Chicago Transit Authority Train Noise Exposure

BY

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THESIS

Submitted as partial fulfillment of the requirements
for the degree of Master of Science in Public Health Sciences
in the Graduate College of the
University of Illinois at Chicago, 2015

Chicago, Illinois

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ACKNOWLEDGEMENTS

First of all, I would like to express my deepest gratitude to my advisor, Dr. Rachael Jones, for her great support of my study and research, for her enthusiasm, motivation, and immense knowledge. Her guidance helped me through all the process of my research and writing this thesis. I have been amazingly fortunate to have an advisor like her.

I would like to thank the rest of my thesis committee: Dr. Lisa Brosseau and Mr. Salvatore Cali, for their supports and insightful comments.

I would like to thank all participants who helped me collect data on Chicago Transit Authority trains. Without their support, I could not finish my work.

I also thank the Pilot Project Research Training Grant from the National Institute of Occupational Safety and Health (NIOSH)—Training Grant Number T42/OH008672.

Last, but not least, I want to send a special gratitude to my loving parents, Binh Phan and Mai Nguyen for their dedication and the many years of support during my studies. Also, I would like to thank my husband Tan for his understanding, support, and encouragement which made this thesis possible.

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LIST OF ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
AL	Action Level
BART	Bay Area Rapid Transit
CTA	Chicago Transit Authority
dB	Decibel
dBA	A-weighted Decibel
ER	Exchange Rate
Hz	Hertz
L_{eq}	Equivalent continuous noise level/ Average noise level
L_{peak}	Peak Noise Level
L_{max}	Maximum Noise Level
NIHL	Noise-Induced Hearing Loss
NIOSH	National Institute for Occupational Safety
OSHA	Occupational Safety and Health Administration
PEL	Permissible Exposure Limit
REL	Recommended Exposure Limit
SE	Standard Error
SPL	Sound Pressure Level
TWA	Time-Weighted Average
TLV	Threshold Limit Value
UIC	University of Illinois at Chicago
WHO	World Health Organization

SUMMARY

The Chicago Transit Authority (CTA) is the second largest public transport system in the United States, and serves the Chicago metropolitan area and 35 suburbs. Riding CTA trains can be unpleasant due to noise, but it is unclear if the noise is high enough to cause adverse health outcomes for train riders and drivers. The goal of this study is to characterize the noise exposure of riders on the CTA trains and to identify factors influencing noise levels.

Twenty-eight students were recruited to participate in this study. Participants were asked to ride a specific train route while wearing a noise dosimeter and complete a questionnaire about factors that might influence noise levels. Participants rode in the first car, where the driver's cab is located. We used CEL-35x dBadge noise dosimeters, set to integrate sound levels over 1-minute intervals with a 5 dB exchange rate, an 80 dB threshold and a 90 dB criterion. Noise measurements were taken in train car only.

Train drivers have longer duration exposure than riders. The estimated 8-hour noise doses, however, do not exceed the exposure limits. The linear-mixed effect regression models showed that the 1-min and segment-average noise levels of the Blue line, which were about 78 dBA, were significantly higher than all the other lines. The segment-average noise level for segments involving travel through tunnels (77dBA) was 2 dBA significantly higher than elevated segments and 3 dBA higher than ground segments.

The Blue line had higher noise levels than other train lines, but noise doses do not exceed occupational exposure limits for ride or 8-hour durations. Train drivers may have different exposures than riders, however, because they are in a cab with operational windows. Future work should confirm that drivers' noise exposures are below exposure limits.

I. INTRODUCTION

A. Chicago Transit Authority

The Chicago Transit Authority (CTA) is the second largest public transport system in the United States, and serves the Chicago metropolitan area and 35 suburbs. The CTA accounts for 83% of the public transit trips in the Chicago area. There are eight train lines operated by CTA, named the Red, Blue, Brown, Green, Orange, Purple, Pink, and Yellow Lines. These eight lines travel over 224 miles of track (CTA, 2014). The Red Line travels from Howard Street station at Chicago's northern border, underground through the Loop, and continues south to 95th Street. The Blue Line travels from O'Hare International Airport through the Loop to Forest Park on Chicago's West side. The Green Line travels east from Harlem through the Loop to Ashland and Cottage Grove on Chicago's South side. The Orange, Purple, Pink, and Brown Lines depart from the Loop to Midway International Airport, Linden, 54th and Cermak, and Kimball, respectively. The Red Line has the highest daily ridership (Figure 1), followed closely by the Blue Line.

Figure 1. CTA average daily boarding by lines by Sept. 2013 (CTA, 2014).

B. **Health Impacts of Noise Exposure**

The World Health Organization (WHO) estimated that occupational noise causes 16% of disabling hearing loss in adults worldwide (Nelson et al., 2005). According to the National Institute for Occupational Safety and Health (NIOSH), hearing loss is the most common occupational disease and the second most common self-reported occupational illness or injury in the United States (NIOSH, 2011). There are approximately twenty-two million workers who are exposed to hazardous noise among United States industries. Masterson et al. found the prevalence of hearing loss among workers in the transportation and support industry was 13.24% (Masterson et al., 2013).

There are several types of hearing loss, only some of which are the result of noise exposure. Hearing loss can be caused by the ageing process, which is termed presbycusis. Nosoacusis is hearing loss attributable to all other causes such as mumps, rubella, and ototoxic drugs (AIHA 2013). Noise-induced hearing loss (NIHL) can result from occupational and nonoccupational exposure to noise; that due to nonoccupational noise exposure to noise is called sociacusis (AIHA 2013). Both NIHL and presbycusis can be distinguished in audiometric testing because they impact hearing sensitivity at different frequencies.

The NIHL is caused by exposure to sound levels that damage the hair cells of cochlea, and can cause a permanent or temporary threshold shift in hearing sensitivity. Temporary threshold shift is a decrease in hearing sensitivity and can be recovered within a few minutes or hours, but permanent threshold shift is irreversible (NIOSH 1998). The NIHL occurs predominantly at higher frequencies, 3,000 (Hertz) Hz and 6,000 Hz, with the most potent effect at 4,000 Hz. This is different from presbycusis, which produces hearing loss at high frequencies in a down-sloping pattern (Kirchner et al., 2012).

Noise can cause annoyance, which is defined by the WHO (2004) as “a feeling of resentment, displeasure, discomfort, dissatisfaction, or offense which occurs when noise interferes with someone’s thought, feelings, or daily activities.” There is evidence that populations exposed to sound levels of 37 A-weighted decibels (dBA) for more than a year have annoyance, and have severe annoyance when exposed to sound levels of around 42 dBA for more than a year (WHO 2004).

Limited epidemiologic evidence suggests that noise exposure may cause chronic illness. A cohort study by Sorensen et al. on noise exposure and breast cancer concluded that a 10-decibel (dB) increase in railway noise significantly increased the risk of estrogen receptor negative breast cancer among women aged 50–64 years (Sorensen et al., 2014). Noise exposure may also cause adverse cardiovascular effects (Babisch et al., 1999; Banerjee et al., 2013).

C. **Noise Definition and Measurement**

1. **Noise definition and basic qualities of sound**

Occupational noise can be caused by any sound in the work environment. Sound propagates as a wave of pressure disturbances that travel through any elastic medium (OSHA, 2013). Sound pressure is the magnitude of the pressure disturbances, or vibrations. The range of sound pressure is very large. Low sound pressure can cause faint sounds. High sound pressure can cause loud noise, and can cause pain. Sound pressure level, L_p , is the sound pressure, P , relative to the reference sound pressure, $P_0=20 \mu\text{Pa}$, and has units of decibel, dB (AIHA 2003):

$$L_p = 20 \log (P/P_0)$$

The reference sound pressure is the threshold of normal human hearing at 1,000 Hz.

Sound frequency, f , is a measure of sound pressure cycles that occur per second (Hz). Sound frequency is perceived as pitch (AIHA 2003).

Sound power is the amount of energy per unit time radiating from a source and is usually measured in watts. Sound power level, L_w , is the sound power, W , relative to the reference sound pressure, $W_0=10^{-12}$ watts, and has the units of decibel, dB (AIHA 2003):

$$L_w = 10 \log (W/W_0)$$

Noise intensity is heard as loudness. Loudness is the human response to sound and it depends on sound pressure and frequency (OSHA 2013).

Noise can be continuous, intermittent, or impulsive. If the variations in noise level involve maxima at intervals of one second or less, it can be considered as continuous. Intermittent noise is a mixture of relatively quiet and noisy periods. Impulsive noise is a very loud noise that lasts less than one second. According to the Occupational Health and Safety Association (OSHA) monitoring requirements, all continuous, intermittent, and impulsive noise from 80 dB to 130 dB are integrated by noise measurement devices (OSHA, 2015, CCOHS, 2015).

2. **Noise unit and weighting scale**

A dB is the unit to measure sound. One dB is the minimum difference in sound loudness that is often noticeable. Decibel is:

$$L=10 \log (A/B)$$

where L is the sound loudness, A is sound power, and B is a reference quantity of 10^{-12} W (AIHA, 2003). The upper end of human hearing occurs at sound pressure 10 million times the human hearing threshold. Thus, the dB scale is used because it can compress the noise range relevant to human hearing to a more manageable range.

In regard to noise monitoring instruments, three weighting filters (A, B, and C) have been used to estimate equal loudness perception of human hearing for pure tones. The dBA approximates the equal loudness response of human hearing to different sound pressure levels (SPLs) relative to the references of SPL at 40 dB and frequency 1,000 Hz. In other words, the dBA is characterized by 40-phon-equal-loudness contour. Similarly, B-weighted and C-weighted scales are characterized by 70-phon and 100-phon-equal-loudness contours, respectively. The C-weighted sound level measurements are not really different from A-weighted sound level measurement unless the measured sound has frequency below 25 Hz or above 10,000 Hz. Comparison of the three weighting filters found the dBA better characterizes health risk than the two other filters. Therefore, A-weighted sound level is widely accepted and used in many noise regulations (AIHA, 2003). In this study, noise will be measured using the A-weighted scaling to best represent human ear sensitivity.

a. **How we hear**

The function of the ear involves three stages. The first stage includes modification of the acoustic waves by the outer ear, which directs the waves to the tympanic membrane or eardrum. The second stage is the conversion and amplification of the modified acoustic wave to the vibration of the eardrum that is amplified by the ossicles and transmits sound pressure through the middle ear to the inner ear. The last stage is the transformation of the mechanical movement of the acoustic wave into nerve impulses. The brain perceives and interprets the nerve impulses as sound (OSHA 2013).

b. **Noise measurements**

Equivalent continuous noise level, denoted $L_{eq,T}$, is the average noise level over the sample time. However, since the dB is a logarithm, instantaneous measures of noise level cannot be arithmetically averaged. Instead, $L_{eq,T}$ is calculated:

$$L_{eq,T} = 10 \log \left[\frac{1}{T} \int_0^T 10^{L_A(t)/10} dt \right] \quad (1)$$

where $L_{A(t)}$ is A-weighted noise level as a function of time (AIHA, 2003). The maximum noise level, L_{max} or L_{peak} is the highest noise level during the sample time—e.g., the maximum value of $L_A(t)$. Average sound level can also be reported as time-weighted average (TWA), which is a long-term average, typically over an 8-hour time period.

Noise exposure limits consider both the magnitude and duration of exposure. Noise intensity and duration are believed to be directly correlated to hearing damage, so regulatory and advisory agencies generally allow a doubling of noise intensity when the duration of exposure is halved, and vice versa. The exchange rate (ER) is the relationship between the change in the allowable exposure time and the increase or decrease in noise level. The dB scale is logarithmic, so a doubling of sound power occurs when sound intensity increases by 3 dB. The OSHA uses a 5-dB exchange rate (OSHA, 2013), while the American Conference of Governmental Industrial Hygienists (ACGIH) and NIOSH use 3-dB exchange rate (NIOSH, 1998). The difference in exchange rates among NIOSH/ACGIH and OSHA results in a markedly increased difference in dose and allowable exposure duration as noise intensity increases. For example, assuming that the duration of exposure is the same, a dose of 90 dB is twice the dose of 85 dB when using a 5-dB ER. If 3-dB ER is used, a dose of 90 dB is twice the dose of 87 dB instead.

Noise dose, D , in percent, is calculated according to the following formula:

$$D = \left(\sum_{i=1}^n \frac{C_i}{T_i} \right) \times 100 \quad (2)$$

where n is the number of noise values, C_i is the total time of exposure at a specific noise level, and T_i is the allowable exposure time for that noise level based on the policies of NIOSH, ACGIH, or OSHA. In this study noise levels were recorded every minute, so $C_i = 1$ minute.

The noise dose (Equation 1) is used to calculate the 8-hour TWA sound level. As specified by OSHA, the calculation is:

$$\text{TWA} = 16.61 \log_{10}(D/100) + 90 \quad (3) \quad (\text{OSHA 2013})$$

As specified by NIOSH and ACGIH, the calculation is:

$$\text{TWA} = 10 \log_{10}(D/100) + 85 \quad (4) \quad (\text{NIOSH 1998})$$

Equations 2 and 3 differ because OSHA uses exchange rate of 5 dBA and noise criteria of 90 dBA while NIOSH and ACGIH uses 3 dBA exchange rate and noise criteria of 85 dBA.

The instrument used to measure noise exposure is a dosimeter. Dosimeters may be fixed in place, hand-held, or worn on the body. Dosimeters measure SPL and integrate or average sound over a period of time. In this study, a body-worn dosimeter was used to quantify sound-level measurement. One-minute integrated and peak sound pressure levels were recorded.

Audiometry testing is used to monitor a person's hearing over time. Tested frequency range is from 250 to 8,000 Hz. According to OSHA, an employer has to implement an audiometric testing program. The test can be conducted by either professionals and trained technicians. Also, it is required that employers need to implement a hearing conservation program if their employees are exposed to 8-hour TWA of 85 dBA or greater. Noise monitoring in the workplace can estimate the noise exposure of employees and determine if exposures are at or above this level.

3. **Noise exposure standards**

The OSHA permissible exposure limit (PEL) for noise is 90 dBA, as an 8-hour TWA. In addition, OSHA requires employers to administer a hearing conservation program when employees are exposed to noise levels at or above an 8-hour TWA of 85 dBA, the action level. The OSHA action level uses criterion level of 90 dBA, a threshold level of 80 dBA, and an exchange rate of 5dBA. The OSHA PEL has the same criteria as the action level except for the threshold of 90 dB (OSHA, 2013).

The NIOSH recommended exposure limit (REL) is 85 dBA, as an 8-hour TWA. The NIOSH uses a criterion level of 85 dBA, a threshold level of 80 dBA, and an exchange rate of 3 dBA (NIOSH 1998). Table I describes the OSHA, NIOSH, and ACGIH allowable exposure times at the exposure limit. Note that the ACGIH Threshold Limit Value (TLV) is identical to the NIOSH REL.

TABLE I

ALLOWABLE EXPOSURE TIME FOR OSHA PEL, NIOSH REL, AND ACGIH TLV TO COMPLY WITH CRITERIA LEVELS 90 DBA AND 85 DBA, AND USING A 5-DBA AND 3-DBA EXCHANGE RATE, RESPECTIVELY.

Sound Pressure Level (dBA)	Allowable Duration of Exposure (hours)		
	OSHA PEL	NIOSH REL	ACGIH TLV
75	>24	>24	> 24
85	16	8	8
90	8	2.52	2.52
100	2	0.25	0.25
105	1	0.08	0.08
115	0.25	0.008	0.008

4. **Noise exposure on public transportation**

Despite the heavy utilization of public transportation in urban areas, there has been limited research about the magnitude of noise exposure among drivers and riders. Most intra-city or regional trains are separate from intercity or national commuter trains, and may use different technology. Intra-city trains often operate over shorter distances than railways, and therefore tend to have more stops and a quick braking system, while intercity trains tend to slowly reduce their speed. In the Chicago area, for example, the CTA trains provide service primarily to the city of Chicago on dedicated tracks, while the Metra trains provide intercity service and may share tracks with freight trains.

Previous studies of noise in public transit systems in the United States were conducted in New York and the San Francisco Bay Area. Table II summarizes noise levels associated with public transportation globally.

In New York City, Neitzel et al. (2009) measured noise exposure in 30 subway train lines, 6 railways, and 13 bus lines. The average noise level inside subway train cars, L_{eq} , was 79.3 dBA, while the average maximum level, L_{max} was 90.5 dBA. Almost 20% of the time, noise level was above 85 dBA, and two subway lines had L_{eq} greater than 85 dBA. This suggests that the noise exposure of train drivers might exceed the OSHA Action Level of 85 dBA over an 8-hour work shift. Neitzel et al. (2009) also found that L_{eq} on the MTA subway was higher underground than above ground; though, when underground, L_{eq} was lower inside the train car than on the platform.

In California, Dinno et al. (2011) measured noise levels repeatedly on individual segments of the Bay Area Rapid Transit (BART) between two stations. A total of 268 L_{eq} measurements were made on segments, and 22% were above 85 dBA. Moreover, L_{peak} measurements massed around 112 dB, with three exceeding 140 dB, the threshold of impulsive noise recommended by OSHA (OSHA, 2015). The investigation estimated that riders are exposed, at a minimum, around 60 min/day at $L_{eq} \geq 70$ dBA and about 20 min/day at $L_{eq} \geq 85$ dBA when the trains are in motion. This study found train speed was associated with the average noise level but not associated with the peak noise level. In addition, the average noise level was significantly higher on segments enclosed by tunnels.

While the Neitzel et al. and Dinno et al. studies considered the noise experience of passengers, the only study focused on drivers was performed by Malleon et al. (1989), who measured the exposure of drivers in the London Transport Underground. Malleon et al. (1989) found noise exposures, as an 8-hour TWA, were less than 85 dBA.

TABLE II**NOISE EXPOSURES ASSOCIATED WITH PUBLIC TRANSPORTATION, GLOBALLY**

Population	Location	Vehicle	Measurement Type	Measurement Duration	Range or Average (dBA)	Related health impacts	References
Bus Drivers	Curitiba City, Brazil	Local conventional buses	L _{EX} *	8 hours	78.98	28% claimed high annoyance	(Bruno et al., 2013)
Train Drivers and Conductors	Norway	Regional train	TWA	8 hours	70–85	No work-related hearing loss observed	(Lie et al., 2013)
Underground Train Drivers	Victoria line Train, United Kingdom	Local train	L _{eq}	8 hours	83.5	NA	(Malleon, 1989)

NOISE EXPOSURES ASSOCIATED WITH PUBLIC TRANSPORTATION, GLOBALLY

Population	Location	Vehicle	Measurement Type	Measurement Duration	Range or Average (dBA)	Related health impacts	References
Residential Neighborhoods Near Railways	At railroad crossings and inside the home of residents, Brazil	Regional railway traffic	L_{eq}	N/A	80–92***	Irritability, headache, poor concentration and insomnia	(Zannin et al., 2014)
Train Riders	In Vehicle and Platforms or Terminals, New York	Local subways	L_{eq}	N/A	79.4–80.4	NA	(Neitzel et al., 2009)
Train Riders	In vehicle, Bay Area Rapid Transit Trains, San Francisco	BART train line	L_{eq}	Sound level was integrated over 1-min interval	83	NA	(Dinno et al., 2011)

*** Train passing with horn blowing, the noise levels were measured at the facades of homes closest to the rail way.

* $L_{EX, 8h}$ is the L_{eq} - Equivalent Continuous Sound Level corrected for the length of the working shift in 8 hours (Acoustic Glossary, 2015)

5. **Objective**

The objective of this study was to characterize the noise exposure of riders on CTA trains. To our knowledge, this is the first study of noise levels on Chicago public transit. Research in New York City and the San Francisco Bay Area suggests that riders may experience high noise levels while riding trains. Based on these studies, the noise exposure of riders in Chicago is not likely to approach the 8-hour TWA occupational exposure limits of OSHA, NIOSH, and ACGIH, but peak exposures may exceed 147 dB (Dinno et al., 2011). These peak exposures may put riders at risk for hearing damage, particularly if they have additional noise exposures, and suggest that quantification of noise exposures on CTA trains is an important environmental and occupational hazard.

Findings of high noise exposure for riders may indicate the potential for an occupational hazard among train drivers, who have longer duration exposures; and may inform policy makers and CTA about the likelihood of annoyance and discomfort among riders. This research will contribute to our understanding of the magnitude and determinants of urban noise exposures. The specific objectives are:

- A. Summarize measured noise levels on CTA trains.
- B. Quantify differences in mean noise levels among CTA train lines, if any.
- C. Calculate and summarize noise levels among segments of each train line.
- D. Identify factors that influence noise levels on CTA trains, if any.
- E. Assess the risk of noise-induced hearing loss associated with riding CTA trains.

II. METHODS

A. Overview

The general approach to data collection was to ask participants to ride CTA train lines while wearing a noise dosimeter, and to complete a short questionnaire about features of the train and train ride that might influence noise levels. Participants were asked to ride a specific train route, and to sit in the first car. Participant ridership resulted in monitoring of seven of the eight lines at least four times each. The Yellow Line—to Skokie—was not included because it is short and has relatively low ridership (Figure 1). Since riding the complete length of some train lines required more than two hours, participants rode half of the route (e.g., from downtown to one end of the Red Line). The noise dosimeter data and questionnaire were used to address all study objectives.

We use the following terms to describe portions of the CTA train system:

- The term *train line* refers to the seven train lines, defined by their colors.
- The term *train branch* refers to the length of a train line extending from the Loop to a terminus. For example, the Blue line has two branches extending from the Loop to O’Hare International Airport and from the Loop to Forest Park. The Red and Green lines also have two branches, while the Pink, Brown, Purple, and Orange lines have one branch.
- The term *train segment* refers to the distance between two stations. Each train segment was classified as being primarily underground, aboveground and elevated.

B. Participant Recruitment

Participants were recruited by sending referral via the University of Illinois at Chicago (UIC) online mailing service and signs posted around UIC. Recruitment materials specified that participants needed to wear a noise dosimeter and answer a questionnaire. Consent forms were distributed to the participants before they participated into the study, and participants were asked to

give verbal consent to participate. This study was approved by the UIC Institutional Review Board, research protocol 2014-0602.

Participation was incentivized with a \$40 gift card. The value of \$40 was judged appropriate because participants spent approximately two hours riding the train, during which time they must complete a questionnaire, and spend additional time collecting and returning the dosimeter.

Participants were not specifically reimbursed for the CTA fare (\$2.25), as many participants have a U-Pass or other CTA pass, and the participation incentive exceeds the CTA fare.

C. **Sampling Strategy**

Noise levels on seven of the eight train lines were measured four times. We chose a minimum of four samples on each train line to ensure sufficient sample size of quantifying exposure variability. We recruited at least four participants for each train line route. Since riding the complete length of some train lines required more than two hours, participants rode half of the route (e.g., from downtown to one end of the Red Line). We did not sample the Yellow Line since there are a small number of riders on this line compared to other lines (Figure 1). Ultimately, we had 28 samples among 7 train lines.

We considered allocating the samples among the train lines based on ridership, to capture the ridership-average noise exposure. However, the noise exposure of the “average” CTA rider is also a function of the section of each train line ridden. Ultimately, we determined that a balanced sampling design would allow us to estimate the ridership-average noise exposure with consideration of ridership of specific train line sections with fewer samples, if that became of interest.

Participants were asked to sit or stand at the middle of the car, consistent with previous studies (Neitzel et al., 2009, Dinno et al., 2011). Participants were asked to ride in the first car of the

train, to best approximate the experience of the train driver. This also had the effect of eliminating the potential effect of train car position on the noise level.

D. **Data Collection Method**

The noise level meter used is the dBadge CEL 350 (Casella CEL, Inc, Buffalo, New York). These meters measure average and peak sound pressure levels over 60-second intervals, and provide lists and charts of the logged 60 second L_{eq} and L_{peak} , as well as average and peak noise levels for the total time period measured. The dosimeters were calibrated before being given to participants and after being returned. Dosimeters were clipped on participants' clothing while riding the train. Data were downloaded using the manufacturer's software. The following noise metrics were calculated: L_{eq} , L_{peak} , segment L_{eq} and L_{peak} , single-ride TWA, and 8-hour TWA. The L_{eq} (dBA) and L_{peak} (dB) parameters are calculated by the noise dosimeter. Segment L_{eq} and L_{peak} are calculated using equation (1). The single-ride TWA sound level (dBA) is calculated using equation (3) and (4). Noise dose for each train ride is calculated using equation (2). We used the single-ride dose to estimate the 8-hour projected dose of the train drivers by the following formula: Single-ride dose $\times$ 8 hours $\div$ sampled time.

The questionnaire captured information about factors on the train ride that might influence noise levels, including the arrangement of seats (which indicates the train car model and approximate years of service). In addition, for each segment of the train, participants were asked to record:

- The time of arrival and departure from each station.
- The occupancy level—low (many vacant seats), moderate (most seats full and a few people standing), high (seats full and many people standing), and overfull (crowded standing, like a can of sardines).

- The occupant activity level—quiet (most people reading or listening to music on headphones), some talking, or loud talking or music.
- The number of passing trains between two stations (segment)

Maps were used to classify the condition of each segment of each train as primarily: elevated, above ground (on a road or berm), or underground.

E. **Analysis Plan**

Objective A: Summarize measured noise levels on CTA trains.

The noise level (L_{eq} , L_{peak} , ride-duration TWA, 8h-TWA) was summarized in dBA or dB, by train line. Standard summary statistics were used to calculate mean values and variance measures. For each train line, we also summarized the noise levels by conditions of the line segments (above ground, underground or elevated). Graphical methods were used to explore patterns in the data, such as boxplots to compare noise levels among train lines.

Objective B: Quantify differences in mean noise levels among CTA train lines, if any.

We used mixed-effect regression models to compare statistical differences in L_{eq} and L_{peak} levels among train lines. We used $\alpha=.05$ to define statistical significance. Mixed-effect regression models were used to account for the correlation of noise levels within a train ride.

Objective C: Calculate and summarize noise levels among segments of each train line.

To attain this objective, the noise level was calculated for each line segment. Time of station arrival and/or departure was used to match the noise-level data to each line segment. For each segment, we calculated L_{peak} and L_{eq} . Summary statistics and mixed-effect regression models were applied to characterize the noise levels in each segment. Graphical methods were also used to explore the data.

Objective D: Identify factors that influence noise levels on CTA trains, if any.

We used exploratory data analysis and mixed-effect regression models to determine what factors, if any, influence noise levels on CTA trains. Exploratory data analyses included graphical methods and simple statistics, such as t-tests and correlation coefficients. Factors identified as potentially contributing to noise levels on CTA trains were included as a fixed effect in a mixed-effect regression model. The independent variables were L_{eq} and L_{peak} measured each minute and by train segment. A unique identifier for train ride was used as a random effect to account for repeated measurements.

Objective E: Assess likelihood of noise-induced hearing loss associated with riding CTA train lines.

Since ACGIH TLV and NIOSH REL have the same noise criteria, we tabulated descriptive statistics and compared L_{eq} and L_{peak} noise doses based on the OSHA PEL and ACGIH TLV.

III. RESULTS

A. Summarize Measured Noise Levels on Chicago Trains

Table III describes the 1-min average noise level (L_{eq}) and the 1-min peak noise level (L_{peak}) by train branch (L_{peak}). For the Blue, Red, and Green Lines, there are two branches from downtown to both end points of each line. The Purple, Orange, Brown and Pink Lines have only one branch from downtown, because the lines depart from the Loop.

TABLE III

SUMMARY OF MEAN AND PEAK 1-MINUTE NOISE LEVEL (L_{eq} AND L_{peak}) BY TRAIN BRANCH

Line	Branch	N	Mean (SD) 1-min Noise Level		Mean (SD) Duration (minutes)
			L_{eq} (dBA)	L_{peak} (dB)	
Blue	Downtown → O'Hare	2	78.30 (3.72)	110.7 (3.40)	30 (2.82)
Blue	Downtown → Forest Park	2	77.37 (3.53)	109.3 (3.15)	46.5 (6.36)
Red	Lake → Howard	2	72.25 (2.69)	107.6 (2.69)	40 (1.41)
Red	Lake → 95 th Street	2	72.86 (1.86)	109.8 (4.27)	29 (4.24)
Green	Roosevelt → Cottage/Ashland	2	72.83 (2.47)	107.7 (2.95)	22 (4.24)
Green	Roosevelt → Harlem	2	72.15 (4.18)	110.0 (4.52)	31.5 (3.53)
Purple	Downtown → Linden	4	71.23 (2.57)	106.9 (3.64)	63.75(4.42)
Orange	Downtown → Midway	4	73.41 (3.22)	108.6 (2.85)	37 (1.63)
Brown	Downtown → Kimball	4	72.73 (2.33)	109.5 (3.90)	50 (5.29)
Pink	Downtown → Cermak	4	73.46 (3.64)	107.3 (3.45)	39.25 (3.86)

The train branches with the highest mean L_{eq} are the Blue Line to O'Hare (78.30 dBA), and to Forest Park (77.37 dBA). The lowest mean L_{eq} was measured on the Purple Line (71.23 dBA). The mean L_{eq} was similar between the two branches of the Red, Blue, and Green Lines, respectively.

Similarly, the highest mean 1-min peak noise level (L_{peak}) is on the Blue Line branch from downtown to O'Hare (110.7 dB) and the lowest is on the Purple Line (106.9 dB). The peak noise levels have a similar pattern as the average noise levels. The L_{peak} was correlated with L_{eq} for all

train lines ($p < .05$). However, the mean L_{peak} of the Green Line from Roosevelt to Harlem is particularly high (110.0 dB), and has high variability (standard deviation 4.52 dBA).

The summary statistics in Table IV are consistent with the graphical presentation in Figure 2, which displays the box-plots of the 1-min average noise level and the 1-min peak noise level by train line.

Figure 2. One-min average noise level (L_{eq}) and 1-min peak noise level (L_{peak}) by train line.

Noise levels were tabulated for segments of train lines between stations (Table IV). This table describes the mean of the segment-average noise level ($S.L_{eq}$) and the mean of the segment-peak noise level at each station ($S.L_{peak}$). The mean of $S.L_{eq}$ and $S.L_{peak}$ are highest for the Blue Line branch from downtown to O'Hare (78.87 dBA and 111.0 dB, respectively). The $S.L_{eq}$ and $S.L_{peak}$ have the same patterns with the L_{eq} and L_{peak} (Table III). Figure 3 describes the average noise level and peak noise level at each station by train colors, and is consistent with Table IV.

TABLE IV

MEAN AND STANDARD DEVIATION (SD) OF NOISE LEVEL BY SEGMENT ($S.L_{PEAK}$ AND $S.L_{EQ}$) BY TRAIN LINE BRANCH

Line	Branch	N	Mean (SD) Segment Noise Level		Mean (SD) Duration (minutes)
			$S.L_{eq}$ (dBA)	$S.L_{peak}$ (dB)	
Blue	Downtown → O'Hare	2	78.87 (3.32)	111.0 (3.05)	30 (2.82)
Blue	Downtown → Forest Park	2	78.13 (3.19)	109.9 (2.45)	46.5 (6.36)
Red	Lake → Howard	2	72.43 (2.21)	108.1 (2.05)	40 (1.41)
Red	Lake → 95 th Street	2	73.17 (1.15)	109.9 (3.51)	29 (4.24)
Green	Roosevelt → Cottage/Ashland	2	73.30 (2.21)	108.5 (2.45)	22 (4.24)
Green	Roosevelt → Harlem	2	72.31 (4.05)	110.2 (4.48)	31.5 (3.53)
Purple	Downtown → Linden	4	72.10 (2.45)	107.9 (3.58)	63.75(4.42)
Orange	Downtown → Midway	4	73.87 (2.95)	108.8 (2.38)	37 (1.63)
Brown	Downtown → Kimball	4	73.11 (2.01)	110.0 (3.42)	50 (5.29)
Pink	Downtown → Cermak	4	73.72 (3.63)	107.28 (3.44)	39.25 (3.86)

Figure 3. Segment-average noise level ($S.L_{eq}$) and segment-peak noise level ($S.L_{peak}$) by train line.

The average and peak noise level plotted against the number of passing trains is shown in Figure 4. It was most common that 1–2 trains passed the train ridden by the study participant between stations. There is no visible association between the number of passing trains and the $S.L_{eq}$ and $S.L_{peak}$ values (Figure 4). Similar plots were done for occupancy level and occupant activity level but there were no visible associations between $S.L_{eq}$ and $S.L_{peak}$ and these variables. As a result, further statistical analyses were not performed.

Figure 4. Segment-average train noise level and segment-peak noise level by the number of passing trains at each station.

B. **Quantify Differences in Mean Noise Levels among Chicago Train Lines**

1. **Comparing the 1-minute peak noise levels between train lines**

The 1-min L_{peak} values were compared between train lines using a mixed-effect model, with train line as the fixed effect and train ride as the random effect, to account for the repeated noise measurement on each ride (Table V). The intra-class correlation is 22%, indicating that train ride explains 22% of the variation in the noise levels, after adjusting for the fixed effects. The mean L_{peak} levels on the Brown (109.64 dB) and Blue Lines (110.18 dB) are statistically significantly different than the intercept, which is the mean L_{peak} levels on the Pink Line, 106.89 dB. The mean L_{peak} levels on the Purple, Orange, Green, and Red Lines are higher than the intercept, but the differences are not statistically significant ($p > .05$). Other statistically significant contrasts estimated from the 1-min L_{peak} regression model in Table V are shown in Table VI. Consistent with Table V, L_{peak} of Blue and Brown Lines are significantly higher than L_{peak} of Pink Line ($p < .05$) (Table VI). In addition, the Blue Line L_{peak} is also higher than Purple Line ($p < .05$) and the difference is 2.58 dB.

TABLE V

LINEAR MIXED-EFFECT MODEL FOR 1-MIN L_{PEAK} AND L_{EQ}

	1-min L _{peak}			1-min L _{eq}		
<i>Quality of Model Fit:</i>						
AIC	2886			2693		
Log Likelihood	-1434			-1337		
<i>Random effects (SD):</i>						
Intercept	1.61			1.86		
Residual	3.07			2.55		
<i>Fixed effects:</i>						
	Value	SE	p-value	Value	SE	p-value
Intercept	106.89	0.87	0.00	73.79	0.97	0.00
Purple	0.71	1.22	0.57	-1.42	1.37	0.31
Orange	1.54	1.24	0.23	0.07	1.38	0.96
Brown	2.75	1.22	0.03	-0.83	1.37	0.55
Blue	3.29	1.25	0.02	4.15	1.38	0.01
Green	1.40	1.26	0.28	-1.58	1.39	0.27
Red	1.52	1.24	0.24	-1.54	1.38	0.28

TABLE VI

SIGNIFICANT L_{PEAK} AND L_{EQ} CONTRASTS BETWEEN TRAIN LINES, WITH SE ESTIMATES FOR THE DIFFERENCE AND 95% CIs

Train Lines Compared	Contrast	SE	95% CI
L_{peak}			
Blue-Purple	2.58	1.24	0.14, 5.01
Blue-Pink	3.29	1.25	0.84, 5.74
Brown-Pink	2.75	1.22	0.35, 5.14
L_{eq}			
Blue-Red	5.69	1.39	2.95, 8.43
Blue-Purple	5.57	1.38	2.86, 8.28
Blue-Orange	4.08	1.39	1.34, 6.82
Blue-Brown	4.98	1.38	2.27, 7.69
Blue-Green	5.73	1.41	2.97, 8.50
Blue-Pink	4.15	1.38	1.43, 6.87

2. Comparing the 1-minute average noise levels between train lines

The 1-min L_{eq} were compared between train lines using a mixed-effect model, with train ride as the random effect and train line as a fixed effect (Table V). The intra-class correlation is 34.7%, indicating that train ride explains 34.7% of the variation in the noise levels, after adjusting for the fixed effects. There is only one significant difference in the mean L_{eq} levels: between Blue and Pink Line ($p < .05$). The L_{eq} of the Blue Line is 4 dBA higher than the L_{eq} of Pink Line. The differences of L_{eq} between the Pink Line and the train lines other than the Blue Line are not

significant ($p > .05$). This result is consistent with the 1-min L_{eq} levels in Table IV. Statistically significant contrasts estimated from the 1-min L_{eq} regression model in the Table V are shown in Table VI. We can see that the mean of L_{eq} of the Blue Line is higher than all the other train lines ($p < .05$). None of the L_{eq} contrast between other train lines are statistically significantly different.

C. Calculate and Summarize Noise Levels among Segments of Each Train Lines

The noise levels are summarized by the location of train segment—primarily in a tunnel, ground level, or at elevation (Table VII). The mean $S.L_{eq}$ is highest for train segments involving tunnels, 77.23 dBA, while the mean of $S.L_{peak}$ is highest for train segments primarily at ground level, 110.29 dB.

TABLE VII

SUMMARY OF SEGMENT-NOISE LEVELS BY LOCATION

Segment Primarily	Mean (SD) Segment Noise Level	
	$S.L_{eq}$ (dBA)	$S.L_{peak}$ (dB)
In Tunnel	77.23 (4.03)	109.47 (3.13)
On Ground	75.16 (3.67)	110.29 (2.84)
Elevated	73.01 (2.82)	108.61 (3.40)

D. **Identify Factors That Influence Noise Levels on Chicago Trains**

To follow up on the summary statistics suggesting that noise level varied with train track location (Table VII), differences were tested using a mixed-effect model with train ride as the random effect and track location as a fixed effect. The overall mean $S.L_{eq}$ at elevated stations is 73.60 dBA (Table VII). The mean $S.L_{eq}$ of train segments involving travel through tunnels is significantly higher than the mean $S.L_{eq}$ of elevated stations ($p < .05$). Ground and elevated segments were not significant different, but tunnel segments 1.97 dBA were louder than ground segments (95% CI: 1.04, 2.89), on average.

Differences in segment-peak noise levels between train track locations were tested using a mixed-effect model with train ride as the random effect (Table VIII). The mean $S.L_{peak}$ of train segments primarily at ground level is significantly higher than the mean $S.L_{peak}$ of elevated segments (108.80 dB, the intercept). There was no significant difference in peak noise levels between ground and tunnel segments.

TABLE VIIILINEAR MIXED-EFFECT MODEL FOR S.L_{EQ} AND S.L_{PEAK}

	S.L _{eq}			S.L _{peak}		
<i>Quality of the Model Fit:</i>						
AIC	2615.84			2802.92		
Log Likelihood	-1302.92			-1396.46		
<i>Random effects (SD):</i>						
Intercept	2.27			1.69		
Residual	2.34			2.83		
<i>Fixed effects:</i>						
	Value	SE	p-value	Value	SE	p-value
Intercept	73.60	0.45	0.00	108.80	0.36	0.00
Ground	0.17	0.41	0.68	0.91	0.47	0.05
Tunnel	2.14	0.50	0.00	-0.11	0.59	0.84

Since the Blue Line has a louder noise level than the other train lines, and tunnels were found to be contributing to the noise level, we considered whether the number of tunnels through which the Blue Line travels explained the high noise level on the Blue Line. This was accomplished using a mixed-effect regression model with train ride as a random effect, train color, and track location (tunnel versus non-tunnel segment). The model results (Table IX) show that both tunnel and Blue Line are independent statistically significant effects ($p < .05$). This means that the number of tunnels does not fully explain the noise level on the Blue Line.

TABLE IX

LINEAR MIXED-EFFECT MODEL FOR $S.L_{EQ}$ WITH TRAIN RIDE AS A RANDOM EFFECT,
TRAIN COLORS AND TRACK LOCATION AS FIXED EFFECTS

	S.Leq		
Quality of Model Fit:			
AIC	2591.45		
Log Likelihood	-1285.72		
Random effects (SD):			
Intercept	1.62		
Residual	2.33		
Fixed effects:			
	Value	SE	p-value
Intercept	73.73	0.85	0.00
Purple	-1.64	1.19	0.18
Orange	0.13	1.21	0.91
Brown	-0.62	1.19	0.61
Blue	4.07	1.22	0.00
Green	-0.93	1.22	0.45
Red	-1.51	1.21	0.22
Tunnel	1.89	0.44	0.00

E. **Comparing Noise Level With Standards**

Table X includes the OSHA Action Level (AL) Dose and ACGIH TLV Dose per ride and 8-hour exposure to the noise level of the corresponding rides. The OSHA PEL dose and 8-hour projected dose were not calculated because all of the 1-min L_{eq} of all train rides are below the OSHA PEL threshold of 90 dBA. In addition, the 1-min average noise levels of the Brown, Red, and Purple Lines are under the OSHA AL and ACGIH TLV threshold of 80 dBA; therefore, the doses per ride and per 8 hour of these train lines were not calculated.

The 8-hour projected dose estimates the dose for an 8-hour work shift. It assumes that the single-ride dose remains constant for 8 hours. Since research participants were asked to ride on the first car of the train and sit close to the train drivers, the dose and 8-hour projected dose could be used to estimate the noise exposure of the train drivers. According to OSHA, an employer must implement a hearing conservation program if the employee dose is at or above 50% of the PEL. As shown in the Table IX, the Blue Line has the highest values of all measures, but none of the exposures exceeds 50% dose. The highest Blue Line OSHA and TLV 8-hour projected doses are on the O'Hare branch, which are 12.98% and 25.24%, respectively.

The TWA exposures per ride and per 8-hour period were calculated using equations (3) and (4). The TWA exposures calculated by the ACGIH equation are higher than those calculated by the OSHA equation because the dose used in the ACGIH equation has smaller allowable exposure time than the OSHA equation, and because the exchange rate is 3 dBA for ACGIH instead of 5 dBA for OSHA. The highest OSHA AL and TLV 8h-TWA exposures are on the O'Hare branch of the Blue Line, 75 dBA and 79 dBA respectively. In addition, the OSHA and TLV TWA exposure per ride and per 8-hour exposure period on the O'Hare branch are higher than the TWA values on the Forest Park branch. Some of the OSHA AL TWA exposures per ride could not be calculated but the dosimeter software provided an estimate. Estimated doses are marked with two stars in Table X.

TABLE X**COMPARISON WITH OSHA AND NIOSH NOISE STANDARDS**

Line	Branch	Calculated OSHA Action Level				Calculated TLV			
		Per ride		Per 8 hours		Per ride		Per 8 hours	
		TWA (dBA)	Dose (%)	TWA (dBA)	Dose (%)	TWA (dBA)	Dose (%)	TWA (dBA)	Dose (%)
Blue	Downtown—Forest Ride 1	54.8	0.76	74.08	11.01	66.39	1.38	78	19.94
Blue	Downtown—Forest Ride 2	52.6	0.56	72.62	8.99	64.44	0.88	76.5	14.13
Blue	Downtown—O’Hare Ride 1	55.86	0.88	73.26	9.82	66.67	1.47	77.14	16.39
Blue	Downtown—O’Hare Ride 2	59.25	1.41	75.27	12.98	69.36	2.73	79.02	25.24
Brown	Downtown—Kimball Ride 1	27.3**	*	*	0.2**	*	*	*	*
Brown	Downtown—Kimball Ride 2	20.2 **	*	*	0.1**	*	*	*	*
Brown	Downtown—Kimball Ride 3	43.4**	*	*	1.6 **	*	*	*	*
Brown	Downtown—Kimball Ride 4	44.4**	*	*	1.5**	*	*	*	*
Green	Downtown—Ashland	11.2**	*	*	0.0**	*	*	*	*
Green	Downtown—Cottage Grove	36.7**	*	*	1.5**	*	*	*	*

COMPARISON WITH OSHA AND NIOSH NOISE STANDARDS

Line	Branch	Calculated OSHA Action Level				Calculated TLV			
		Per ride		Per 8 hours		Per ride		Per 8 hours	
		TWA (dBA)	Dose (%)	TWA (dBA)	Dose (%)	TWA (dBA)	Dose (%)	TWA (dBA)	Dose (%)
Green	Downtown—Harlem Ride 1	39.3**	*	*	1.2**	*	*	*	*
Green	Downtown—Harlem Ride 2	47.33	0.27	66.97	4.11	61.23	0.42	72.97	6.27
Orange	Downtown—Midway Ride 1	36.5	0.06	54.61	0.74	54.03	0.08	64.95	0.99
Orange	Downtown—Midway Ride 2	35.2	0.05	53.89	0.67	53.45	0.07	64.44	0.88
Orange	Downtown—Midway Ride 3	29.7 **	*	*	0.3**	*	*	*	*
Orange	Downtown—Midway Ride 4	27.7 **	*	*	0.2**	*	*	*	*
Pink	Downtown—Cermak Ride 1	48.33	0.31	66.56	3.88	62.24	0.53	73.22	6.65
Pink	Downtown—Cermak Ride 2	47.6	0.28	65.79	3.49	61.33	0.43	72.30	5.38
Pink	Downtown—Cermak Ride 3	36.5	0.06	54.7	0.75	54.03	0.08	65.17	1.04
Pink	Downtown—Cermak Ride 4	34.1**	*	*	0.4 **	*	*	*	*
Purple	Downtown—Linden Ride 1	25.2**	*	*	0.1**	*	*	*	*

COMPARISON WITH OSHA AND NIOSH NOISE STANDARDS

Line	Branch	Calculated OSHA Action Level				Calculated TLV			
		Per ride		Per 8 hours		Per ride		Per 8 hours	
		TWA (dBA)	Dose (%)	TWA (dBA)	Dose (%)	TWA (dBA)	Dose (%)	TWA (dBA)	Dose (%)
Purple	Downtown—Linden Ride 2	30.3**	*	*	0.2**	*	*	*	*
Purple	Downtown—Linden Ride 3	39.6**	*	*	0.6**	*	*	*	*
Purple	Downtown—Linden Ride 4	50.7**	*	*	3.3**	*	*	*	*
Red	Downtown—Howard Ride 1	33.4**	*	*	0.5 **	*	*	*	*
Red	Downtown—Howard Ride 2	41.3**	*	*	1.3 **	*	*	*	*
Red	Downtown—95th Ride 1	36.0 **	*	*	0.8 **	*	*	*	*
Red	Downtown—95th Ride 2	41.5**	*	*	1.9**	*	*	*	*

*: Not applicable because the noise level is below the OSHA Action Level and TLV threshold of 80 dBA.

** : Casella software calculations.

IV. DISCUSSION

Patterns of the segment noise levels were consistent with patterns of the 1-min noise levels. The 1-min average (L_{eq}) and segment-average noise levels ($S.L_{eq}$) on the Blue Line were significantly higher than other train lines ($p < .05$). The mean L_{eq} between the two branches of the Blue line were not significantly different from each other. This similarity between branches was also observed for the Green and Red Lines. The Purple Line had the lowest average noise level (71.23 dBA). Both the Red and Blue lines run underground through the Loop (on different tracks), but the mean L_{eq} level of the Blue Line was 5.7 dBA higher than the Red Line ($p < .05$). We have provided evidence that some factors including tunnel and variation among train lines can contribute to the differences in noise levels. Some factors not considered in this study, such as wheel, brake conditions, and the quality of the track, may explain some differences among train lines.

In the Neitzel et al. study on New York City's Mass Transit System, the mean L_{eq} measured inside the MTA and PATH trains was 79.3 dBA and 79.2 dBA, which are a little higher than the mean L_{eq} of the Blue Line. The mean L_{eq} measured in the BART study was about 4 dBA higher than the mean L_{eq} on the Blue Line (Dinno et al., 2011).

There were three measured L_{peak} values that exceeded 120 dB, which is the threshold for hearing impairment in children used by WHO (WHO 1999). The maximum of L_{peak} value was on the Blue Line, 127 dB, which does not exceed the recommendation of impulsive noise exposure of 140 dB by OSHA (OSHA 2015). This maximum L_{peak} on the CTA was lower than the maximum L_{peak} recorded in the BART study (147 dB), and L_{peak} values above 120 dB were recorded less frequently in Chicago than in the BART study (Dinno et al., 2011).

In the noise study conducted in New York City by Neitzel et al. (2009), they measured noise level at the vehicle boarding platform to capture noise level of vehicles passing a station and found platform noise levels to be significantly higher than the combined noise measurement across stations. Therefore, I proposed a hypothesis that the number of passing trains is associated with the noise level within the monitored train ride. However, the scatter plot (Figure 4) showed no association between passing trains and noise levels.

Noise level varied with train track locations. The mean of $S.L_{eq}$ of train segments involving travel through tunnel, 76.96 dBA, was significantly higher than the mean $S.L_{eq}$ of elevated segments and ground segments, which were 73.85 and 74.81 dBA respectively ($p < .05$). The mean $S.L_{peak}$ of train segments on the ground level was significantly higher than the mean $S.L_{peak}$ of elevated segments, but the difference of the mean $S.L_{peak}$ between ground segments and tunnel segments was not statistically significant ($p > .05$). Elevated L_{eq} level observed in tunnels is consistent with the study in New York (Neitzel et al., 2009) and in the BART study (Dinno et al., 2011). Dinno et al. found that the L_{eq} increased by 5.1 dBA in segments involving travel through the tunnels (Dinno et al., 2011).

The Blue Line has the highest single-ride dose and 8-h projected dose, but the single-ride and 8-hour projected doses of all train lines did not exceed the OSHA AL or ACGIH TLV standards. The OSHA requires employers to implement a hearing conservation program if employees are exposed above 50% of the noise dose. The TLV 8-hour TWA is highest on the O'Hare branch of the Blue Line, 79 dBA, and this value does not exceed the TLV occupational exposure limit of 85 dBA. However, train drivers may have a unique exposure because they have longer exposure durations than riders and are in a separate cab from riders. In particular, the driver cab has openable windows; and opening the windows could increase noise exposure for the train operator. Therefore, the noise exposure on the Blue Line may pose potential health risks to train drivers. The TWA 8-hour levels

on the Blue Line calculated by the ACGIH TLV equation are similar with the mean 8-hour noise exposure of bus drivers in Curitiba City Brazil, which are from 74 dBA to 79 dBA (Bruno et al., 2013).

The study in New York found the L_{eq} noise level on the underground platform was significantly higher than the L_{eq} measured inside train car (Neitzel et al., 2009). We did not examine the noise levels on the platform at CTA stations but it can be anticipated that the noise levels on CTA platforms are probably higher than the noise levels measured in the train car because of the shielding offered by the train car to riders. Since decibels are logarithms, therefore, a small increase in noise level cause the risk of hearing loss more intense.

The doses per ride on CTA train lines are relatively small and do not exceed OSHA AL and TLV standards, which means noise levels on CTA trains are not likely to pose noise-related health risks to train riders. Diaz et al. (2005) found that the noise exposure during transportation accounts for 12.6% of the total daily noise exposure perceived by an inhabitant of the Madrid region in Spain, where the mean L_{eq} on subway was about 79 dBA, which is similar with the average noise levels on the Blue Line.

Dinno et al. (2011) found the L_{eq} increased linearly, with average velocity by $0.52 \text{ dBA km}^{-1} \text{ h}^{-1}$. We were not able to obtain GIS data of CTA train lines or information about segment length from CTA; therefore, average velocity could not be constructed using segment lengths. This is an area for future work.

In addition, we had a small sample size of 28 train rides and could not measure the noise levels on all train tracks. For example, we could only measure the noise levels of the Purple, Orange, Pink, and Brown Lines one way, on the track departing from downtown. We hope that we can expand this study to measure noise levels on the other tracks departing from Linden, Midway

International Airport, 54th/Cermak, and Kimball to downtown. From there, we can compare the noise levels on different tracks of the same train line.

V. CONCLUSION

Our results indicate that noise exposure on CTA train lines is not high enough to pose significant health risks for train riders. The noise doses per 8 hours and 8-hour TWA were calculated on each train line to estimate occupational noise exposure of train drivers. Although these values do not exceed the OSHA and TLV standards, train drivers may have unique exposures because they are in separate cab from riders and have longer exposure durations than riders. We noted significant differences between the mean noise levels on some train lines. The mean average noise level on the Blue Line is significantly higher than the other train lines. In addition, the mean 1-min average noise level of train segments involving travel through tunnels was significantly higher than that of ground and elevated segments. Public health authorities can recommend CTA to put notification on the Blue Line to warn riders about possible high noise exposure in the tunnel.

In order to capture the occupational exposure of train drivers, future studies should focus on asking train drivers to wear a noise dosimeter during their work shift. If their noise exposure exceeds the TLV of 85 dBA, hearing protection should be required for CTA train drivers. The highest 8-h TWA noise exposure inside the train is 79 dBA; therefore, the noise level outside could be much louder than that. Therefore, research in the future should take into account of noise exposure in the environment as well.

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APPENDICES

APPENDIX A

COMPARING THE SEGMENT-PEAK NOISE LEVEL ($S.L_{PEAK}$) AND SEGMENT-AVERAGE NOISE LEVELS (L_{EQ}) BETWEEN TRAIN LINES

The segment-peak noise levels ($S.L_{peak}$) were compared between train lines using mixed-effect model, with the random effect is train ride (Table XI). The intra-class correlation is 24%, indicating that train ride explains 24% of the variation in noise levels, after adjusting for the fixed effects. As shown in Table XII, $S.L_{peak}$ levels of Blue Line and Brown Line are statistically higher than the intercept, which is the mean $S.L_{peak}$ level on the Pink Line, 108.11 dB.

The pattern of statistically significant contrasts was similar for $S.L_{peak}$ and L_{peak} (Table V). Specifically, $S.L_{peak}$ levels of Blue and Brown Line are significantly higher than $S.L_{peak}$ of the Pink Line ($p < .05$). In addition, $S.L_{peak}$ of the Blue Line is also significantly higher than $S.L_{peak}$ of the Purple Line, and the difference is 2.49 dB.

APPENDIX A (continued)

TABLE XI

LINEAR MIXED-EFFECT MODEL FOR SEGMENT-PEAK NOISE LEVELS

	S.L _{peak}		
Quality of Model Fit:			
AIC	2795.92		
Log Likelihood	-1388.96		
Random effects (SD):			
Intercept	1.59		
Residual	2.83		
Fixed effects:			
	Value	SE	p-value
Intercept	107.27	0.85	0.00
Purple	0.56	1.20	0.65
Orange	1.49	1.22	0.23
Brown	2.61	1.20	0.04
Blue	3.19	1.22	0.02
Green	2.12	1.24	0.10
Red	1.73	1.22	0.17

APPENDIX A (continued)

TABLE XII

SIGNIFICANT $S. L_{PEAK}$ CONTRASTS BETWEEN TRAIN LINES, WITH SE ESTIMATES FOR THE DIFFERENCE AND 95% CIs

Train Lines Compared	Contrast	SE	95% CI
Blue-Purple	2.63	1.22	0.23, 5.02
Blue-Pink	3.19	1.22	0.78, 5.59
Brown-Pink	2.61	1.20	0.26, 4.97

The segment-average noise levels ($S. L_{eq}$) were compared between train lines using a mixed-effect model, with train ride is the random effect and train line as the fixed effect (Table XIII). The intra-class correlation is 32.1%, indicating that train ride explains 32.1% of the variation in noise levels, after adjusting for train line. Consistent with the mixed effect model of 1-min L_{eq} (Table V), only the $S. L_{eq}$ level of the Blue Line differs significantly from the intercept, which is the mean $S. L_{eq}$ on the Pink Line, 73.73 dBA. Additionally statistically significant contrasts are shown in Table XIV.

APPENDIX A (continued)

TABLE XIII

LINEAR MIXED-EFFECT MODEL FOR SEGMENT-AVERAGE NOISE LEVEL

Quality of Model Fit:			
AIC	2607.66		
Log Likelihood	-1294.83		
Random effects (SD):			
Intercept	1.63		
Residual	2.37		
Fixed effects:			
	Value	SE	p-value
Intercept	73.73	0.85	0.00
Purple	-1.64	1.20	0.19
Orange	0.13	1.21	0.91
Brown	-0.62	1.20	0.61
Blue	4.77	1.22	0.00
Green	-0.94	1.23	0.45
Red	-0.94	1.21	0.45

APPENDIX A (continued)

TABLE XIV

SIGNIFICANT S.L_{EQ} CONTRAST BETWEEN TRAIN LINES, WITH SE ESTIMATES FOR THE DIFFERENCE AND 95% CI

Train Lines Compared	Contrast	SE	CI
Blue-Red	5.71	1.23	3.30, 8.12
Blue-Purple	6.42	1.21	4.03, 8.80
Blue-Orange	4.64	1.22	2.23, 7.05
Blue-Brown	5.40	1.21	3.01, 7.78
Blue-Green	5.71	1.24	3.27, 8.12
Blue-Pink	4.77	1.22	2.38, 7.17

APPENDIX B

Observation Instruction

A. Blue Line Observation Instruction

1. Occupancy categorization

Please observe the number of riders on the car when leaving the station. Circle one of the categories:

- **LOW:** Many open seats on the car, though a few riders may be standing.
- **MEDIUM:** Most of the seats are full and some riders are standing.
- **HIGH:** Most of the seats are full and many riders are standing (crowded).

2. Time

Please record the time indicated on the digital clock when doors are opened at each station. The time will be recorded to the minute, such as 9:31.

3. Passing train observation

Please record the time when another train passes by. The time will be recorded to the minute, such as 9:31.

4. Surrounding environment

Record the time when the train changes from being **ELEVATED** into **TUNNEL** between **UIC–HALSTED** and **CLINTON**.

Record the time when the train changes from **TUNNEL** to being **ELEVATED** between **DIVISION** and **DAMEN**.

APPENDIX B (continued)

Record the time when the train changes from being **ELEVATED** into **TUNNEL** between **CALIFORNIA** and **LOGAN SQUARE**.

Record the time when the train changes from **TUNNEL** to **GROUND** between **BELMONT** and **ADDISON**.

Record the time when the train changes from **GROUND** to **TUNNEL** between **ROSEMONT** and **O'HARE**.

5. Unusual circumstances

Please record unusual circumstances that could increase the noise level on the train.
For example, note if people are talking loudly or playing music.

6. Train car model

Please note if the train car has center-facing seats (write “center”).

APPENDIX B (continued)

Direction: Blue line from Forest Park to O'Hare					
Train car model:					
Date:					
<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Surrounding environment (Time)</i>	<i>Unusual circumstances</i>
Forest Park					
Harlem					
Oak Park					
Austin					
Cicero					
Pulaski					
Kedzie- Homan					
Western					

APPENDIX B (continued)

<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Surrounding environment (Time)</i>	<i>Unusual circumstances</i>
Illinois Medical District					
Racine					
UIC-Halsted					
Clinton					
La Salle					
Jackson					
Monroe					
Washington					
Clark/Lake					
Grand					
Chicago					

APPENDIX B (continued)

<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Surrounding environment (Time)</i>	<i>Unusual circumstances</i>
Division					
Damen					
Western					
California					
Logan Square					
Belmont					
Addison					
Irving Park					
Montrose					
Jefferson Park					
Harlem					
Cumberland					

APPENDIX B (continued)

<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Surrounding environment (Time)</i>	<i>Unusual circumstances</i>
Rosemont					
O'Hare					

APPENDIX B (continued)

B. Brown Line Observation Instruction

1. Occupancy categorization

Please observe the number of riders on the car when leaving the station. Circle one of the categories:

- **LOW:** Many open seats on the car, though a few riders may be standing.
- **MEDIUM:** Most of the seats are full and some riders are standing.
- **HIGH:** Most of the seats are full and many riders are standing (crowded).

2. Time

Please record the time indicated on the digital clock when doors are opened at each station. The time will be recorded to the minute, such as 9:31.

3. Passing train observation

Please record the time when another train passes by. The time will be recorded to the minute, such as 9:31.

4. Surrounding environment

Recording the time when the train change from being elevated to on ground between **Rockwell and Francisco**.

5. Unusual circumstances

Please record unusual circumstances that could increase the noise level on the train. For example, note if people are talking loudly or playing music.

6. Train car model

Please note if the train car has center-facing seats (write “center”).

APPENDIX B (continued)

Direction: Pink line to 54th/ Cermak					
Train car model:					
Date:					
<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Surrounding environment (Time)</i>	<i>Unusual circumstances</i>
Washington/Wells					
Quincy					
LaSalle/ Van Buren					
Harold Washington Library					
Adams/Wabash					
Madison/Wabash					
Randolph/Wabash					
State/Lake					
Clark/Lake					
Merchandise Mart					

APPENDIX B (continued)

<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Surrounding environment (Time)</i>	<i>Unusual circumstances</i>
Chicago					
Sedgwick					
Armitage					
Fullerton					
Diversey					
Wellington					
Belmont					
Southport					
Paulina					
Addision					
Irving Park					
Montrose					
Damen					

APPENDIX B (continued)

<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Surrounding environment (Time)</i>	<i>Unusual circumstances</i>
Western					
Rockwell					
Francisco					
Kedzie					
Kimball					

APPENDIX B (continued)

C. Green Line Observation Instruction

1. Occupancy categorization

Please observe the number of riders on the car when leaving the station. Circle one of the categories:

- **LOW:** Many open seats on the car, though a few riders may be standing.
- **MEDIUM:** Most of the seats are full and some riders are standing.
- **HIGH:** Most of the seats are full and many riders are standing (crowded).

2. Time

Please record the time indicated on the digital clock when doors are opened at each station. The time will be recorded to the minute, such as 9:31.

3. Passing train observation

Please record the time when another train passes by. The time will be recorded to the minute, such as 9:31.

4. Unusual circumstances

Please record unusual circumstances that could increase the noise level on the train. For example, note if people are talking loudly or playing music.

5. Train car model

Please note if the train car has center-facing seats (write “center”).

APPENDIX B (continued)

Direction: Harlem/Lake to Oak Park				
Train car model:				
Date:				
<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Unusual circumstances</i>
Harlem/Lake				
Oak Park				
Ridgeland				
Austin				
Central				
Laramie				
Cicero				
Pulaski				
Conservatory-Central Park Drive				
Kedzie				

APPENDIX B (continued)

<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Unusual circumstances</i>
California				
Ashland				
Morgan				
Clinton				
Clark/Lake				
State/Lake				
Randolph/Wabash				
Madison/Wabash				
Adams/Wabash				
Roosevelt				
35th-Bronzeville- IIT				
Indiana				
43rd				

APPENDIX B (continued)

<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Unusual circumstances</i>
47th				
51st				
Garfield				
Halsted				
Ashland/63rd				
King Drive				
Cottage Grove				

APPENDIX B (continued)

D. Orange Line Observation Instruction

1. Occupancy categorization

Please observe the number of riders on the car when leaving the station. Circle one of the categories:

- **LOW:** Many open seats on the car, though a few riders may be standing.
- **MEDIUM:** Most of the seats are full and some riders are standing.
- **HIGH:** Most of the seats are full and many riders are standing (crowded).

2. Time

Please record the time indicated on the digital clock when doors are opened at each station. The time will be recorded to the minute, such as 9:31.

3. Passing train observation

Please record the time when another train passes by. The time will be recorded to the minute, such as 9:31.

4. Surrounding environment

Recording the time when the train change from being elevated to on ground between **Pulaski** and **Midway**.

5. Unusual circumstances

Please record unusual circumstances that could increase the noise level on the train. For example, note if people are talking loudly or playing music.

6. Train car model

Please note if the train car has center-facing seats (write “center”).

APPENDIX B (continued)

Direction: Orange line to Midway					
Train car model:					
Date:					
Station	Time	Occupancy	Passing train observation (Time)	Surrounding environment (Time)	Unusual circumstances
Harold Washington Library					
La Salle/Van Buren					
Quincy					
Washington Wells					
Clark/Lake					
State/Lake					
Randolph/Wabash					
Madison/Wabash					
Adams/Wabash					
Roosevelt					

APPENDIX B (continued)

<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Surrounding environment (Time)</i>	<i>Unusual circumstances</i>
Halsted					
Ashland					
35th/Archer					
Western					
Kedzie					
Pulaski					
Midway					

APPENDIX B (continued)

E. Purple Line Observation Instruction

1. Occupancy categorization

Please observe the number of riders on the car when leaving the station. Circle one of the categories:

- **LOW:** Many open seats on the car, though a few riders may be standing.
- **MEDIUM:** Most of the seats are full and some riders are standing.
- **HIGH:** Most of the seats are full and many riders are standing (crowded).

2. Time

Please record the time indicated on the digital clock when doors are opened at each station. The time will be recorded to the minute, such as 9:31.

3. Passing train observation

Please record the time when another train passes by. The time will be recorded to the minute, such as 9:31.

4. Surrounding environment

Recording the time when the train change from being elevated to on ground between **Central and Linden.**

5. Unusual circumstances

Please record unusual circumstances that could increase the noise level on the train. For example, note if people are talking loudly or playing music.

6. Train car model

Please note if the train car has center-facing seats (write “center”).

APPENDIX B (continued)

Direction: Purple line to Linden					
Train car model:					
Date:					
<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Surrounding environment (Time)</i>	<i>Unusual circumstances</i>
Clark/Lake					
State/Lake					
Randolph/Wabash					
Madison/Wabash					
Adams/Wabash					
Harold Washington Library					
LaSalle					
Quincy					
Washington/Wells					
Merchandise Mart					
Chicago					

APPENDIX B (continued)

<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Surrounding environment (Time)</i>	<i>Unusual circumstances</i>
Armitage					
Fullerton					
Diversey					
Wellington					
Belmont					
Howard					
South Boulevard					
Main					
Dempster					
Davis					
Foster					
Noyes					

APPENDIX B (continued)

<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Surrounding environment (Time)</i>	<i>Unusual circumstances</i>
Central					
Linden					

APPENDIX B (continued)

F. Red Line Observation Instruction

1. Occupancy categorization

Please observe the number of riders on the car when leaving the station. Circle one of the categories:

- **LOW:** Many open seats on the car, though a few riders may be standing.
- **MEDIUM:** Most of the seats are full and some riders are standing.
- **HIGH:** Most of the seats are full and many riders are standing (crowded).

2. Time

Please record the time indicated on the digital clock when doors are opened at each station. The time will be recorded to the minute, such as 9:31.

3. Passing train observation

Please record the time when another train passes by. The time will be recorded to the minute, such as 9:31.

4. Surrounding environment

Recording the time when the train changes from **GROUND** to be **ELEVATED** between **SOX-35TH** and **CERMAK/CHINATOWN**.

Recording the time when the train changes from being **ELEVATED** to **TUNNEL** between **CERMAK/CHINATOWN** and **ROOSEVELT**.

Recording the time when the train changes from **TUNNEL TO** being **ELEVATED** between **NORTH/CLYBOURN** and **FULLERTON**.

5. Unusual circumstances

Please record unusual circumstances that could increase the noise level on the train. For example, note if people are talking loudly or playing music.

6. Train car model

Please note if the train car has center-facing seats (write “center”).

APPENDIX B (continued)

Direction: Red line from 95th to Howard					
Train car model:					
Date:					
Station	Time	Occupancy	Passing train observation (Time)	Surrounding environment (Time)	Unusual circumstances
95th/Dan Ryan					
87th					
79th					
69th					
63rd					
Garfield					
47 th					
Sox-35th					
Cermak-Chinatown					
Roosevelt					

APPENDIX B (continued)

<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Surrounding environment (Time)</i>	<i>Unusual circumstances</i>
Harrison					
Jackson					
Monroe					
Lake					
Grand/State					
Chicago/State					
Clark/Division					
North/Clybourn					
Fullerton					
Belmont					
Addison					
Sheridan					

APPENDIX B (continued)

<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Surrounding environment (Time)</i>	<i>Unusual circumstances</i>
Wilson					
Lawrence					
Argyle					
Berwyn					
Bryn Mawr					
Thorndale					
Granville					
Loyola					
Morse					
Jarvis					
Howard					

APPENDIX B (continued)

G. Pink Line Observation Instruction

1. Occupancy categorization

Please observe the number of riders on the car when leaving the station. Circle one of the categories:

- **LOW:** Many open seats on the car, though a few riders may be standing.
- **MEDIUM:** Most of the seats are full and some riders are standing.
- **HIGH:** Most of the seats are full and many riders are standing (crowded).

2. Time

Please record the time indicated on the digital clock when doors are opened at each station. The time will be recorded to the minute, such as 9:31.

3. Passing train observation

Please record the time when another train passes by. The time will be recorded to the minute, such as 9:31.

4. Surrounding environment

Recording the time when the train changes from being elevated to on ground between **Pulaski** and **Kostner**.

5. Unusual circumstances

Please record unusual circumstances that could increase the noise level on the train. For example, note if people are talking loudly or playing music.

6. Train car model

Please note if the train car has center-facing seats (write “center”).

APPENDIX B (continued)

Direction: Pink line to 54th/ Cermak					
Train car model:					
Date:					
<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Surrounding environment (Time)</i>	<i>Unusual circumstances</i>
Clark/Lake					
State/Lake					
Randolph/Wabash					
Madison/Wabash					
Adams/Wabash					
Harold Washington Library					
LaSalle					
Quincy					
Washington/Wells					
Clinton					

APPENDIX B (continued)

<i>Station</i>	<i>Time</i>	<i>Occupancy</i>	<i>Passing train observation (Time)</i>	<i>Surrounding environment (Time)</i>	<i>Unusual circumstances</i>
Morgan					
Ashland					
Polk					
18th					
Damen					
Western					
California					
Kedzie					
Central Park					
Pulaski					
Kostner					
Cicero					
54th/Cermak					

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