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PASSENGER NOISE EXPOSURE IN LONDON UNDERGROUND

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1 INTRODUCTION

The London Underground network carries almost half of London's commuters, and is the most heavily used mode of public transport in London. Its routes are 402 km long in total and it is used by over 1.2 billion passengers annually[1].

Though very efficient and convenient, travelling by Tube can be a noisy experience which could have potential impact on commuters' hearing health. There is a wealth of research and information on impacts of occupational noise on hearing health. However, there is very little known on the potential impacts of transportation noise on passengers' hearing health.

The aim of this study is to determine and assess potential noise induced hearing loss caused by commuting on the London Underground when various practical noise exposure scenarios are considered.

2 BACKGROUND

2.1 Noise in London Underground

Previous studies of passengers' noise exposure in London Underground agreed that noise can reach potentially harmful levels. A study on the Victoria Line[2] conducted in 2004 reported the average values inside a train at levels of 88-89 dB L_{Aeq}. Later, a more detailed study[3] focused on the noise levels between stations while inside the trains. It reported that levels sometimes reached values above 85 dB LAeq for the duration of travel between adjacent stations. It was also shown that on average, noise levels inside subsurface trains are approximately 5 dBA higher than inside aboveground trains and levels inside deep level lines can be up to 10 dBA higher than aboveground. A more recent study[4] reported noise levels on London Underground platforms often exceeding 80 dB L_{Aeq} for the time it takes for a train to enter, board and depart from the station. The L_{Aeq} levels were shown to occasionally surpass 85 dB.

In contrast to previous and available research, this study not only considers specifically the noise exposure inside carriages or on the platforms. Instead, it takes into consideration complete journeys made on the noisiest routes of London Underground, from the entrance to the initial station, to the exit on the destination station. Moreover, a sound level meter more suited for noise exposure is utilized leading to less uncertainty and more reliability on the results obtained.
In addition, this study also compares noise exposure levels in London Underground against more sustainable means of transport – cycling.

2.2 Noise induced hearing loss

Noise induced hearing loss is defined as irreversible damage to the hearing ability caused by exposure to high levels of noise[5].

People exposed to noise can develop permanent hearing loss varying in severity depending on the level and duration of exposure. This disability can affect numerous aspects of their everyday life, including the impairment of speech communication, perception of acoustic warning signals and appreciation of music. Permanent damage to hair cells in the inner ear usually takes long time and is a progressive process. What follows is a raise of hearing thresholds along the audible frequency range, called Noise Induced Permanent Threshold Shift (NIPTS). However, before the permanent damage is done a reversible temporary effect on hearing, called noise-induced Temporary Threshold Shift (TTS) occurs[6]. According to Health and Safety Executive in Great Britain, some 17000 people in the UK suffer deafness, Temporary Threshold Shift (TTS) and Permanent Threshold Shift (NIPTS) as a result of exposure to excessive noise at work[7].

Noise exposure due to transportation noise, i.e. railway and traffic noise, has been reported to affect millions of people worldwide and has been related to various health related issues such as sleep disorder, fatigue, stress and even adiposity[8]. The workers of transportation industry have been identified as a group, which is often exposed to harmful levels of noise exposure exceeding 85 dB L_{Aeq}[9]. However, no research or data could be found on the potential risk of hearing loss of passengers using underground railway systems for commuting or travelling.

Methods for estimating a risk for noise induced hearing loss are described in a dedicated international standard[6]. The document applies to calculations of the risk of noise-induced hearing loss due to any daily repeated noise exposure. Calculations are based on statistical data and therefore cannot be applied to the prediction or assessment of hearing loss of individual persons except in terms of statistical probabilities. Results of studies following this standard are presented as minimum NITPS values for given percentage of population after certain duration of exposure.

In the absence of specific regulations, standards or guidelines recommending limits on noise exposure levels inside train carriages, occupational noise level limits and their estimated hearing health risk are considered in this study.

2.3 Noise exposure limits

Various occupational noise exposure values are suggested in the literature to correspond with high risk of hearing loss in different parts of the world. In Australia[10], for instance, the maximum allowed occupational noise exposure is limited to $L_{Aeq,8h}$ of 85 dB and L_{CPeak} of 140 dB. However, the same document states that '*over long periods, repeated noise exposure at between 75 and 85 dB may be a small risk to some people*'. In Canada[11] the maximum allowed ranges depending on part of the country between $L_{Aeq,8h}$ 85dB and 90 dB while the recommended L_{CPeak} limit is 140 dB.

World Health Organization states[12] that there is sufficient evidence showing that prolonged exposure to occupational noise at $L_{Aeq,8h}$ of 75 dB or higher can lead to hearing loss in adults. This level is confirmed as potentially harmful by BS ISO 1999:2013[6], which gives $L_{Aeq,8h}$of 75 dB as a value above which long exposure may lead to noise induced hearing loss.

In United Kingdom, the occupational noise exposure is regulated by Control of Noise at Work Regulations 2005[13]. The noise exposure limits set out by the regulations are summarized in table 1:

Table 1: Noise exposure limits from Control of Noise at Work Regulations 2005

	$L_{EP,d}$*	L_{CPeak}
Lower exposure action values	80 dBA	135 dBC
Upper exposure action values	85 dBA	137 dBC
Exposure limit values	87 dBA	140 dBC

*$L_{EP,d}$is a daily (8hours) personal exposure level and corresponds to $L_{Aeq,8h}$

3 METHODOLOGY

3.1 Measurements

Preliminary measurements were taken inside the trains on the noisiest six London Underground lines (Bakerloo, Central, Jubilee, Northern, Piccadilly and Victoria) in order to determine the noisiest routes. These routes then were used for complete journey measurements on which this study is based. Noise levels and corresponding noise exposure levels were measured between stations using a state-of-the-art personal noise exposure meter in two series for each measured part.
L_{Aeq} and L_{CPeak} parameters values were recorded. The author carried out the preliminary measurements by wearing the personal noise exposure (or dosemeter) meter on his left shoulder and sitting in a carriage seat closest to the doors.

The complete journey noise exposure measurements were taken in the same way as preliminary measurements. However, these included in the measurement period all parts of a typical journey. This included walking to the platform from the station entrance, waiting for the trains on the platforms, travelling inside carriages, walking on interchanges and walking to the exit from the station. Similarly as for preliminary measurements, L_{Aeq} and L_{CPeak} values were recorded in at least two series. Corresponding noise exposure values expressed as percentage of the Lower exposure action values were also provided and recorded by the dosemeter.

The complete journey study covered the noisiest routes identified in the preliminary measurements. These are listed below and shown graphically in Figure 1:

- Leytonstone – Paddington
- Morden – Leyton
- Canning Town – Queen's Park
- Leyton – White City
- Queen's Park – Leyton
- Leytonstone – Aldgate East

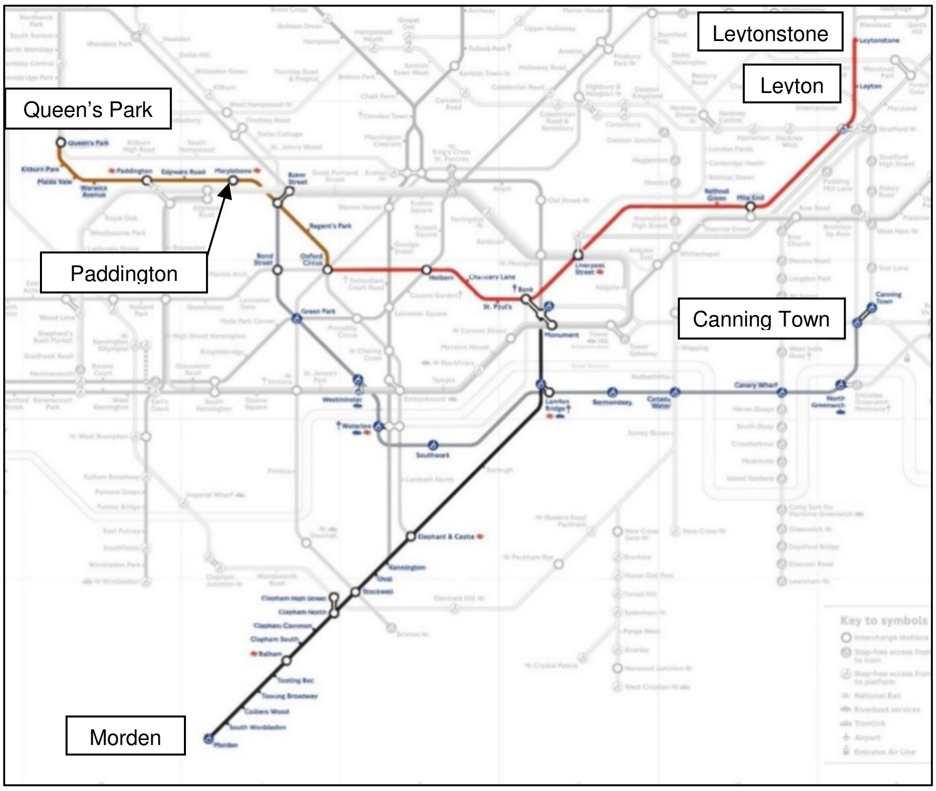

Figure 1: Complete journey routes

3.2 Buses and cycling

To compare the noise exposure levels for alternative ways of commuting, the daily commuting route taken on a daily basis by the author was measured using separately three different means of transport. London Underground, buses and cycling.

- **London Underground**: Journey made on the Central and District line trains between Leytonstone and Aldgate East stations. Measurements included 9 minutes' walk on the street each way between home and Leytonstone station and 6 minutes' walk each way between Aldgate station and work. The total journey time was 42 minutes each way.
- **Buses**: Journey by buses involved buses routes no. 257 and no. 25 and included 9 minutes' walk on the street from home to and from the bus stops. Measurements were taken while sitting on the top deck. The total journey time was 65 minutes each way.
- **Cycling:** Bicycle journey between the author's home and his workplace. The total journey time was 25 minutes each way.

For each survey conducted outside the London Underground, a windshield for a half-inch microphone was adapted to the personal noise exposure meter microphone opening in order to minimise potential wind noise. It was ascertained that the adapted windshield caused no sound attenuation.

3.3 Equipment used

For all the surveys sound pressure level measurements were taken using a sound level meter with dosimetry capabilities (dosemeter). At the beginning and at the end of each measurement session, the meter was calibrated using a calibrated Class 1 Casella CEL-120/1 calibrator.

The dosemeter used (SoundBadge[14]) is a modern 5 cm of diameter sound level meter designed as a personal sound exposure meter. It meets the specification for Class 2 instrument according to BS EN 61252:1997[15] and it comes prepared to be worn on the shoulder of the subject under study. It allows for monitoring and recording of different parameters simultaneously, such as L_{eq}, L_{Max}, L_{Peak} and stores data every 250 ms in both A and C weighting.

3.4 Calculations

Methods for determining occupational noise exposure are regulated in Europe and United Kingdom by *ISO 9612:2009*[13]. As there is no specific standard or guideline available for the determination of noise exposure of passengers due to transportation noise, *ISO 9612:2009* and Noise at Work Regulations have been employed for this study. *ISO 9612:2009* requires noise exposure levels to be given as $L_{EX,8h}$ – which is in effect A-weighted noise exposure level normalized to a nominal 8-hour working day. This parameter is equivalent to $L_{Aeq,8h}$ and $L_{EP,d}$ specified in the Control of Noise at Work Regulations 2005.
Three measurement strategies are described within *ISO 9612:2009.* Full-day measurement method has been chosen as most suitable for this study. The method is based on measurements which cover not only work related noise but also the periods of the day outside of work.

Though usually noise exposure commonly relates to occupational noise, the BSI ISO 1999:2013[6] mentions that hearing loss does not result from occupational noise alone, and that non-occupational noise exposure such as commuting, time spent at home and recreational activities should be taken into account for a more complete calculation of noise exposure.
Similarly, Control of Noise at Work Regulations 2005 suggest that commuting noise exposure can be considered in noise exposure calculations by stating: *"In these Regulations, a reference to an employee being exposed to noise is a reference to noise which arises while he is at work, or arises out of or in connection with this work"*[12].

The analysis of the impact of commuting by London Underground on passengers hearing health was based on ISO 1999:2013[5]. Noise Induced Permanent Threshold Shift (NIPTS) calculations were also performed in accordance with the procedure provided in this standard.

4 RESULTS ANALYSIS

4.1 Preliminary measurements

Preliminary measured data showed that certain parts of the London Underground are exceptionally noisy compared to overall noise levels on the London Underground. The part of the Central Line between Leyton and Bank stations was the noisiest of all the lines considered in this study. The journey between Leyton and Bank involving six stations took on average 12 minutes and measured $L_{Aeq,12min}$ = 90.9 dB (excluding the time waiting on the stations).

Figure 2 shows the results of the preliminary measurements on the Central Line. The L_{Aeq} values were normalized to 2 minutes, the average travel duration between the stations on this part of the Central Line.

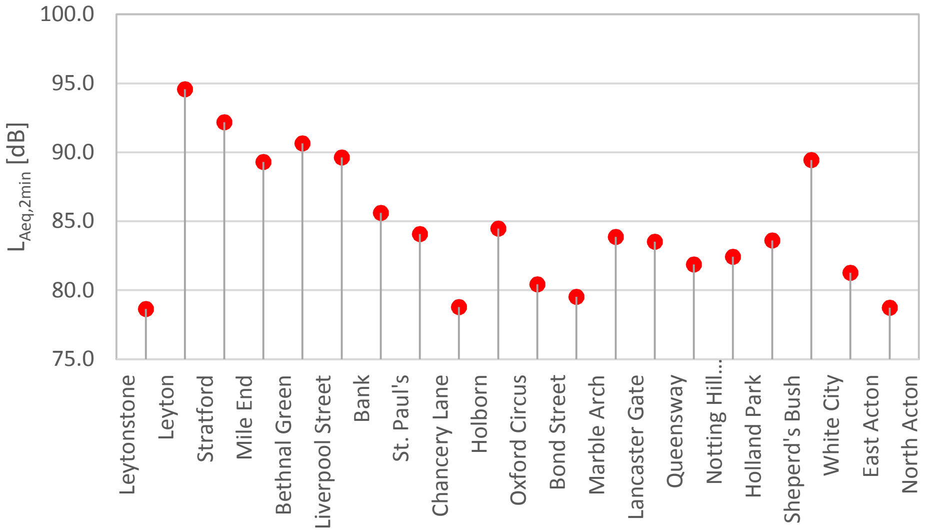

Figure 2: Preliminary measurements on the Central Line

4.2 Complete journey noise exposure measurements

Table 2 below compares the measured noise exposure levels on each of the routes against Control of Noise at Works Regulations 2005 limits. Measurements involved the two ways of a journey (onwards and return).

Table 2: Measured complete journey routes

Route	$L_{Aeq,T}$	Total Monitoring Duration (T)	L_{CPeak}	$L_{EX,8h}$	Lower action dose
Leytonstone - Paddington	85.5 dB	1:22 h	129.6 dB	78.1 dB	65 %
Leyton - Morden	84.3 dB	1:38 h	131.1 dB	77.8 dB	60 %
Leyton – Queen's Park	85.1 dB	1:26 h	127.9 dB	77.7 dB	59 %
Leyton – White City	85.2 dB	1:18 h	127.2 dB	77.5 dB	56 %
Canning Town – Queen's Park	85.2 dB	1:20 h	123.8 dB	77.4 dB	56 %

4.3 Impact of commuting noise

Occupational noise exposure assessment predictions can estimate the maximum time allowance for a noisy activity to be undertaken before the noise limits are reached. This time allowance would be affected by commuting noise exposure if its level is significant. Examples of assessments resulting in allowable time spent on certain construction related activities including commuting noise exposure are shown in table 3.

Table 3: Maximum allowable times for some noisy occupational activities

Equipment/activity	L_{Aeq}*	**Time needed for lower action values to be reached**	
		Without commuting	**Commuting included****
Hydraulic breaker	95.7 dB	13 min	5 min
Disc cutter	94.7 dB	16 min	6 min
Drilling concrete	95.1 dB	15 min	5 min

* Continuous and steady noise level

** Based on Leytonstone – Paddington route noise exposure of 78.1 dB $L_{EX,8h}$

As seen in table 3, if commuting noise exposure is taken into account, it can reduce the time allowed for activities to be undertaken by an employee before the legal noise exposure limits are reached. These exposure time reductions can be very high if the lower action limit is considered and substantial for cases considering upper action and limit values. For the scenarios analysed in table 3, exposure to lower action value can be reduced even up to three times from 15 to 5 minutes allowance.

The data and analysis above shows that noise assessments which do not include commuting to work exposure, can underestimate the risk of noise induced hearing loss.

4.4 Noise induced hearing loss

Maximum value of $L_{EX,8h}$ measured for a commuting journey was at the level of 78.1 dB for Leytonstone – Paddington route. According to ISO 1999:2013, Noise Induced Permanent Threshold Shift (NIPTS) for $L_{EX,8h}$ below 80 dB can occur only for frequencies from 3000 to 6000 Hz. Therefore in this study, only 3000 Hz, 4000 Hz and 6000 Hz frequencies are considered for analysis of commuting noise. When analysing combined noise exposures, 2000 Hz frequency was also included.

ISO 1999:2013 provides methods for determining the NIPTS values caused by noise exposure of certain level over specified duration of time for different percentages of population. Measurements of Leytonstone – Paddington route were analysed according to these guidelines and the results are presented in table 4.

It can be seen that Permanent Threshold Shifts caused only by commuting does not reach 1 dB of NIPTS. However, after 10 years 50% of the population using Leytonstone – Paddington route will have their hearing threshold at the 4000 Hz octave band raised by at least 0.5 dB and by at least 0.6 dB after 40 years. 5% of the worst affected users will have their threshold raised by at least 0.7 dB after 10 years and at least 0.9 dB after 40 years of exposure. For all other octave bands, most of the population will not have their hearing threshold raised by more than 0.2 dB.

Table 4: Estimation of NITPS values caused by commuting on Leytonstone – Paddington route for a number of years

Frequency	**NIPTS for given exposure duration and percentage of population**					
	10 years of exposure			**40 years of exposure**		
	95 % of population	**50 % of population**	**5 % of population**	**95 % of population**	**50 % of population**	**5 % of population**
3000 Hz	0.0 dB	0.1 dB	0.1 dB	0.1 dB	0.1 dB	0.2 dB
4000 Hz	0.3 dB	0.5 dB	0.7 dB	0.4 dB	0.6 dB	0.9 dB
6000 Hz	0.0 dB	0.1 dB	0.1 dB	0.0 dB	0.1 dB	0.1 dB

Another illustrative hypothetical example is presented in table 5 illustrating the important contribution of commuting noise on hearing health. In this case the NIPTS values for the occupational noise exposure of a waitress in a busy restaurant in Central London were calculated and compared against NIPTS values for waitress' occupational noise exposure combined with commuting. The results are shown in tables 5 and 6. The waitress' occupational daily noise exposure was measured at a level of 82.3 dB $L_{EX,8h}$.

Table 5: Estimation of NIPTS due to occupational noise for a waitress in a busy restaurant for a number of years

Frequency	**NIPTS for given exposure duration and percentage of population**					
	10 years of exposure			**40 years of exposure**		
	95 % of population	**50 % of population**	**5 % of population**	**95 % of population**	**50 % of population**	**5 % of population**
2000 Hz	0.0 dB	0.1 dB	0.4 dB	0.2 dB	0.3 dB	0.6 dB
3000 Hz	0.5 dB	1.4 dB	2.4 dB	1.4 dB	2.0 dB	3.5 dB
4000 Hz	1.4 dB	2.7 dB	3.9 dB	2.3 dB	3.5 dB	5.2 dB
6000 Hz	0.2 dB	1.2 dB	2.2 dB	0.8 dB	1.6 dB	2.8 dB

Table 6: Estimation of NIPTS for a waitress' occupational noise combined with commuting noise exposure for a number of years

Frequency	**NIPTS for given exposure duration and percentage of population**					
	10 years of exposure			**40 years of exposure**		
	95 % of population	**50 % of population**	**5 % of population**	**95 % of population**	**50 % of population**	**5 % of population**
2000 Hz	0.0 dB	0.3 dB	0.9 dB	0.5 dB	0.8 dB	1.5 dB
3000 Hz	0.8 dB	2.2 dB	3.9 dB	2.2 dB	3.2 dB	5.6 dB
4000 Hz	2.0 dB	3.8 dB	5.5 dB	3.3 dB	4.9 dB	7.3 dB
6000 Hz	0.4 dB	1.9 dB	3.5 dB	1.3 dB	2.6 dB	4.5 dB

By subtracting values in table 5 from the corresponding values in table 6 for the same duration of exposure and percentage of population, the impact on hearing thresholds caused by commuting can be obtained. For example, commuting noise after 40 years would raise the hearing threshold of 5 % of the population at 4000 Hz band by 2.1 dB.

The biggest impact of commuting noise on hearing health can be observed when combining commuting noise with occupational noise exposure, both of the same level.
Table 7 shows NIPTS results of such scenario based on Leytonstone – Paddington route noise exposure levels (78.1 dB $L_{EX,8h}$) and the a typical occupational noise exposure also of 78.1 dB $L_{EX,8h}$.

Table 7: Estimation of NIPTS for commuting noise exposure combined with assumed occupational exposure at the same level for a number of years

Frequency	**NIPTS for given exposure duration and percentage of population**					
	10 years of exposure			**40 years of exposure**		
	95 % of population	**50 % of population**	**5 % of population**	**95 % of population**	**50 % of population**	**5 % of population**
2000 Hz	0.0 dB	0.0 dB	0.1 dB	0.0 dB	0.1 dB	0.1 dB
3000 Hz	0.3 dB	0.8 dB	1.5 dB	0.8 dB	1.2 dB	2.1 dB
4000 Hz	1.0 dB	1.9 dB	2.7 dB	1.6 dB	2.4 dB	3.6 dB
6000 Hz	0.1 dB	0.7 dB	1.3 dB	0.5 dB	1.0 dB	1.7 dB

The maximum hearing threshold impact for the measured journey between Leytonstone and Paddington is shown in Table 8, which shows the difference between values of Tables 7 and 6.

Table 8: Estimation of maximum NIPTS impact from commuting on Leytonstone – Paddington route for a number of years

Frequency	**Statistical NIPTS for given exposure duration and percentage of population**					
	10 years of exposure			**40 years of exposure**		
	95 % of population	**50 % of population**	**5 % of population**	**95 % of population**	**50 % of population**	**5 % of population**
2000 Hz	0.0 dB	0.0 dB	0.1 dB	0.0 dB	0.1 dB	0.1 dB
3000 Hz	0.1 dB	0.7 dB	1.4 dB	0.7 dB	1.1 dB	1.9 dB
4000 Hz	0.7 dB	1.4 dB	2.0 dB	1.2 dB	1.8 dB	2.7 dB
6000 Hz	0.1 dB	0.6 dB	1.2 dB	0.5 dB	0.9 dB	1.6 dB

From results obtained in Table 8, it can be observed that commuting for 40 years by Leytonstone – Paddington route in above scenario would result in an increase of the hearing threshold between 3000 and 6000 Hz frequency range by at least 0.9 to 1.8 dB for 50% of population. The most affected frequency is 4000 Hz with 1.2 dB increase of hearing threshold for 95% of population, 1.8 dB for 50% and 2.7 dB for 5% of the worst affected members of population. All of that caused by commuting noise only.

The estimated values shown in tables 7 and 8 demonstrate that occupational noise exposure when combined with commuting noise while travelling on the London Underground for a long time can damage the hearing at certain frequency bands for a substantial share of the population.

4.5 Other means of transport

Table 9 presents average noise exposure values obtained from a daily commuting route using London Underground, buses and cycling.

Table 9: Comparison of commuting noise exposure levels from different means of transport.

Means of transport	Monitoring Time	LCPeak	LEX,8h	Lower action level dose
London Underground	1 h 24 min	129.6 dB	73.0 dB	20.3 %
Buses	2 h 09 min	139.0 dB	64.6 dB	3.1 %
Cycling	0 h 51 min	125.2 dB	65.7 dB	3.6 %

Results from table 9 show that using the London Underground to commute is the option that would provide the highest noise exposure contribution towards the allowable occupational daily maximum exposure level.

5 CONCLUSIONS

Noise exposure levels during a typical commute journey on noisy London Underground lines did not exceed the Control of Noise at Work Regulations 2005 limits. However, if noise exposure resulting from commuting noise is taken into account as contribution to occupational noise exposure calculation of typical noisy jobs, then the maximum time a worker can be exposed at the workplace will have to be substantially reduced.

Ignoring accumulated commuting noise in occupational noise exposure assessments can lead to underestimation of employees' noise exposure.

Analysis of potential noise induced hearing loss due to commuting on London underground showed that commuting noise on its own will not produce significant hearing threshold shifts, even after a lengthy exposure. However, when commuting noise exposure is combined with occupational noise over lengthy exposures, hearing threshold shifts can be noticeable.

It is suggested that noise exposure from commuting in noisy means of transport should be accounted as a contributor into the occupational noise exposure level assessments. A “complete occupational noise exposure level” parameter is proposed and is here defined as the combination of commuting and occupational noise exposure contributors.

Commuting on London underground can produce noticeably higher levels of noise exposure contributions than commuting using a bicycle or using buses.

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