3-5-2010

A pilot Study of Riders’ Noise Exposure on Bay Area Rapid Transit Trains

Alexis Dinno
Portland State University, alexis.dinno@pdx.edu

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Portland State University, School of Community Health

In presentation to the
2nd Annual NW Environmental Health Conference

March 5, 2010

alexis.dinno@pdx.edu

BART

(Image by Jon Davis, through http://commons.wikimedia.org/wiki/File:Lafayette_BART_-_005.jpg on a Creative Commons Attribution Share-Alike License)

How loud is 'too loud?'

"With regularity, readers contact ChronicleWatch about tunnel noise in BART—about how trains in the under-the-bay tube make excessive sounds as they speed to and from San Francisco, and how BART trains in other system tunnels make similar ear-splitting sounds."

—Johnathan Curiel, *San Francisco Chronicle*, Dec. 11, 2008 page B-2.

"After enduring another week of the screeching and howling while traversing BART's Transbay Tube, I feel compelled to inquire as to when BART plans on rectifying this."

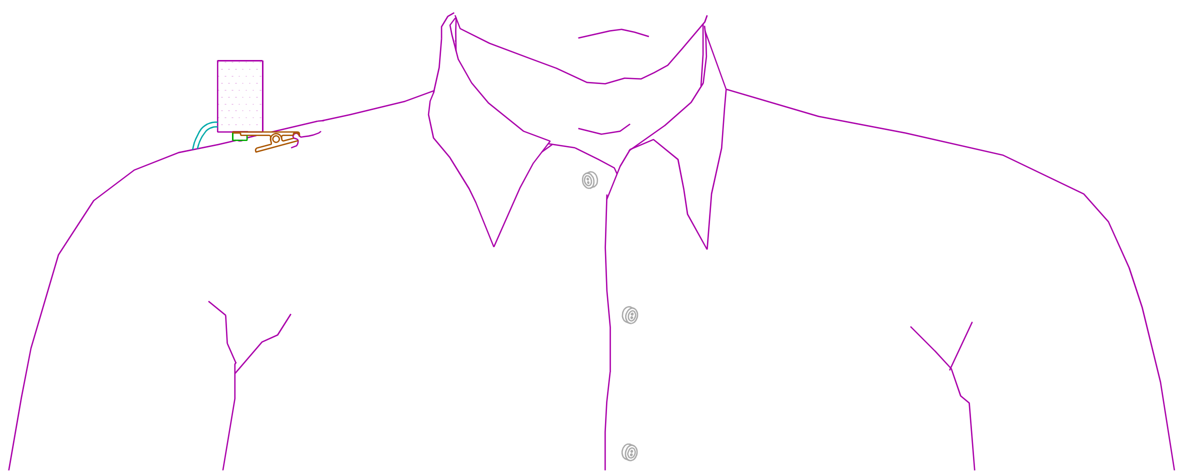
—John (from cyberspace), *The Oakland Tribune*, April 25th, 2007.

System map produced by BART for 2008.

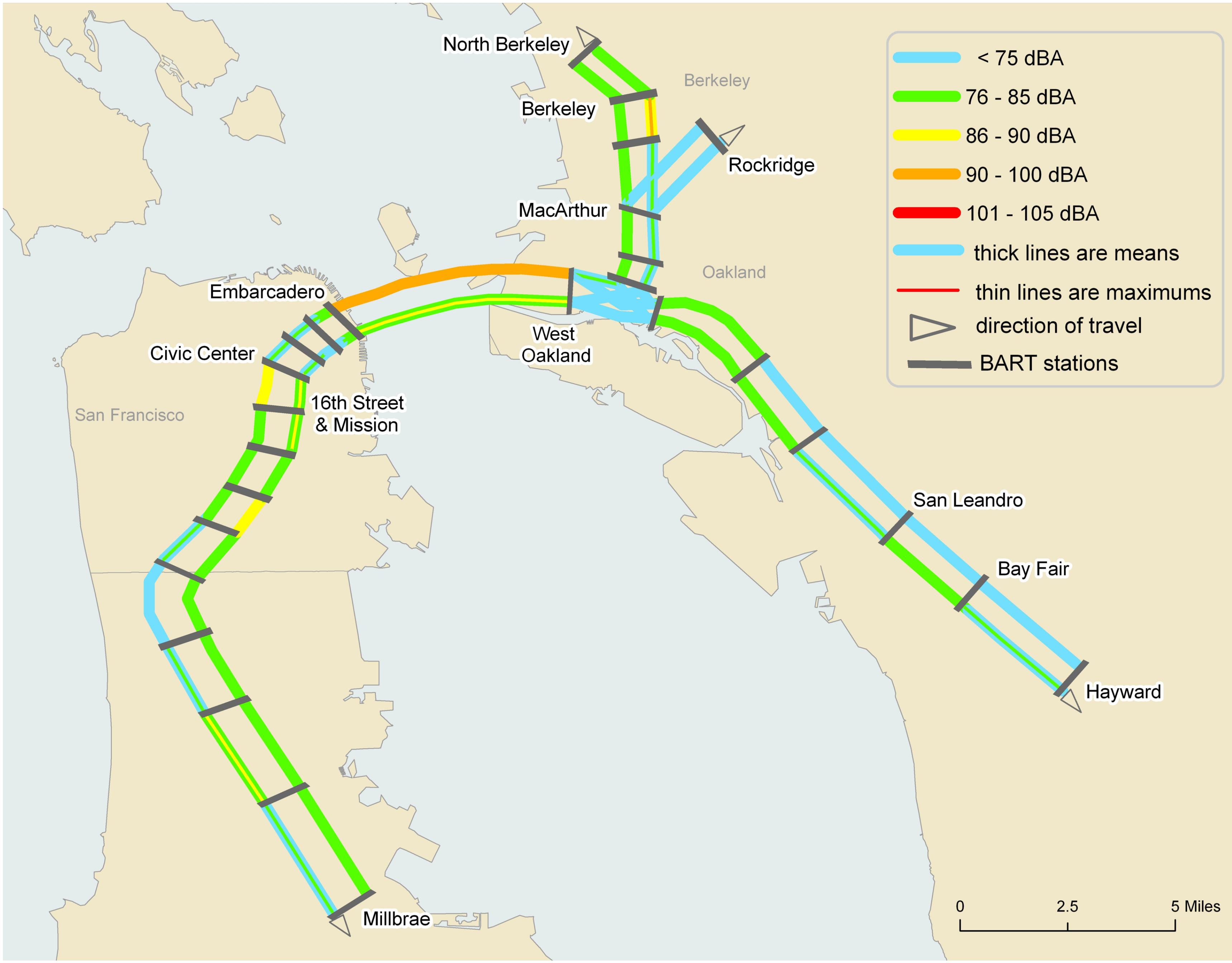
Quest Q-300 logging noise dosimeter

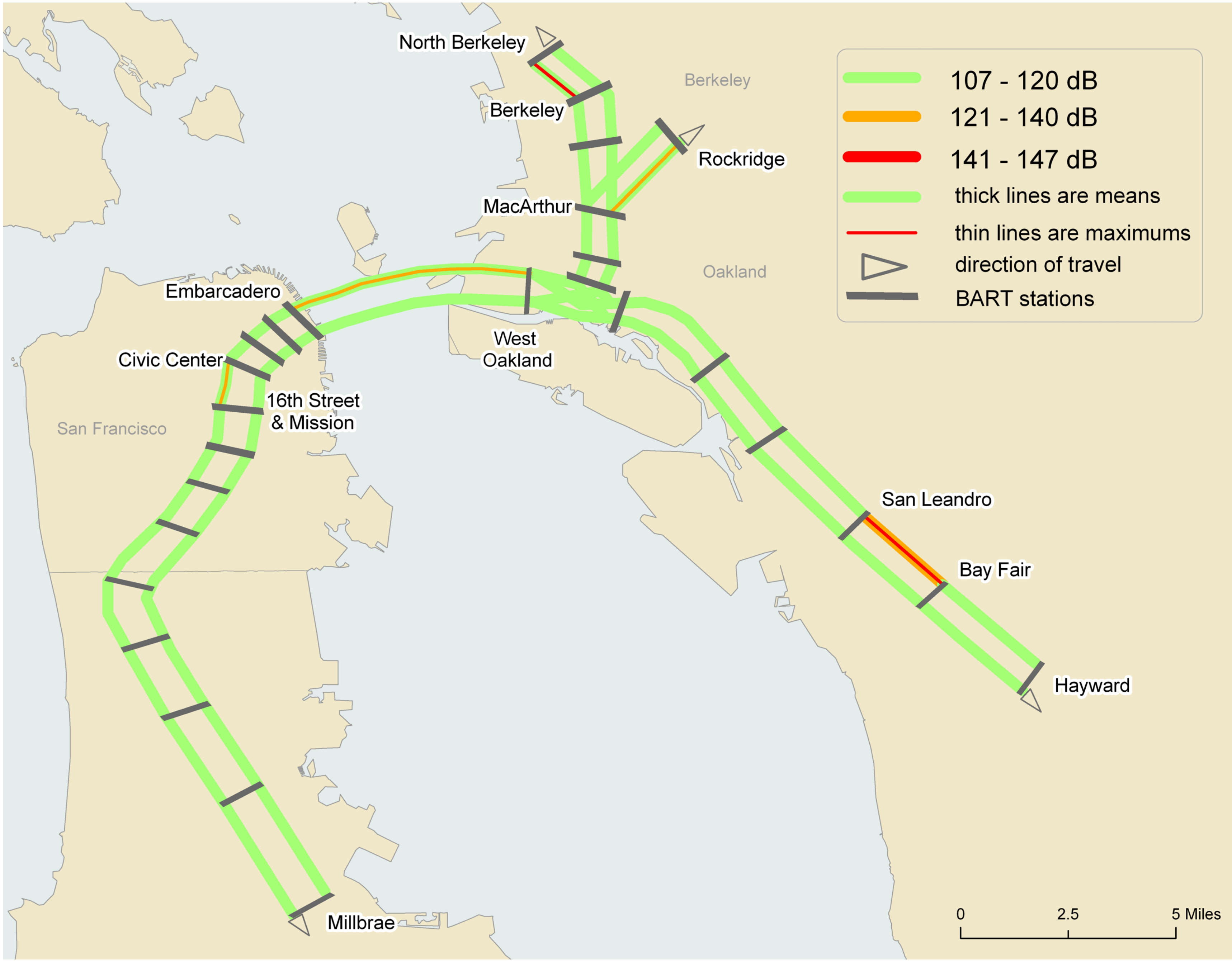
(Dosimeter image from http://www.envisupply.com/rentals/instruments/QuestNoiseDosimeter.htm)

The microphone is worn attached to the shoulder, as shown in the instruction manual image below.

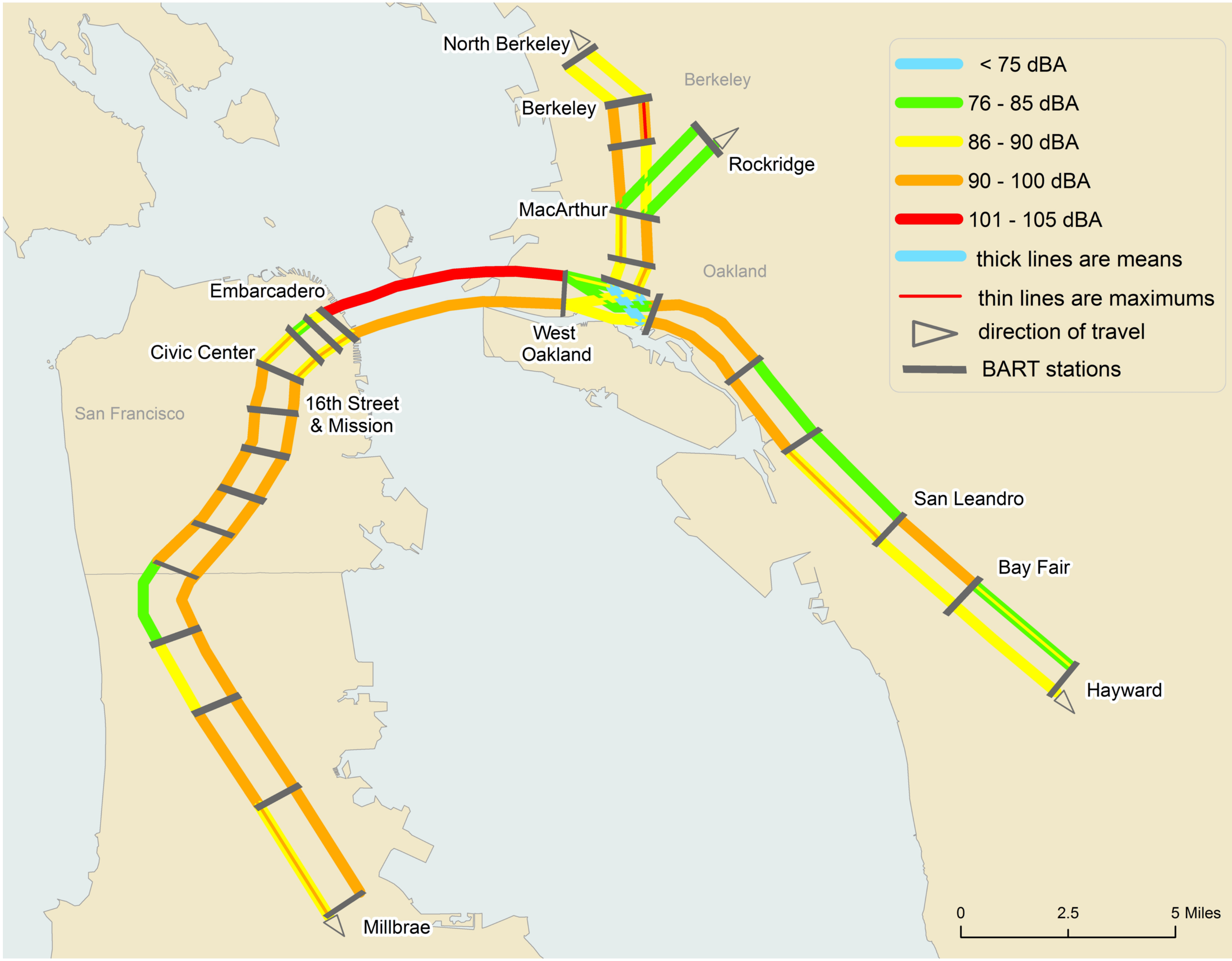


System map produced by BART for 2008.


North Berkeley
Berkeley
Rockridge
MacArthur
Embarcadero
West
Oakland
Civic Center
16th Street
& Mission
San Francisco
San Leandro
Bay Fair
Hayward
Millbrae
< 75 dBA
76 - 85 dBA
86 - 90 dBA
90 - 100 dBA
101 - 105 dBA
thick lines are means
thin lines are maximums
direction of travel
BART stations
0
2.5
5 Miles



North Berkeley
Berkeley
Berkeley
Rockridge
MacArthur
Oakland
Embarcadero
West Oakland
Civic Center
16th Street & Mission
San Francisco
San Leandro
Bay Fair
Hayward
Millbrae
107 - 120 dB
121 - 140 dB
141 - 147 dB
thick lines are means
thin lines are maximums
direction of travel
BART stations
0
2.5
5 Miles



North Berkeley
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BART stations
0
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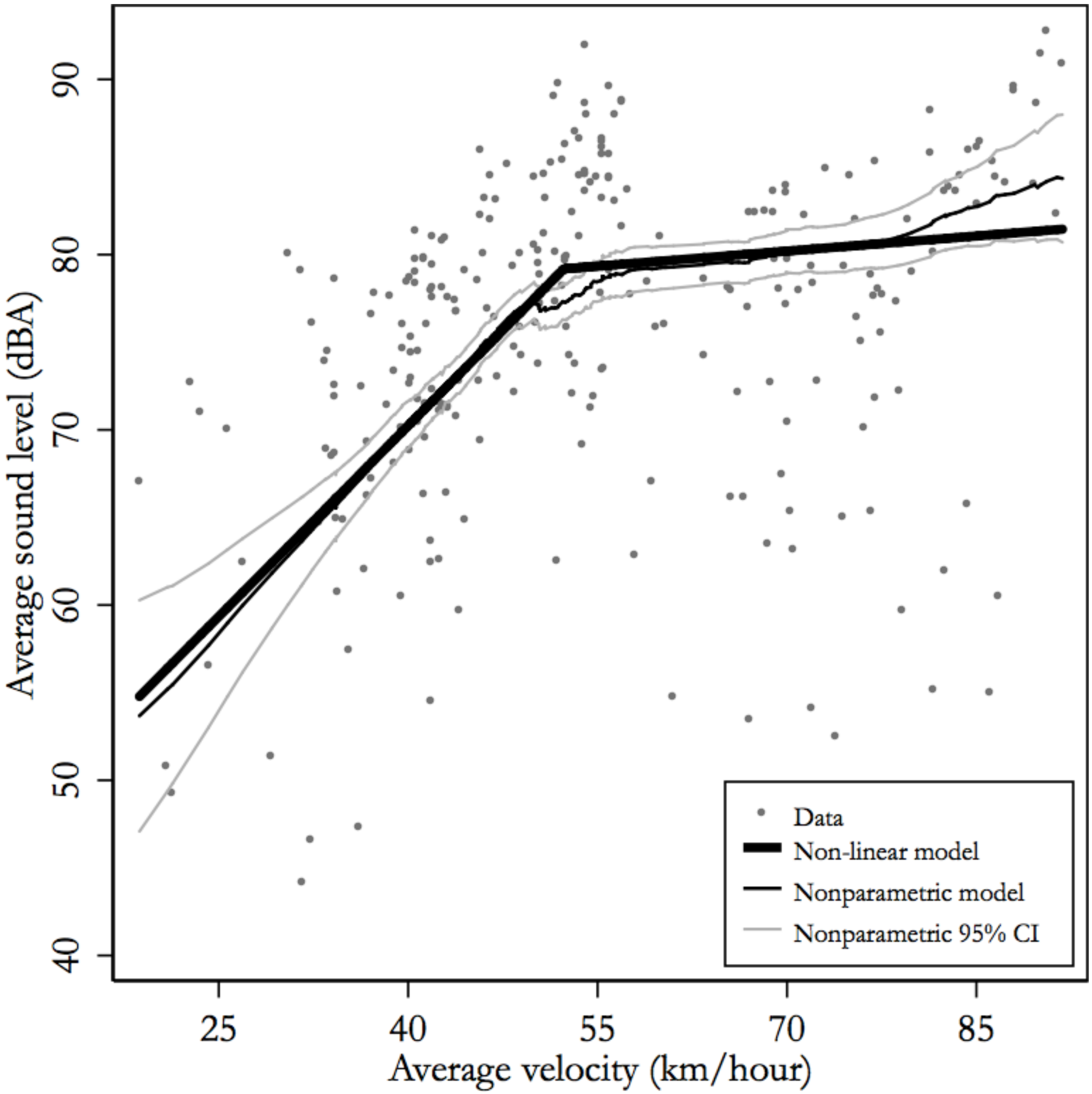
5 Miles

(Image by Paul http://commons.wikimedia.org/wiki/File:BART_B_interior.jpg on a Creative Commons Attribution NonCommercial ShareAlike license)

(Image http://commons.wikimedia.org/wiki/File:BART_C2_car_no._2542_interior.JPG by a GNU Free Documentation license)



Average sound level (dBA)
40
50
60
70
80
90
25
40
55
70
85
Average velocity (km/hour)
Data
Non-linear model
Nonparametric model
Nonparametric 95% CI

Thank you

Prepared script for "A pilot study of riders' noise exposure on Bay Area Rapid Transit trains" by Alexis Dinno of Portland State University, School of Community Health
In presentation to the 2nd Annual NW Environmental Health Conference in Portland OR 2010.

Hi. I am Alexis Dinno, a professor at Portland State University's School of Community Health. Today I present 'A pilot study of riders' noise exposure on Bay Area Rapid Transit trains' which distills and reflects on a paper written by myself, Cynthia Powell and Margaret Mary King currently in submission to the Journal of Urban Health.

Bay Area Rapid Transit, or BART—logo shown here •—is a regional public rapid commute train system serving the northern portion of the San Francisco Peninsula, the East Bay, and portions of Contra Costa County. An average of 360,000 rides are taken on the system each weekday • on trains much like this one shown leaving Lafayette station in Contra Costa County. Despite occasional hiccups, and an early fatal tragedy in the system's Transbay Tube, BART enjoys high customer satisfaction in most areas. However, there is a widely held perception that BART is too loud.

How loud is "too loud?" In a sample of two people named 'John' writing in local newspapers, we find •:

"*After enduring another week of the screeching and howling while traversing BART's Transbay Tube, I feel compelled to inquire as to when BART plans on rectifying this*," and the second wrote "*With regularity, readers contact ChronicleWatch about tunnel noise in BART—about how trains in the under-the-bay tube make excessive sounds as they speed to and from San Francisco, and how BART trains in other system tunnels make similar ear-splitting sounds.*"

My interest in noise on BART trains arose through my own personal experiences as a frequent rider. This is a map of the BART system •. I first rode BART when I was 6 or 7 years old, from the Rockridge station here in Oakland under the trans-bay tube to San Francisco's downtown. (Incidentally, as the train headed down under the ground on that first ride, I was *devastated* that the tunnel walls were not made of glass: how else were we supposed to see all the fish under the Bay? I still feel the pangs of disappointment…) Flashing forward several decades to my 30s, I lived *here* in San Francisco, played *here* in Berkeley, and for a year taught part-time *here* in Hayward. Over the 'Oughties' I felt that BART was getting louder. Especially after a scheduling change started running trains a little faster about seven years ago.

What was my experience of "louder?" Well… I took to always wearing good ear plugs my final years there. In fact, I witnessed child and adult passengers covering their ears with their fingers while riding BART, wearing ear protection such as plugs or audio muffles, and pairs of individuals leaning close together and literally shouting at high volume in order to carry on conversation. Friends who were not accustomed to regularly riding BART would complain of headaches on the rare occasions of their rides. Exposure to loud noises—especially prolonged exposures—are associated with risk of hypertension, psychosomatic stress, and hearing impairment. Many riders take BART twice a day daily for 45-minute commutes or longer, some of them also have their headphones on and the sound turned way up…

So I thought to myself *someone* needs to take a noise dosimeter to BART, characterize sound exposure for riders, and make some noise about it (har har har)! I said this a lot to myself and to others. But it turns out that the squeaky wheel sometimes has to lay town tracks to the nearest lube station. In short, I had to get the dosimeter and find out for myself.

• A dosimeter is a fancy-pants sound-level meter that, through a microphone mounted on the shoulder, precisely records noise in different ways so as to specifically characterize how humans are being exposed to sound. Dosimeters are expensive. Not being wealthy, I decided to call around to the various occupational and environmental health departments at area universities. It turned out that Cal State where I was then teaching had three of these dosimeters, and was willing to get them calibrated to the specifications of the Occupational Health and Safety Administration, and set me loose with them (although I did not wear the pink shirt, or sport the cleft chin).

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Thus prepared, I set out to measure noise experiences by riders on BART trains. But where exactly? Riding the entire length of a single line can take close to two hours in one direction. I knew that I wanted to measure noise separately for both directions, because there were places between two stations—such as the rail segment heading from Ashby to Downtown Berkeley station—where the noise got *really* bad, but only in one direction. Given my limited time and energy, and zero budget, I decided to make most of my measurements between 24th Street Station in San Francisco, North Berkeley Station, and the Hayward station with a few extra trips thrown in. There were 268 measurements in all. I was also going to enjoy the fact that nearly every round trip would take me through that loathed Transbay Tube.

This is a map •—which, like the two following maps was produced by my coauthor Cythia Powell, a geographer at San Francisco State University—showing mean and maximum average weighted sound levels measured in dBA for the portions of the BART system which I travelled with my a dosimeter. This and other maps are reproduced on the back of your handouts. Average weighted sound level is a measure of total noise exposure, high levels—here indicated by those which are any color but blue—indicate risk for psychosomatic stress and hypertension. The thickest part of each line represents the mean average, and the thin portion in the center represents the maximum average sound level. The shape and exact position of line segments have been distorted to facilitate visual discrimination, and should be interpreted as schematic. As you can see, the majority of rail segments between stations have mean noise levels representing risk of psychosomatic stress and hypertension. And that Transbay Tube is especially loud.

• This slide shows a similar map of peak unweighted sound pressure—thick lines again representing means, and thin center lines representing maximums. Peak sound is a measure of instantaneous loudness, for example what makes a single automotive backfire "louder" in some sense than the sustained rumble of its idling engine. Rock concerts are legally limited to 120dB, which is the National Institute for Occupational Safety & Health-mandated level for risk of acute hearing damage in children. In adults the NIOSH-mandated level is 140dB. You can see that isolated measures above the 120dB level were made throughout the system, and several measure peaked above 140dB. We were surprised by the recorded peak for the above-ground—that is, not enclosed by a tunnel—northbound rail segment between Bay Fair and San Leandro stations which showed repeated very high peak noise exposures.

• *This* slide maps slow maximum weighted sound pressure measures, which are measures of loudness across a 5 second moving window. This dosimetry measure captures risk of psychosomatic stress, cardiovascular disease, including hypertension, and chronic hazard for hearing loss. As you can see, these are very high levels throughout the BART system, and especially in that Transbay Tube.

We also collected data on train velocity, wet weather conditions, rail segment enclosure, and whether a BART car's floor was carpeted, as shown here •, or had the newer hard composite flooring like this •. We explored whether these phenomena or their interactions predicted our three dosimetry measures.

We found that average velocity had different effects on our three dosimetry measures, as detailed in the table in your handout. Average sound level increased linearly with average velocity by 0.72 dBA per kilometer per hour, with that effect almost completely saturating above approximately 52 km/hour as illustrated here •. This graph shows the effect of average velocity on average sound level modeled with a nonlinear breakpoint in the effect of average velocity at 52 kilometer per hour (shown with the thick black line) overlaid on top of a nonparametric smoothing model of average sound level—where average weighted sound level is a nonparametric function of velocity, an indicator of tunnel enclosure and an indicator of composite flooring—(shown with the thin black line) with 95% point-wise confidence intervals (shown with the thin grey lines), and the dots are the raw data. This kind of nonparametric regression model permits us to ‘let the data speak’ about the way two or more variables relate, *without* making any assumption of linearity (or any other functional relationship). Nonparametric results can then inform our construction of parametric models, such as the break-point model drawn here, which quantifies the relationship through a good approximation.

Unweighted peak sound pressure was not found to be significantly related to average velocity. Slow maximum weighted sound pressure was found to decrease linearly by -0.11dBA per kilometer per hour in cars running on line segments without tunnels, but to increase linearly by 0.19dBA per kilometer per hour in cars running on segments with tunnels.

Average weighted sound level increased by 7.2dBA on line segments enclosed by tunnels. Slow maximum weighted sound pressure increased by 2.50dBA, with the above described significant interaction with average velocity.

Presence of the newer composite flooring was associated with an increase of 2.6dBA in the average sound level, and was associated with an increase of 1.5dBA in slow maximum weighted sound pressure. Flooring was not associated with peak sound pressure level.

The presence of wet weather as indicated by water on the ground was not associated with any of our three noise dosimetry measures.

This pilot study provides evidence of levels of noise exposure that may be deleterious to the health of BART passengers. The average sound level and slow maximum weighted sound pressure indicate exposures to very loud noise for extended periods well above published ranges associated with increased cardiovascular and psychosomatic health risks. 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 presents a threat of hypertension and the host of health problems associated with chronically heightened psychosomatic stress. Peak sound pressure 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. Hearing may also be threatened by BART noise indirectly, as many people employ headphones while riding BART (for example while using digital music players), and the loud background noise may spur 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 small individual health risks, 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 roughly 360,000 fares each weekday—may amount to large public health concerns. Moreover, from a vulnerabilities perspective such as that advocated by Richard Levins, populations already under stress, suffer greater extremes and greater uncertainty in health outcomes as a result of stresses. Because BART serves the elderly and economically and race/ethnically marginalized communities in many of its locations, 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 train-specific conditions (such as velocity and flooring), but also to rail conditions (such speed limit, and tunnels). These finding may point at possible remediation (such revised speed limits on longer segments, and those enclosed by tunnels). The findings are also suggestive of the possibility that specific line segments could be improved for noise. Indeed, last year BART deployed a rail-polishing machine, to improve conditions which lead to some of the noise experienced by riders on trains. Factors not considered here—such as wheel and brake conditions, or other rail conditions—may also contribute to noise levels.

BART appears to be operating under conditions presenting several kinds of noise-related health hazard. It remains to be seen if and how passenger noise exposure will be affected by BART's rail-grinders (personal observation suggests that noise is still a problem). BART, being a public institution, should serve its passengers at a minimum by loudly advertising the health hazard imposed by the noisy conditions under which it operates, even by suggesting ways for passengers to protect themselves from hazardous noise, and most fully by making train rides quieter. BART could also establish ongoing regular measurement of noise dosimetry for the protection of its riders' health.

There are also lessons here for advancing civic science.

First, when the public perceives hazardous phenomena in their day-to-day, they are likely correct, and it is relatively easy to check up on that hazard and give it a more formal expression. As researchers, we can thus also be advocates for public perceptions of the environment.

Second, these data were collected without any funding, and with material support—the dosimeters, and the mapping software—lent from existing academic resources. So checking up on publicly expressed experiences of environmental hazard can also be accomplished relatively cheaply. Incidentally, outside of customer satisfaction surveys, which uniformly grade BART poorly on noise, BART has made no audiology studies of its public system since the initial study in 1973.

Finally, the scientific narrative thus produced—the charts, graphs, numbers and maps—can serve multiple audiences. Following the successful peer-review publication of the story I have been telling here, there will be op-eds and letters to the editor sent to local newspapers, and there will be stories pitched to Bay Area-local radio stations. A second funded study of noise dosimetry could evaluate the effectiveness of BART's rail polishers, and provide much more detailed measures for the entire BART system.

I conclude with a consideration of built versus natural environments. While the BART system is obviously an artifact of human engineering, we also examined both weather conditions in terms of water on the ground, and tunnel enclosures, in many ways dictated by the topography of the landscape. At the risk of stirring contention in this session, I would ask whether attending to health concerns in the environment is best served by forcing a distinction between "built" and "natural" environments. I submit that instead we should consider that all human environments are both built and not built (or natural) to varying degrees, and that our best understanding of health comes by tracking down who or what is responsible for exposure to health hazards and health resources.

Thank you.

Portland State UNIVERSITY

Alexis Dinno, Sc.D.,M.P.H.,M.E.M.
Assistant Professor

503-725-3076 tel
503-725-5100 fax
alexis.dinno@pdx.edu
www.pdx.edu/sch

School of Community Health
College of Urban & Public Affairs
Post Office Box 751
Portland, OR 97207

450D Urban Center
506 SW Mill Street, Suite 450
Portland, OR 97201

A PILOT STUDY OF RIDERS' NOISE EXPOSURE ON BAY AREA RAPID TRANSIT TRAINS

Presented by Alexis Dinno
Portland State University, School of Community Health
Coauthors: Cynthia Powel and Margaret Mary King

ABSTRACT

Background Noise exposure is a concern on Bay Area Rapid Transit (BART) due to hearing loss, and increased cardiovascular and psychosomatic health risks.

Objectives This cross-sectional pilot study quantitatively assesses and communicates noise exposure of BART riders using three dosimetry measures.

Methods We made 268 dosimetry measurements on a convenience sample of 51 line segments. Dosimetry measures are 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.

Results This study provides evidence of levels of hazardous levels of noise exposure in all three dosimetry measures. Peak sound pressure levels indicate acute exposures damaging to adult hearing on about one percent of line segment rides, and acute exposures damaging to child hearing on about two percent of such rides. Slow maximum A-weighted sound pressure and average sound level indicate exposures well above ranges associated with increased cardiovascular and psychosomatic health risks in the published literature.

Conclusions We have provided evidence that 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 enclosed by tunnels). The findings are also suggestive of the possibility that specific rail segments could be improved for noise.

The table at right provides parameter estimates for full and restricted and nonlinear least squares models (average sound level), and ordinary least squares models (peak pressure and slow maximum pressure). Where:

L is the average sound (dBA).

P is the peak unweighted sound pressure (dB).

S is the slow maximum weighted sound pressure level (dBA).

v^c is centered average velocity in (km/hour).

v_b is change in the slope of average velocity at the break, modeled by max(average velocity – θ_v, 0)

θ_v is estimated breakpoint at which centered average velocity changes slope

T indicates presence of a tunnel longer than three cars on the line segment

v^cT multiplicative interaction between v^c and *T*.

f indicates presence of newer hard floor instead of older carpet

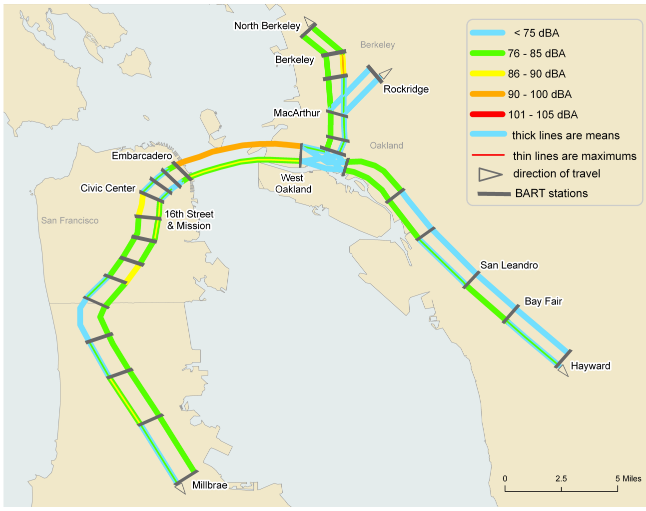
w indicates presence of rain water during the ride

	Full model parameter estimate (sd) p-value[a]			Restricted model parameter estimate (sd) p-value[a]		
L: average sound level (dBA)						
α_0	80.1	(1.37)	<0.001	80.1	(1.38)	<0.001
α_{v^c}	0.693	(0.101)	<0.001	0.726	(0.112)	<0.001
α_{v_b} (break at 52 km/hour)	-0.630	(0.160)	<0.001	-0.669	(0.162)	<0.001
α_T	9.50	(2.46)	<0.001	7.17	(0.908)	<0.001
α_{v^cT}	0.32	(0.196)	0.125			
α_{v_bT}	-0.357	(0.253)	0.178			
α_f	2.83	(0.912)	0.003	2.60	(0.856)	0.002
α_w	-1.34	(1.33)	0.317			
RMSE	6.800			6.865		
R^2	0.491			0.476		
P: peak pressure (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			
β_{v^cT}	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		
S: slow max. pressure (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
γ_{v^cT}	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	0.462			0.462		

Note: All models account for clustering in line segments, and thereby estimate robust standard errors. N = 266 for all models. The full nonlinear least squares model of average sound level converged in 10 iterations, and the restricted model converged in 9 iterations.

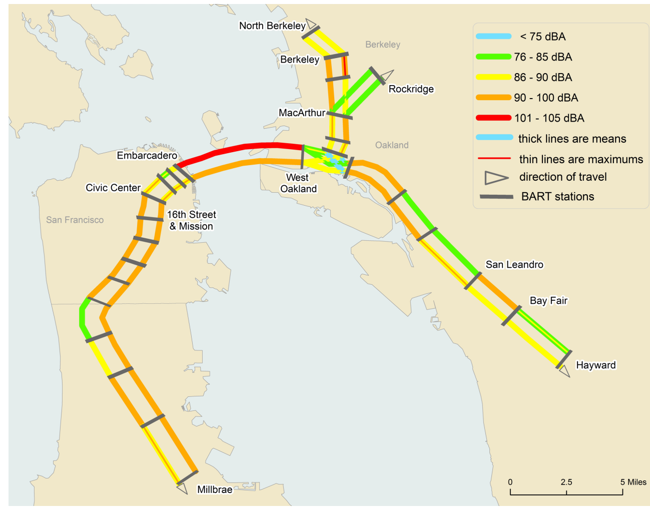
[a] All p-values were corrected for multiple comparisons using the false discovery rate.

Average sound level map



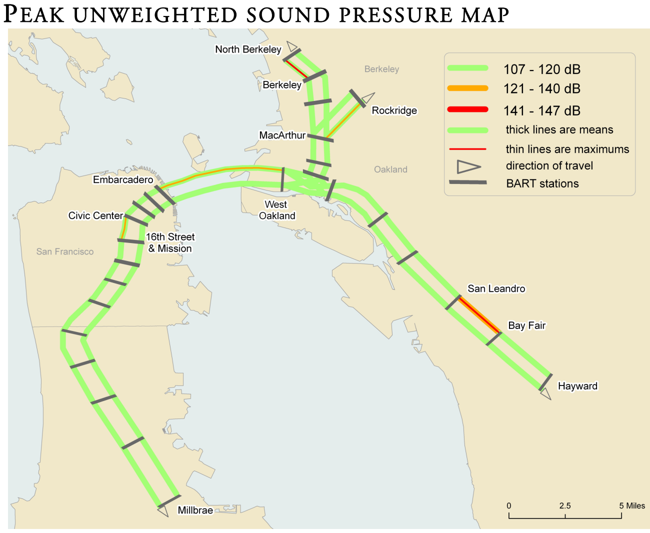
Map of mean and maximum average sound levels (dBA). The shape and exact position of line segments have been distorted to facilitate visual discrimination, and should be interpreted as schematic.

Weighted slow-maximum sound pressure map



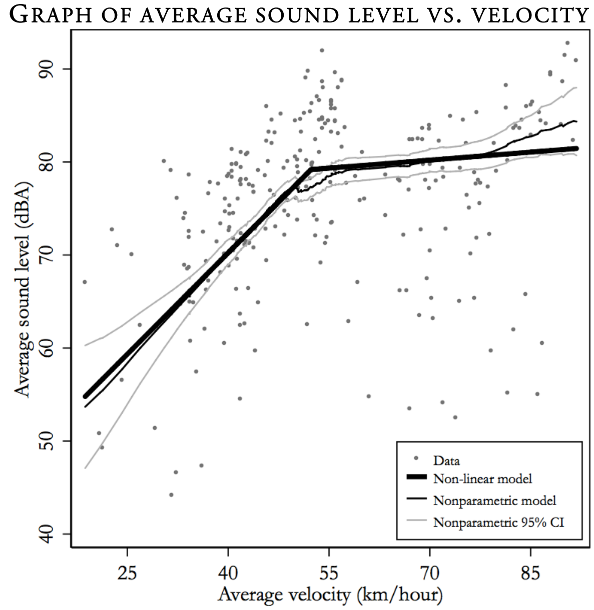
Map of mean and maximum A-weighted slow maximum sound pressure (dBA). The shape and exact position of line segments have been distorted to facilitate visual discrimination, and should be interpreted as schematic.

Peak unweighted sound pressure map



Map of mean and maximum peak unweighted sound pressure (dB). The shape and exact position of line segments have been distorted to facilitate visual discrimination, and should be interpreted as schematic.

Graph of average sound level vs. velocity



Effect of average velocity on average sound level modeled with a nonlinear breakpoint in the effect of average velocity at 52 km/hour (thick black line) overlaid on top of a nonparametric model of mean sound level—$L \sim f_v(v) + f_T(T) + f_f(f)$—(thin black line) with 95% point-wise confidence intervals (thin grey lines), and the raw data.