout is a confluence for many transportation axes and lines (including 21, 22, 24, 25, 30, 31, 8, 21, 15, and 16) that connect Omdurman with Khartoum and Khartoum North,

TABLE 6c
Levels of noise pollution in Khartoum North attributable to transportation connections with Khartoum and Omdurman, 2009

Khartoum North (Bahri)	Axes and lines by number	No. of MB operating locally	Leq (dB)	Total No. of MB (operating locally + connecting)	current Leq (dB)	Difference (dB)
Axis 10	19	465	71.1	1 027	74.9	3.8
Axis 10: Mouasasa crossing	10, 19, 21, 24, 34	1 427	71.1	1 989	79.3	8.2
Axis 11a: Bahri central–Blue Nile Bridge crossing	17, 19, 28	685	64.3	884	73.9	9.6
Axis 11b: Kober–Hilat Kuku	18, 20, 33, 34	593	64.3	792	73.3	9.0
Axis 11c: Hilat Kuku–Suq Wihda	33, 34	230	64.3	429	69.3	5.0

the noise level here is as high as 77.94 dB.

The impact of intercity transportation connections between Khartoum North and the towns of Khartoum and Omdurman is shown in Table 6c. Axis 10 (Figure 3) has increased by 3.8 dB due to axis 19, raising the noise level from 71.1 dB to 74.9 dB; in addition, axis 10's meeting with transportation axes and lines 10, 19, 21, 24, and 34 (Figures 3 and 4), going to and from Omdurman, had added 8.2 dB to the previous noise level, raising it to 79.3 dB.

Over the length of axis 11, many noise-level additions are detected. First, axis 11 connects with axes and lines 17, 19, and 28 (see Figures 3 and 4), coming from Khartoum, at the Blue Nile Bridge, adding 9.6 dB to the previous noise level. Second, it is boosted further at Kober when it meets axes and lines 18, 20, 33, and 34 going to the east Nile areas, reaching Kuku (see Figures 3 and 4), to add 9.0 dB more. Finally, this axis meets transportation lines 33 and 34, going to Mina Bari and Suq Libya, which add a further 5 dB.

Discussion

Three interrelated transportation connections (intra-city, intercity, and first-order transportation stations) currently serve Greater Khartoum's population. The locations of central bus stations reflect British planning of modern Khartoum and Khartoum North (El-Bushra 1976). The number of minibuses operating in Greater Khartoum is related to the population served. The rate of population growth for the three towns was 4.92 % in 1956 and had increased to 13.7 % by 1993 (MFEP 1956–93); population density was 55.6 persons per km^2 in 1973, and increased to 85.5/km^2 in 1983 and 169/km^2 in 1993 (MFEP 1956–93). Khartoum also accepted significant internal migration: of all internal migrants in Sudan, 39 % in 1983 and 45 % in 1993 came to Khartoum (MFEP 1956–93). Since Greater Khartoum is drawing resources from other regions of Sudan, it is expected that urban growth will accelerate, and population growth increases demand for public transportation. Over the next three decades, Africa's urban population is expected to more than double, from 294 billion to 742 million (UNFPA 2008). Urban growth has influenced the level of noise pollution within the three towns—particularly in Omdurman, which has the highest noise levels, since it occupied 1 321 820 person in 1993, projected to grow to 5 000 000 by 2010 based on the annual population growth rate of 13.7 % for Greater Khartoum in 1993, the most recent year for which published statistics are available (MFEP 1956–93).

Rapid urban growth in Greater Khartoum has stimulated the emergence of first-order transportation stations, developing as central bus stations on the peripheries of the three towns. These have been associated with the growth of informal settlements (Babker and Alredaisy 1997), thanks to increasing real-estate demand for housing (MFEP 1956–93). Local people in native villages on the fringes of the three towns have violated the land laws beause they consider land tenure to be a social relationship of appropriation and exclusion. Squatter settlements have developed along westward, south-westward, and northward axes from the fringes of central Omdurman to the margins of Kordofan state and Nahr el Nil state (Alredaisy and Davies 2003); southward and south-eastward from the fringes of central Khartoum to the borders of White Nile and Gezira states; and northward from central Khartoum North to the margins of Nahr el Nil state and north-eastward toward the central Butana plain of eastern Sudan (El-Bushra 1995).

Although the population factor is important in noise pollution, as population growth increases the demand for transportation, government policy on the operation of public transportation is also a determining factor. In the past, the Khartoum state administrative authority operated public transportation; following economic inflation in Sudan and the devaluation of the Sudanese currency since the early 1980s, however, that role was transferred to the local people, who mainly own 15- to 25-passenger minibuses. Because taxi service is expensive, the problem of small passenger capacity and increasing population is solved by increasing the number of MB. Although there are differences in noise levels between the three towns, these are not statistically significant; this indicates that differences by axis are generally balanced when calculating the general value for a town, as well as that road width is not a factor, since roads are constructed to the same standards. Thus, the number of MB is the only influencing factor. Intercity transportation connections have added to the noise levels in all three towns.

The traffic-noise level in Greater Khartoum exceeds the 45 dB proposed by the WHO as the safe noise level for a city. Generally, road improvement has not kept pace with the number of additional vehicles. The effect of road width on increasing levels of noise pollution is evident within urban Khartoum (Alredaisy 2011). New bridges on the Niles will increase future connections because of recent distribution of economic activities within Greater Khartoum.

The noise level of 69.6 dB in Greater Khartoum compares favourably with some and less favourably with other urban centres worldwide. Metropolitan areas in India typically register average noise levels of >90 dB, and Mumbai is rated the third noisiest city in the world (Bhat 2009). According to Miglani (2011), "This type of noise can be augmented by narrow streets and tall buildings, which produce a canyon in which traffic noise reverberates." Similarly, noise levels in Delhi vary between 75 and 86 dB (Sangal 2000), while noise levels in Dhaka are far above the acceptable limit during the working day (Jobair et al. 2001). In Pakistan, Karachi faces the enormous problem of exceedingly high levels of traffic and maximum noise levels of 110 dB(A), recorded from auto-rickshaws, motorcycles, and minibuses (Muhammad et al. 2010); Lahore also recorded 110 dB (WHO 1997). In Iran, a study in Tehran gives an overall mean L_{Aeq} of 74.7 dBA (Mansour et al. 2006), while in Yazd in 2008 the minimum and maximum sound levels appeared to be 70.9 dBA and 80.7 dBA, respectively—above the nationally legislated norm (Nejadkoorki and Naseri 2010). A study of traffic-noise pollution in Brasov, Romania, recorded a median Leq that was frequently over 70 dB (Ţarulescu et al. 2007). In Belo City, Brazil, the average Leq for all urban zones was 69.5 dB; the noise of motor vehicles was found to be the major contributor to noise pollution (Alvares and Souza, n.d.). A study of environmental noise pollution in Curitibi, Brazil, found that 93.3 % of locations studied display extremely high Leq values, >65 dB (Henrique 2003). Another study of noise pollution recorded levels of 78.5 dB in London and 80.4 dB in Newcastle-upon-Tyne (Widex 2008); the WHO (1997) recorded 88 dB in Cairo and 74 dB in Amman. Quantifying noise pollution from urban traffic in Kahramanmaraş, Turkey, revealed that mean noise level exceeded national regulatory criteria and, at over half the locations studied, also exceeded international criteria (Doygun and Gurun

2007). In Australia, Sydney records more than 100 000 noise complaints a year, most relating to noisy neighbours; one of Melbourne's inner-city councils found that noise complaints more than doubled in 2000, after higher-density housing was permitted; and even in thinly populated Tasmania, approximately half of environmental complaints relate to noise (Australian Academy of Science 2011).

Conclusion and Recommendations

The general findings of this study are as follows:
Minibuses contribute significantly to noise pollution in Greater Khartoum.
Spatial variations in noise pollution are evident; noise levels are highest in central bus stations and along main transportation axes, and are increased by higher numbers of minibuses, higher numbers of journeys per day, and greater road width.
Intercity transportation connections have added considerably to noise pollution in Greater Khartoum.
Population growth, spatial expansion of cities, government policy on public transportation, and increasing rates of modernization have influenced the noise environment in Greater Khartoum.
This study, the first on the topic, makes a strong contribution to knowledge on urban noise pollution in Sudan. The study builds a strong case for curbing noise pollution in Greater Khartoum through a plan proposed by the author (see Figure 5). This plan includes main axes, the bodies responsible for its realization, and its time schedule. The main axes of the plan are the introduction of higher-capacity passenger vehicles with low-noise engines; the redistribution of central bus stations; transportation zonation; community education; legislation to limit noise levels; an increase in green areas; the redistribution of central markets; and enhancements to electronic government (see Figure 5). The bodies responsible for realizing this plan include the ministries of transportation, education, information, and justice, as well as the People's Committees at the community level. The time schedule consists of three phases for gradual implementations of the proposed axes in order to curb noise pollution in Greater Khartoum.

Introducing higher-capacity passenger vehicles with low-noise engines to replace existing low-capacity vehicles will reduce noise levels by nearly one-third, since each new vehicle will replace three existing vehicles, regardless of engine type. Redistribution of central bus stations and transportation zonation will divide the town into sectors and evenly redistribute public transportation vehicles. However, widening roads and solving traffic-congestion problems are integral parts of these three axes.

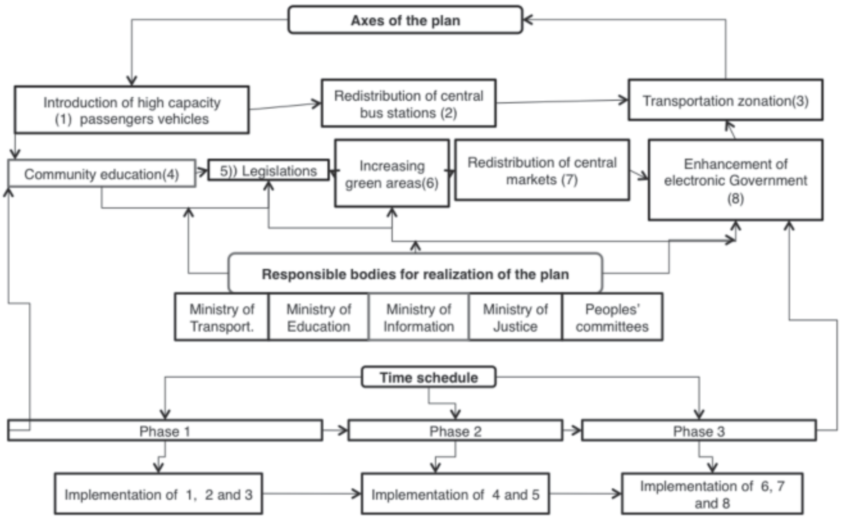


FIGURE 5
Plan to curb noise-pollution impacts in Greater Khartoum

Community education will inform people about transportation networks and the health hazards of noise pollution. Government legislation on permitted noise levels will protect related regulations on organizing transportation. Increasing green areas will reduce noise pollution, as has been confirmed worldwide (e.g., Samara and Tsitsoni 2007). Redistribution of central markets within the town will create new focal points that cut down population movement toward the city centre; the introduction of electronic government to provide services remotely will further enhance this effect.

Realizing this proposed plan depends on collective work by the ministries identified in Figure 5. Operating, modernizing, and organizing transportation network and vehicles is the responsibility of the Ministry of Transport, but this cannot be accomplished without education and media. Schools, TV, radio, and newspapers can transfer information and knowledge about transportation networks, traffic legislation, and the hazards of noise pollution. The Ministry of Justice protects legislation on permitted noise levels and executes penalties. The duties of People's Committees should focus on transferring information to local communities about transportation and noise health hazards through youth clubs and influential religious men and women in those communities.

Implementation of this plan needs to be phased in carefully. In the first phase, it is necessary to provide the infrastructure for curbing noise levels by introducing higher-capacity passenger vehicles with low-noise engines, redistributing central bus stations, and zoning Khartoum town.

The second phase involves raising community awareness about transportation, noise pollution, and legislation. The third phase includes increasing green areas, redistributing central markets within Greater Khartoum, and enhancing electronic government. By this means we can expect to reduce noise levels in Greater Khartoum. However, increasing Sudan's GNP by introducing petroleum exports, increasing the per-capita share of national income, and ending the war in southern and western Sudan would certainly open a more hopeful and promising future for the country as a whole, within which controlling noise and gas pollution in Greater Khartoum is possible.

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