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ABSTRACT

Excessive noise exposure may present a hazard to hearing, cardiovascular and psychosomatic health. Mass transit systems, such as the Bay Area Rapid Transit (BART) system, are potential sources of excessive noise. The purpose of this study was to characterize transit noise and riders' exposure to noise on the BART system using three dosimetry metrics.

We made 268 dosimetry measurements on a convenience sample of 51 line segments. Dosimetry measures were modeled using linear and non-linear multiple regression as functions of average velocity, tunnel enclosure, flooring, and wet weather conditions, and presented visually on a map of the BART system.

This study provides evidence of levels of hazardous levels of noise exposure in all three dosimetry metrics. L_{eq} and L_{max} measures indicate exposures well above ranges associated with increased cardiovascular and psychosomatic health risks in the published literature. L_{peak} indicate acute exposures hazardous to adult hearing on about one percent of line segment rides, and acute exposures hazardous to child hearing on about two percent of such rides.

The noise to which passengers are exposed may be due to train-specific conditions (velocity and flooring), but also to rail conditions (velocity and tunnels). These findings may point at possible remediation (revised speed limits on longer segments, and those segments enclosed by tunnels). The findings also suggest that specific rail segments could be improved for noise.

INTRODUCTION

Bay Area Rapid Transit (BART) is a regional rapid transit rail system connecting portions of San Francisco, Alameda, San Mateo, and Contra Costa Counties. During a typical weekday, passengers take about 360,000 rides on the system.[1] While customer satisfaction with the transit system is generally high, noise on BART trains is consistently reported as one of the greatest factors leading to dissatisfaction,[2] as borne out by complaints reported to local news media.[3-5] Indeed, we have personally witnessed child and adult passengers covering their ears while riding BART, wearing ear protection such as earplugs or earmuffs, and pairs of individuals leaning close together and shouting at high volume in order to carry on conversation. Excessive noise levels associated with other above and below-ground mass transit systems has been documented. [6,7] Most recently, studies of the New York City subway system indicate that noise levels are sufficiently high to be injurious to the hearing health of some portion of the ridership. [8,9]

Noise exposure is a concern on BART for several reasons. As a nuisance, noise inhibits conversation, and can be an unpleasant sensory experience. More concerning, however, are the known and suspected physiological effects of noise on humans. Chronic exposure to high levels of noise is well established as contributing to hearing loss. [10-12] Mounting recent evidence suggests that chronic noise provokes the hypothalamic-pituitary-adrenal axis, activating negative endocrine and vascular outcomes, as seen in the association between chronic noise exposure and increased risk of hypertension,[13-16] increased risk of myocardial infarction,[10,13] and psychosomatic stress. [10,17] Findings have also shown that children living amid chronic noise have elevated levels of stress-induced hormones, as well as elevated blood pressure.[18,19] There is also evidence of negative behavioral outcomes of noise exposure as well,[10,20] including negative behavioral effects of noise on children's cognition, concentration and memory, [17,19-21] and on school performance.[22]

The level of noise on trains results from many interacting factors,[23] including wheel roundness (i.e., deviation from perfectly circular) and wheel trueness (side-to-side wobble in shape), rail condition (e.g., 'corrugation', banking, points, etc.), the speed of a train, whether a particular line segment is in open air or in a tunnel, and the points and curves of a specific line segment among other factors.

This study attempts to quantify BART passengers' potential exposures to hazardous levels of noise using a convenience sample of line segments central to the transit system. We also ask whether different measures of noise exposure are explained by average velocity, tunnel enclosure, flooring, and wet weather conditions.

METHODS

During January, February, and March of 2009, line segments (i.e., the portions of a BART line in a specific direction between one station and the next) were sampled by convenience. The number of samples for the reported segments ranges from 1 to 10.

Measures

Noise dosimetry measurements were made using a Quest Q 300 logging noise dosimeter clipped to the belt, with its microphone clipped to the top of the left shoulder approximately 10 cm from the left ear. Measurements were made separately for each direction in any particular line segment; measurements began with the closing of train doors, and ceased with their opening. The dosimeter's calibration was checked using a QC-10 Calibrator (114 dB at 1000 Hz) a few minutes before the first measurement on each day that measurements were made, and the dosimeter was recalibrated two months before measurements commenced. The dosimeter was set to integrate sound levels over one minute intervals with a 3 dB exchange rate, an 80 dB threshold, an 85 dB criterion and a 115 dB upper limit. We collected average (L_{eq}), maximum (L_{max}) and peak (L_{peak}) sound levels. L_{eq} and L_{max} were A-weighted (dBA), and L_{peak} was unweighted (dB).

In addition, the presence of newer hard composite flooring (versus older carpeting), rain water on the ground, and full or partial enclosure of a line segment by a tunnel were recorded and coded as indicator variables. Average velocity (km/hour) was constructed using line segment lengths from BART GIS data and duration as measured by recorded start and stop times. For two records made when boarding at the Millbrae station, there was a wait of several minutes from the time the doors shut and the time the train commenced moving, and both records were excluded in analyses of average velocity. In all but three cases, measurements were made from the bicycle/wheelchair seat, and in those other three cases were made from the bicycle/handicap/elderly seating.

Descriptive statistics

Unpresented histograms (see appended supplement) characterized the overall distributions of our three dosimetry measures. L_{eq} was massed at about 82 dBA, and was skewed somewhat below the mean with low measures likely resulting from the threshold of 80 dB, thus are likely to be slightly understating the true L_{eq} level. Of the 268 noise dosimetry measurements of L_{eq}, 60 (22%) were above 85 dBA. Measures of L_{peak} massed around 112 dB, but skewed several standard deviations above the mean. Six recorded L_{peak} levels exceeded 120 dB, the World health Organization's (WHO) guideline threshold for hearing impairment in children[24], and three reported L_{peak} levels exceeded 140 dB, the threshold for hearing impairment in adults used by both the National Institute of Occupational Health and Safety (NIOSH) and the WHO [24,25]; the maximum recorded L_{peak} level was above 147 dB. (This level was slightly over the upper end of the dosimeter's

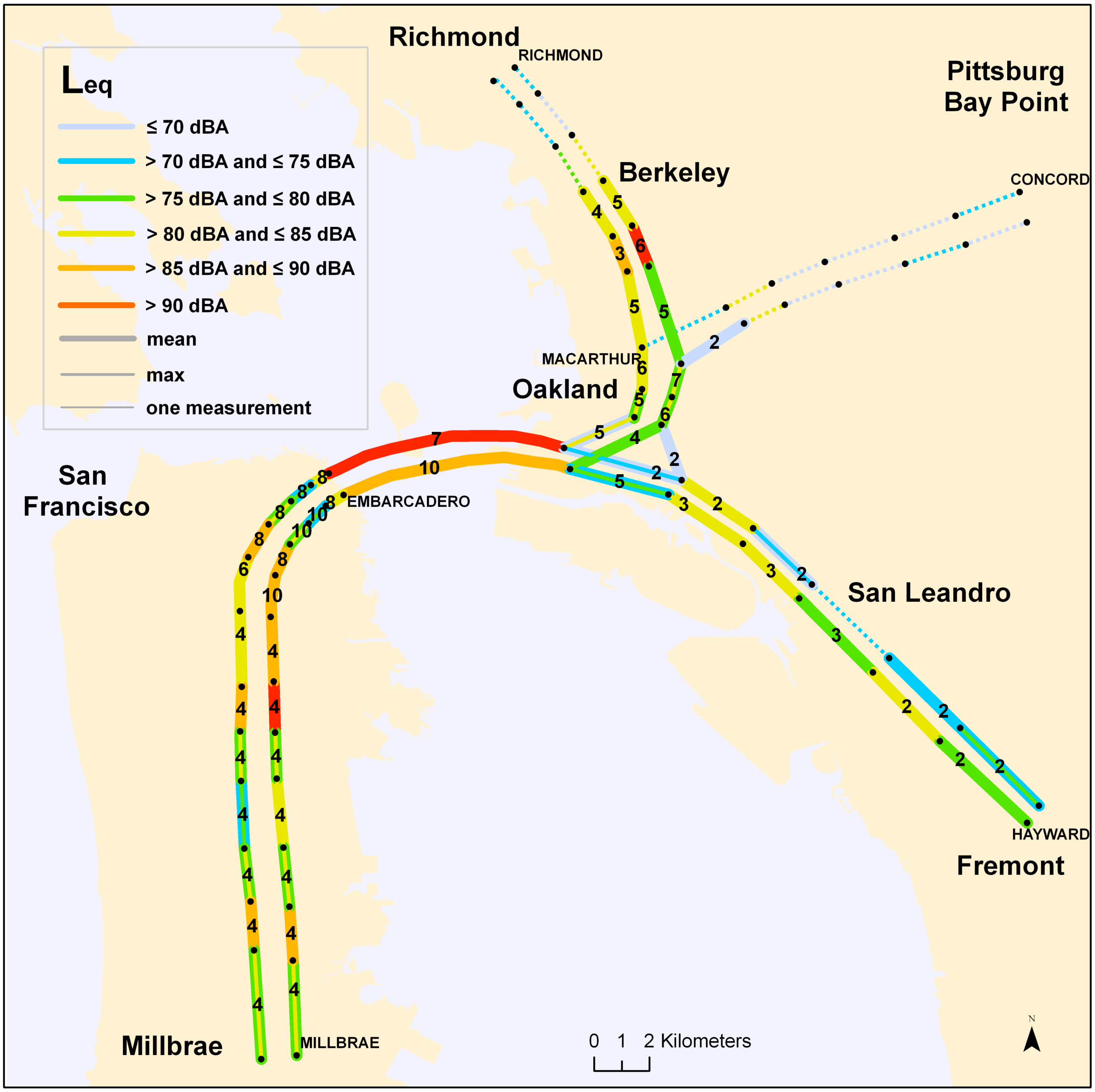

Figure 1 Map of mean and maximum Leq (dBA). The number of observations is overlaid on each line segment except those with a single measurement. The shape and position of line segments have been distorted to facilitate visual discrimination, and should be interpreted as schematic.

listed range, but a sensitivity analysis limiting this value of 144 gave substantively the same results in Table IV, with difference in the restricted model estimate appearing at the 5th significant figure.) L_{max} was massed just under 90 dBA, but is slightly skewed to the right. 141 measurements of L_{max} were greater than 90 dBA, 4 measurements of L_{max} were greater than 100 dBA, and the maximum was greater than 105 dBA. These are very high levels, well exceeding the levels cited in the US

Figure 2 Map of mean and maximum Lpeak (dB). The number of observations is overlaid on each line segment except those with a single measurement. The shape and position of line segments have been distorted to facilitate visual discrimination, and should be interpreted as schematic.

Environmental Protection Agency's (1979) examination of maximum allowable exposures.[26] We considered the effects of time of day as a proxy for passenger noise on all three noise measures using multiple nonparametric smoothing regressions (presented in the appended supplement), but found no relationship in each case. Figures 1a, b and c illustrate the average and maximum recorded values for all three metrics along each line segment for which there were two or more measures, in order to

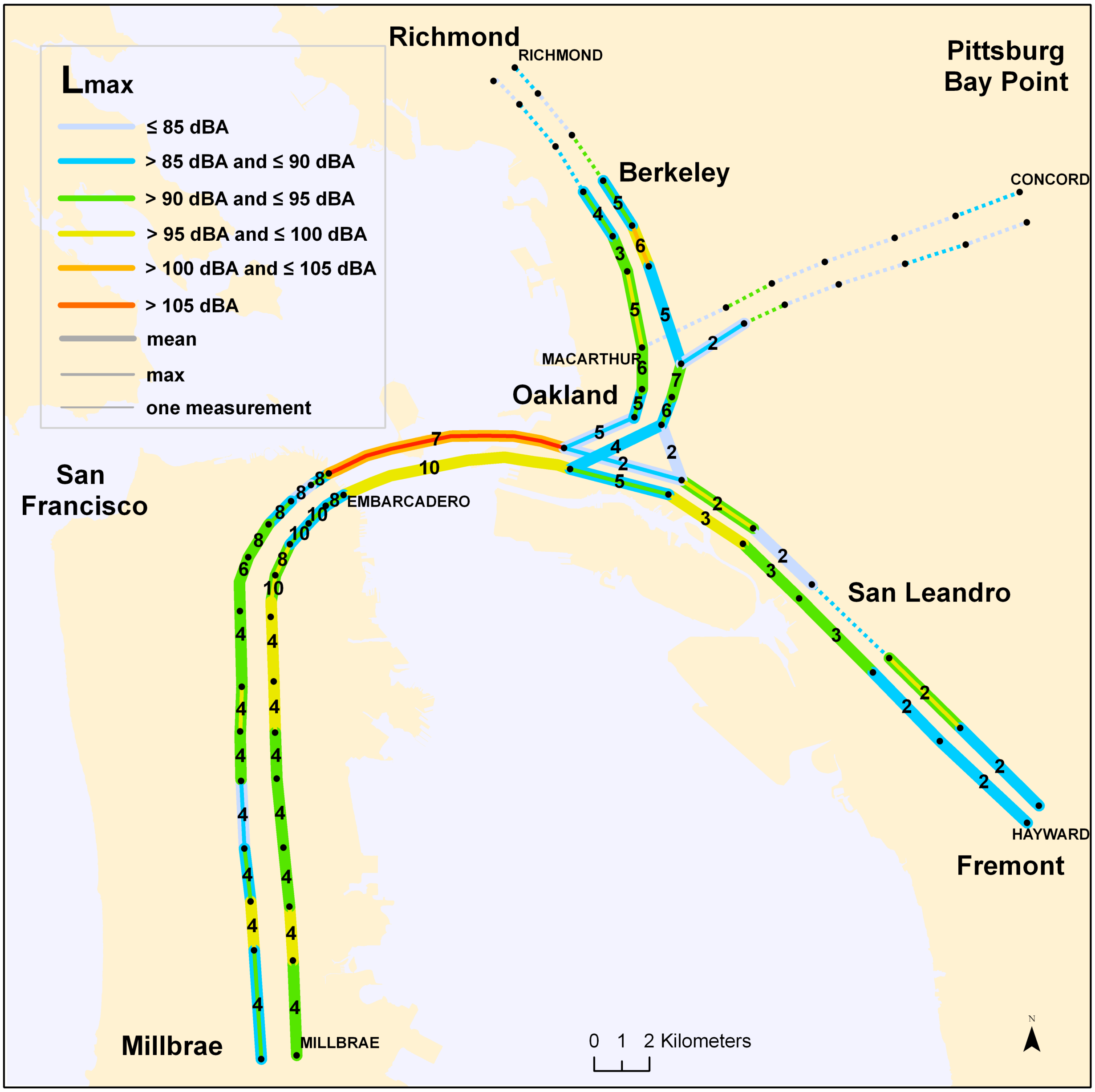

Figure 3 Map of mean and maximum Lmax (dBA). The number of observations is overlaid on each line segment except those with a single measurement. The shape and position of line segments have been distorted to facilitate visual discrimination, and should be interpreted as schematic.

visually characterize the noise exposure of particular rides (color maps annotated with measurements are available in the appended supplement). These maps were generated using the numbers in Table I, which associates average and maximum recorded for each dosimetry measure.

These data can be used to describe exposure to transit noise on BART cars under different plausible transit scenarios. We present three such commute scenarios corresponding to actual

Table I: Dosimetry measures for 51 BART line segments with two or more measures. Numbers given are mean (SD) maximum. N is the number of observations made on each line.

Segment	N	Duration	L_{eq} (dBA)	L_{peak} (dB)	L_{max} (dBA)
12th St–19th St	6	64 (3.4)	88 (4.1) 93	77 (8) 82	109 (4.2) 118
12th St–West Oakland	5	264 (51.3)	84 (2.9) 89	69 (7.4) 80	111 (0.7) 112
16th St–24th St	6	101 (2.1)	92 (0.7) 93	82 (1.2) 83	114 (0.7) 115
16th St–Civic Center	8	119 (7.8)	94 (1.5) 96	87 (1.7) 90	119 (10.6) 140
19th St–12th St	5	65 (8.3)	87 (3) 90	79 (3.3) 82	110 (1.7) 111
19th St–MacArthur	7	222 (104.1)	91 (2.1) 94	79 (2.7) 82	116 (0.9) 117
24th St–16th St	10	103 (7.5)	92 (1.7) 95	86 (2) 90	115 (2.6) 120
24th St–Glen Park	4	143 (4)	93 (0.7) 93	84 (0.6) 85	111 (0.7) 112
Ashby–MacArthur	5	167 (5.9)	95 (1.4) 97	82 (1.4) 84	113 (0.9) 114
Ashby–Berkeley	6	127 (8.3)	98 (1.9) 101	90 (1.9) 93	113 (1.7) 115
Balboa Park–Daly City	4	216 (54.8)	92 (1) 94	80 (2.5) 83	115 (1.3) 116
Balboa Park–Glen Park	4	117 (3.3)	97 (1.1) 98	91 (1.2) 92	115 (1.3) 116
Bay Fair–Hayward	2	218 (2.8)	87 (2.5) 89	77 (3) 79	113 (1.5) 114
Bay Fair–San Leandro	2	272 (81.3)	91 (9.6) 97	73 (3) 75	129 (25.9) 147
Civic Center–16th St	8	117 (2)	92 (1.9) 94	86 (1.6) 88	111 (1.7) 114
Civic Center–Powell	10	70 (3.9)	89 (3) 94	78 (2.8) 82	111 (1.5) 114
Coliseum–Fruitvale	2	173 (5.7)	84 (1.5) 85	68 (5.2) 72	110 (3) 112
Coliseum–San Leandro	3	221 (4)	90 (2.4) 93	79 (1.8) 80	111 (1.6) 113
Colma–Daly City	4	187 (16.1)	93 (1) 94	81 (1.7) 83	112 (1.2) 114
Colma–South San Francisco	4	156 (4.8)	89 (1.2) 90	78 (2) 80	111 (1.4) 113
Daly City–Balboa Park	4	183 (5.4)	91 (2.8) 93	80 (3.8) 83	114 (1.4) 115
Daly City–Colma	4	216 (5.4)	84 (1.6) 86	73 (3.7) 77	112 (1.1) 113
Berkeley–Ashby	3	118 (3.1)	94 (1.6) 95	86 (1.7) 87	112 (2.7) 115
Berkeley–North Berkeley	5	124 (0.7)	88 (2.3) 91	81 (2.3) 85	113 (1.7) 115
Embarcadero–Montgomery	8	59 (1.4)	89 (1.5) 91	82 (1.1) 84	114 (1.4) 116
Embarcadero–West Oakland	10	394 (9.5)	97 (1.8) 100	87 (1.1) 89	114 (1.3) 117
Fruitvale–Coliseum	3	172 (8.1)	92 (1.2) 93	82 (0.7) 83	114 (1.3) 114
Fruitvale–Lake Merritt	2	234 (2.1)	94 (3.7) 96	82 (1.7) 83	112 (1.2) 113
Glen Park–24th St	4	139 (3.5)	96 (0.7) 96	86 (0.8) 87	115 (1) 116
Glen Park–Balboa Park	4	120 (7.8)	95 (1.1) 96	87 (0.8) 88	113 (1.1) 114
Hayward–Bay Fair	2	219 (9.2)	85 (2.5) 87	74 (3.4) 76	112 (2.6) 114
Lake Merritt–12th St	2	154 (2.1)	81 (0.1) 81	62 (0.7) 63	111 (2.4) 113
Lake Merritt–Fruitvale	3	207 (3.8)	95 (1.4) 97	83 (0.8) 84	116 (3.7) 120
Lake Merritt–West Oakland	2	317 (39.6)	85 (0.7) 85	68 (5.7) 72	111 (0.6) 112
MacArthur–19th St	6	179 (28.3)	90 (1.6) 93	80 (1.9) 84	116 (1.2) 118
MacArthur–Ashby	5	180 (16.3)	87 (2.3) 89	75 (3.4) 79	109 (1.7) 111
MacArthur–Rockridge	2	116 (5.7)	83 (3) 85	66 (3.5) 69	117 (7.2) 122
Millbrae–San Bruno	4	490 (300.7)	91 (1.1) 92	79 (2.1) 81	113 (0.4) 113
Montgomery–Embarcadero	8	65 (7.4)	89 (2.2) 93	81 (3) 84	113 (1.4) 115
Montgomery–Powell	8	66 (3.9)	84 (2.3) 88	73 (4.5) 80	106 (1.4) 108
North Berkeley–Berkeley	4	134 (20.1)	90 (0.5) 90	82 (1.4) 84	120 (15.4) 143
Powell–Civic Center	8	75 (10)	87 (3.1) 93	78 (2.7) 83	109 (1.3) 112
Powell–Montgomery	10	73 (13.3)	86 (3.7) 94	73 (5.6) 78	107 (1.9) 111
San Bruno–Millbrae	4	351 (111.5)	88 (3) 92	76 (5) 81	111 (1.4) 113
San Bruno–South San Francisco	4	179 (8.3)	96 (1.3) 97	86 (1.2) 87	114 (1.2) 115
San Leandro–Bay Fair	2	193 (2.1)	89 (1) 90	81 (1.7) 82	116 (3.3) 118
South San Francisco–Colma	4	172 (16.3)	92 (0.9) 93	80 (1.8) 81	112 (0.7) 113
South San Francisco–San Bruno	4	179 (9.9)	95 (0.6) 96	87 (1.4) 88	112 (0.8) 113
West Oakland–12th Street	4	211 (24.7)	86 (2) 88	75 (2.5) 77	111 (0.9) 112
West Oakland–Embarcadero	7	380 (15.6)	101 (3.1) 105	92 (1.7) 94	118 (6.8) 133
West Oakland–Lake Merritt	5	315 (33.9)	89 (2.1) 91	74 (2) 76	112 (2.4) 115

weekday roundtrip commutes of two of the authors during the study period. The average time of these commute scenarios ranged from 58 to 73 minutes, and each scenario comprised 24 line segments round-trip. The minimum mean L_{eq} exposure at different levels by mean time in transit for these three commute scenarios is detailed in Table II. On average, riders experience a minimum exposure between 54 and 61 minutes per day at L_{eq} ≥ 70 dBA, between 19 and 23 minutes per day at L_{eq} ≥ 85 dBA due to noise while BART cars are in motion. Riders on the MacArthur to Daily City commute experience a minimum exposure of 7 minutes per day at L_{eq} ≥ 95 dBA.

Table II Minimum mean L_{eq} exposure times for three roundtrip commute scenarios (h:mm:ss).

	24th Street & North Berkeley	24th Street & Hayward	MacArthur & Daly City
Roundtrip mean transit duration	0:57:57	1:13:06	1:02:25
Mean L_{eq}:			
≥70 dBA	0:53:33	1:01:13	0:53:33
≥75 dBA	0:51:14	0:45:28	0:51:14
≥80 dBA	0:36:27	0:35:44	0:36:27
≥85 dBA	0:22:38	0:18:33	0:22:38
≥90 dBA	0:08:27	0:06:20	0:08:27
≥95 dBA	0:00:00	0:00:00	0:06:34

The number of line segments where mean L_{max} exceeds specific levels for these three commutes are detailed in Table III. Riders in the commute scenarios experience a minimum of between 20 and 22 exposures per day at mean L_{max} ≥ 85 dBA, between 10 and 14 exposures per day at mean L_{max} ≥ 90 dBA, and between 2 and 5 exposures per day at mean L_{max} ≥ 95 dBA. Riders on the two commute scenarios including MacArthur station experienced at least one exposure per day to mean L_{max} ≥ 100 dBA.

Table III Line segments with mean L_{max} at different levels for three roundtrip commute scenarios.

	24th Street & North Berkeley	24th Street & Hayward	MacArthur & Daly City
Total number of segments roundtrip:	24	24	24
Number of segments w/ mean L_{max}:			
≥70 dBA	24	22	24
≥75 dBA	24	22	24
≥80 dBA	24	22	24
≥85 dBA	22	20	21
≥90 dBA	12	10	14
≥95 dBA	4	2	5
≥100 dBA	1	0	1

Data Analysis

We explained our three noise dosimetry measures by velocity, tunnel enclosure, flooring type, and weather conditions using multiple regression frameworks. We began with a full model, removed predictors stepwise according to highest p-value. Preliminary multivariate nonparametric smoothing regression[27,28] of all three dosimetry measures (Equations 1a–1c) suggested that only the relationship between average velocity and L_{eq} was nonlinear (Figure 2), with the linear main effect of velocity virtually saturating at about 53 km/hour. Our preliminary nonparametric additive running-line smoothing regressions were fit using the mrunning package 2.0.0 in Stata (these models used centered average velocity). Such non-linearities are both substantively interesting, and violate the assumption of linearity, which may bias linear regression estimates. Accordingly, we modeled the effect of average velocity on L_{eq} using non-linear least squares regression to model a break point in the linear relationship (Equations 2a and 2b). L_{peak} and L_{max} were modeled using multiple ordinary least squares regression. All regression analyses were conducted in Stata,[29] and average velocity was centered. Full regression models included all predictor variables, plus multiplicative interaction terms for centered average velocity and degree of tunnel enclosure. We estimated full models which

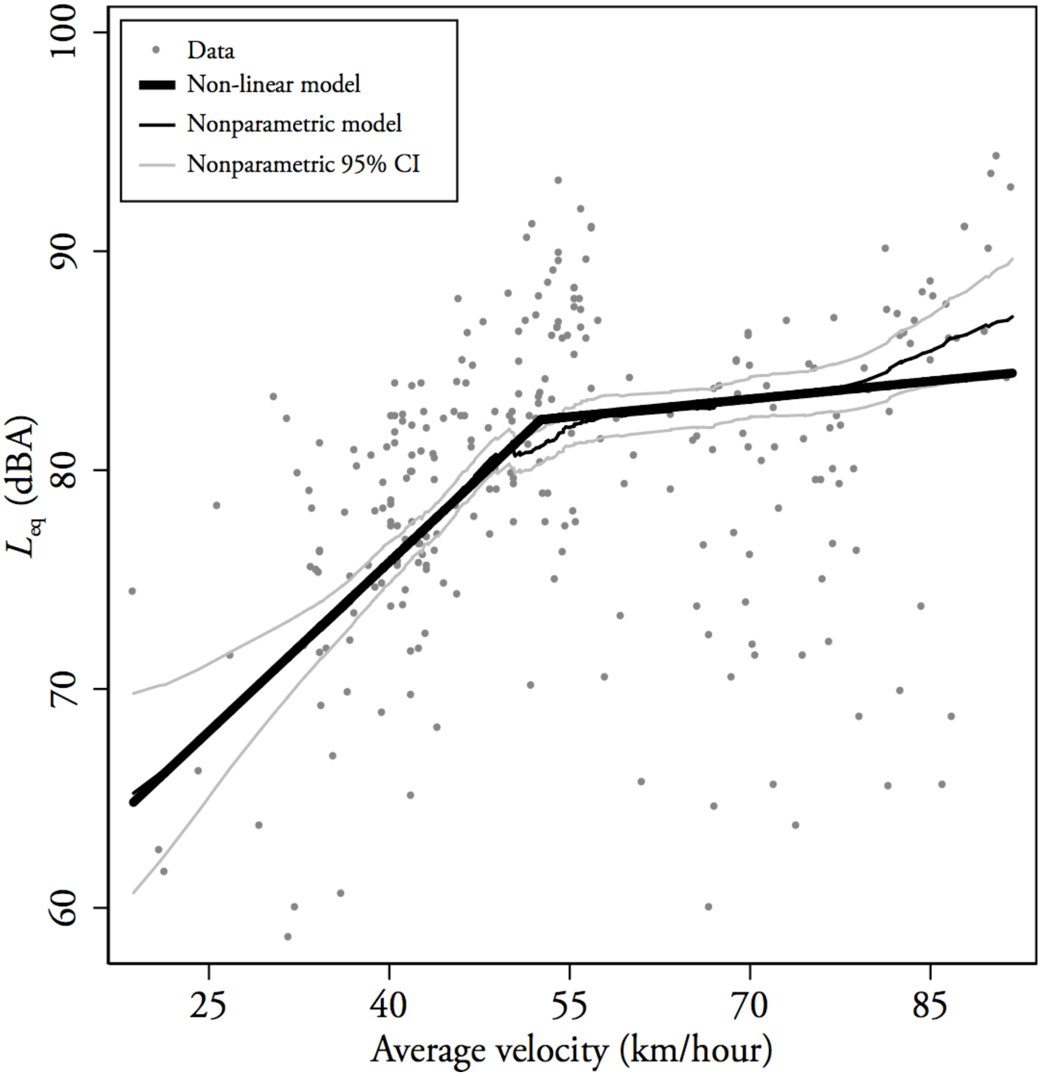

Figure 2 Effect of average velocity on Leq modeled with a nonlinear breakpoint in the effect of average velocity at 52 km/hour (thick black line) overlaid on top of a restricted nonparametric smoothing model of Leq— —(thick black line) with 95% point-wise confidence intervals (thin grey lines), and the raw data.

included all predictors and interactions (Equations 3a and 4a), and restricted models which retained only predictors at the α=0.05 level (Equations 3b and 4b).

$$L_{eq} \sim f_v(v) + f_T(T) + f_{vT}(vT) + f_f(f) + f_w(w) \tag{1a}$$

$$L_{peak} \sim g_v(v) + g_T(T) + g_{vT}(vT) + g_f(f) + g_w(w) \tag{1b}$$

$$L_{max} \sim h_v(v) + h_T(T) + h_{vT}(vT) + h_f(f) + h_w(w) \tag{1c}$$

$$L_{eq} = \alpha_0 + \alpha_v v^c + \alpha_{v_b} v_b + \alpha_T T + \alpha_{v^c T} v^c T + \alpha_{v_b T} v_b T + \alpha_f f + \alpha_w w + \varepsilon^*_{L_{eq}} \tag{2a}$$

$$L_{eq} = \alpha_0 + \alpha_v v^c + \alpha_{v_b} v_b + \alpha_T T + \alpha_f f + \varepsilon^*_{L_{eq}} \tag{2b}$$

$$L_{peak} = \beta_0 + \beta_v v^c + \beta_T T + \beta_{v^c T} v^c T + \beta_f f + \beta_w w + \varepsilon^*_{L_{peak}} \tag{3a}$$

$$L_{peak} = \beta_0 + \varepsilon^*_{L_{peak}} \tag{3b}$$

$$L_{max} = \gamma_0 + \gamma_v v^c + \gamma_T T + \gamma_{v^c T} v^c T + \gamma_f f + \gamma_w w + \varepsilon^*_{L_{max}} \tag{4a}$$

$$L_{max} = \gamma_0 + \gamma_v v^c + \gamma_T T + \gamma_{v^c T} v^c T + \gamma_f f + \varepsilon^*_{L_{max}} \tag{4b}$$

Where:

v^c : centered average velocity in km/hour

v_b : change in slope of average velocity at the break, modeled by max(average velocity $-\theta_v$, 0)

θ_v : estimated breakpoint at which centered average velocity changes slope

T: presence of a tunnel longer than three cars on the line segment (1 = tunnel present)

$v^c T$: multiplicative interaction between v^c and T.

f:presence of newer hard floor instead of older carpet (1 = with hard floor)

w: presence of rain water on the ground during the ride (1 = water on ground)

$\varepsilon^*_{L_{eq}}, \varepsilon^*_{L_{peak}}, \varepsilon^*_{L_{max}}$: model error terms, adjusted for clustering by line segment, assumed normal

Despite the fact that our sample was by convenience, our study obtains very high statistical power (>0.95) with respect to Cohen's[30] *post hoc* analysis of power to detect a change in the sample correlation coefficient (R^2) due to the inclusion of the independent variables. We also have very high power (>0.90) using Kelley and Maxwell's method[31] in our restricted models of both L_{eq} and L_{max}, but are underpowered for the unrestricted models and for L_{peak} generally (see appended supplement).

RESULTS

Clustered regression results are presented in Table IV. We found that average velocity had different effects on our three dosimetry measures. L_{eq} increased linearly with average velocity by 0.52 (95% CI: 0.36, 0.67) dBA per km/hour, with that effect almost completely saturating to 0.05 dBA per km/hour (95% CI: -0.34, 0.45) above approximately 53 km/hour as illustrated in Figure 2. L_{peak} was not found to be significantly related to average velocity. L_{max} was found to decrease linearly by -0.11 dBA (95% CI: -0.32, 0.09) in cars running on line segments without tunnels, but to increase linearly by 0.19 dBA (95% CI: 0.15, 0.24; calculated as described in Figueiras et al. 1998, page 2100)[32] in cars running on segments with tunnels.

L_{eq} increased by 5.1 dBA (95% CI: 3.7, 6.4) on line segments enclosed by tunnels. L_{max} increased by 2.5 dBA (95% CI: -1.7, 6.7), with the above described significant interaction with average velocity.

Presence of the newer composite flooring was associated with an increase of 1.8 dBA (95% CI: 0.58, 3.1) in L_{eq}, and was associated with an increase of 1.5 dBA (95% CI: 0.69, 2.3) in L_{max}. Flooring was not associated with L_{peak}.

The presence of water on the ground was not associated with any of our three noise dosimetry measures.

Table IV: Parameter estimates for full and restricted and nonlinear least squares models (L_{eq}), and ordinary least squares models (L_{peak} and L_{max}).

	Full model parameter estimate (sd) p-value[a]	Restricted model parameter estimate (sd) p-value[a]

y: L_{eq} (dBA)						
α_0	82.9	(1.05)	<0.001	83.0	(1.04)	<0.001
α_{v^c}	0.489	(0.070)	<0.001	0.516	(0.077)	<0.001
α_{v_b} (break at 53 km/hour)	-0.430	(0.124)	0.001	-0.462	(0.122)	<0.001
α_T	6.78	(2.00)	0.001	5.06	(0.680)	<0.001
$\alpha_{v^c T}$	0.260	(0.145)	0.094			
$\alpha_{v_b T}$	-0.278	(0.193)	0.169			
α_f	1.98	(0.658)	0.004	1.81	(0.856)	0.003
α_w	-0.706	(1.06)	0.503			
RMSE	5.030			5.095		
R^2	0.479			0.457		
y: L_{peak} (dB)						
β_0	118	(5.98)	<0.001	113	(0.507)	<0.001
β_{v^c}	-0.352	(0.297)	0.351			
β_T	-5.92	(5.96)	0.387			
$\beta_{v^c T}$	0.425	(0.298)	0.305			
β_f	1.07	(0.517)	0.118			
β_w	-0.121	(0.889)	0.889			
RMSE	4.632			4.766		
R^2	0.073			0.000		
y: L_{max} (dBA)						
γ_0	88.2	(2.07)	<0.001	88.2	(2.07)	<0.001
γ_{v^c}	-0.115	(0.102)	0.310	-0.114	(0.107)	0.258
γ_T	2.51	(2.12)	0.310	2.50	(2.11)	0.258
$\gamma_{v^c T}$	0.309	(0.104)	0.006	0.309	(0.104)	0.005
γ_f	1.56	(0.104)	<0.001	1.52	(0.412)	0.001
γ_w	-0.375	(0.858)	0.660			
RMSE	3.505			3.499		
R^2	0.4708			0.462		

Note: All models accounted for clustering in line segments, thereby estimating robust standard errors. N = 266 for all models. Both the full and restricted nonlinear least squares models of L_{eq} converged in 11 iterations.

[a] All p-values were corrected for multiple comparisons using the false discovery rate[41], using p.adjust() in R version 2.9.

DISCUSSION

This small study provides evidence of potential noise exposures that may be deleterious to the health of BART passengers. The $L_{eq}$and L_{peak} levels reported here are comparable, although somewhat louder, to in-car noise levels recently reported in the New York Metro subway system.[8,9] The reported L_{eq} exposure durations ≥85 dBA in the three commute scenarios translate to 40%–48% of the maximum daily noise exposure levels set by the EPA to broadly protect population hearing.[24,26] This implies compounded noise-related risks for those riders who reside or work in very noisy environments. Our L_{eq} and L_{max} measures indicate exposure to very loud noise for periods somewhat comparable to the daily ranges associated with increased cardiovascular and psychosomatic health risks.[10,12,15,17,18,20,33-37] However, we caveat that these studies generally treated periodic exposures throughout the day, such as those due to proximity to rail systems or traffic. Most BART trips are likely to extend beyond one line segment; for round-trip commuters, such exposure will double in the course of a day. This implies chronic exposure to persistent levels of noise during the workday, and may present a threat of hypertension and other health problems associated with chronically heightened psychosomatic stress. L_{peak} levels indicate acute exposures potentially damaging to adult hearing on about one percent of rides from one station to the very next station, and acute exposures potentially damaging to children's hearing on about two percent of such rides.[24] Hearing may also be threatened by BART noise indirectly, as many people employ headphones while riding BART (e.g., for digital musical players), and BART noise may drive riders to raise headphone volume to damaging levels.

While recognizing that passenger exposures to loud noises on BART are unlikely to exceed an hour or two per day and thus likely to present only a small health risk to individuals, we also consider this from a population perspective; small increases in individual risk for health problems caused by chronic exposure, when multiplied across large populations—such as the hundreds of thousands of riders each weekday—may amount to large public health concerns. [38,39] Moreover, from a vulnerabilities perspective, [40] populations already under stress, suffer greater extremes and greater uncertainty in health outcomes as a result of stresses; because BART serves the elderly, school-age children, and socio-economically marginalized communities, we find vulnerability to noise especially concerning, and a needed avenue for further research.

We have provided evidence that the noise to which passengers are exposed may be due to car-specific conditions (velocity and flooring), but also to rail conditions (speed limit, and tunnels). These finding may point at possible remediation (revised speed limits on longer segments, and those enclosed by tunnels). The findings also suggest the possibility that specific line segments could be physically improved for noise. Factors not considered here—such as wheel and brake conditions, or rail conditions—may also contribute to noise levels.

This study has several limitations. First, the small sample size does not permit an estimation of the distribution of dosimetry responses for each line segment. A thorough sampling of every line segment in the BART system would also give a better picture of passenger exposure. Likewise, we did not account for clustering of variance by car that a larger study would (for example, using cross-classified multilevel models). Better dosimeters could provide more finely spaced measurements permitting a more nuanced visual characterization of gradients of noise dosimetry along single line segments, and assessment of the relationships between more instantaneous measures of velocity and dosimetry measures. Such finely spaced measurements could also permit total counts of L_{peak} and L_{max} events as recommended by the WHO,[24] rather than the 'at least one event per line segment' given by these measures in this study. Our use of average (rather than instantaneous) velocity biases regression results toward finding smaller effects since, if the effects of instantaneous velocity on noise are positive, 'average velocity' will be slightly lower than instantaneous velocity when dosimetry measures are high, and conversely will be higher than instantaneous velocity when dosimetry measures are low.

We conclude by noting that BART's operation appears to produce several kinds of noise-related health hazard. While news reports indicate that BART took steps to improve rail condition in 2009, [3-5] it remains to be seen if and how passenger noise exposure will be affected. BART, being a public institution, should serve its passengers at a minimum by communicating the health hazard imposed by the noisy conditions under which it operates, perhaps even suggesting ways for passengers to protect themselves from hazardous noise and, most fully, by making trains quieter. BART could also establish ongoing noise dosimetry measures for the protection of riders' health. Such a surveillance system could also provide better understanding of velocity/noise measures, since instantaneous train speed is available to BART operators.

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