GROUNDBORNE NOISE AND VIBRATION IN BUILDINGS CAUSED BY RAIL TRANSIT

APTA Track, Noise & Vibration Technical Forum
September 22, 2006
Toronto
PRINCIPAL TEAM MEMBERS

Dr. Jeffrey Zapfe
Acentech Incorporated
Cambridge, MA

Dr. Hugh Saurenman
Zack Dennis
ATS Consulting
Los Angeles, CA

Dr. Sanford Fidell
Fidell Associates, Inc.
Woodland Hills, CA
PROGRAM OBJECTIVES

Develop relationship between rail transit groundborne vibration exposure and human annoyance

• Current Agency complaint experience

• Literature Review

• Develop dosage effect relationships that reflect community response to rail-generated ground vibration. Multiple curves?
PROGRAM OVERVIEW

PHASE 1
- Task 1 – Literature Review
- Task 2 – Survey North American Rail Transit Systems
- Task 3 – Identify Transit Systems for Field Studies
- Task 4 – Develop Field Survey and Measurement Program
- Task 5 – Interim Report #1
- Task 6 – Revised Interim Report #1

PHASE 2
- Task 7a – Field Tests: Pilot Study
- Task 7b – Field Tests
- Task 8 – Human Response Curve
- Task 9 – Interim Report #2
- Task 10 – Final Report
TRANSIT AGENCY SURVEY

- Purpose - obtain impression of whether or not vibration is a significant problem

- Contacted APTA members at agencies by telephone, then e-mailed online survey to appropriate personnel
TRANSIT AGENCY SURVEY RESULTS

• Overall response rate 57% (30 of 55)

• 53% reported no problems or complaints at all

• Only 1 system reported having major problems

• Most vibration problems tended to be focused, rather than system-wide
## TRANSIT AGENCY SURVEY RESULTS

### Complaints

<table>
<thead>
<tr>
<th>Complaints per year</th>
<th>No. Agencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>17</td>
</tr>
<tr>
<td>1 - 5</td>
<td>10</td>
</tr>
<tr>
<td>6 - 20</td>
<td>2</td>
</tr>
<tr>
<td>50+</td>
<td>1</td>
</tr>
</tbody>
</table>
LITERATURE REVIEW
Objectives

• Examine International Standards
  – Evaluation Methods
  – Vibration Limits and Guidelines

• Review Published Literature
  – Laboratory Studies
  – Field Work/Social Surveys
COMMON VIBRATION DESCRIPTORS

- Root-mean-square (rms) acceleration and velocity
- Weighting curves
- Root mean quad weighted vibration (rmq)
- Fourth power vibration dose (m/s^{1.75})
- Imperial and metric units
- Decibels with different reference values
Vibration Weighting Curves (Acceleration)

Frequency Weighting, dB

Frequency, Hz

Wm (KB)
Wk (z)
Wd (xy)
ANSI
BS(z)
BS(xy)
Normalized Vibration Weighting Curves (Velocity)

Critical frequency range for ground vibration

Wm (KB)
Wk (z)
Wd (xy)
ANSI
BS(z)
BS(xy)
COMPARISON OF VIBRATION STANDARDS

The diagram illustrates the vibration thresholds in decibels (VdB) for various countries during both daytime and nighttime, with the FTA limit for residential land uses indicated by a horizontal dashed line.
LITERATURE REVIEW

Related Research

• Laboratory Studies
  – Thresholds of Perception and Equal Annoyance Contours
  – Annoyance vs. Vibration Levels
  – Combined Effects of Noise and Vibration

• Social Surveys
PERCEPTION THRESHOLD

RMS Vibration Velocity Level, VdB re 1µin/s

Frequency, Hz

ANSI Curve
Reiher & Meister '31
Miwa '69
McKay '71
Benson & Dilnot '81
Parsons & Griffin (1) '88
Parsons & Griffin (2) '88
Bellman '02
COMMUNITY RESPONSE SURVEY
Scotland

• Woodroof & Griffin (1986)
  – 459 interviews (160 noticed vibration)
  – 3 axis vibration measured in 52 residences (24-hour)
  – Conclusion: “…vibration is among the least annoying aspects of a railway’s presence in a neighborhood.”
  – vertical vibration most important (greatest axis, greatest sensitivity)
  – best correlated metric
    number of trains/day that can be perceived
COMMUNITY RESPONSE SURVEY
Sweden

- Öhrström (1997)
  - Buildings where inhabitants had complained about vibrations
  - Much higher vibration levels than in Scotland
  - Wide variation in exposure-effect relationships
COMMUNITY RESPONSE SURVEY
Norway

  - 1503 telephone interviews
  - Vibration exposure estimated using semi-empirical model
  - Exposure ranged from below perception to 100 VdB
  - Statistically valid dose-response curves developed using $V_{95}$
NORWEGIAN STUDY (Klaeboe et al, 2003)

Annoyance vs. Vibration Level

![Graph showing the relationship between average vibration velocity level and percentage of people annoyed](image)
LITERATURE REVIEW

Summary

• Vertical vibration sufficient measure
• Not necessary to test inside every home
• Many (1000’s) interviews needed
CANDIDATE SYSTEMS FOR FIELD STUDY

- Heavy Rail
- Light Rail
- Commuter Rail

Sacramento RT
SF Muni
BART
VTA
Caltrain

LA Blue Line
LA Metrolink

TTC GO Transit

CTA
METRA

NYCTA
LIRR
Metro North
Hudson Bergen
SEPTA
Washington Metro

MBTA Green
Red/Blue/Orange Commuter Rail

DART
<table>
<thead>
<tr>
<th>Washington Metro</th>
<th>DART (Dallas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBTA Commuter Rail</td>
<td>Los Angeles Metrolink</td>
</tr>
<tr>
<td>MBTA Green Line</td>
<td>Caltrain (SF to San Jose)</td>
</tr>
<tr>
<td>MBTA Red/Orange/Blue</td>
<td>Sacramento</td>
</tr>
<tr>
<td>Hudson Bergen (NJ)</td>
<td>Los Angeles Blue Line</td>
</tr>
<tr>
<td>Long Island Railroad</td>
<td>San Francisco MUNI-</td>
</tr>
<tr>
<td>Metro North Railroad</td>
<td>VTA San Jose</td>
</tr>
<tr>
<td>NYCTA (New York City)</td>
<td>BART (SF/Oakland)</td>
</tr>
<tr>
<td>GO Transit (metro Toronto)</td>
<td></td>
</tr>
<tr>
<td>TTC - Rapid Transit</td>
<td></td>
</tr>
<tr>
<td>SEPTA</td>
<td></td>
</tr>
<tr>
<td>Chicago METRA</td>
<td></td>
</tr>
<tr>
<td>CTA (Chicago)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mr. Joe Oriolo</td>
</tr>
<tr>
<td></td>
<td>Mr. Joe Oriolo</td>
</tr>
<tr>
<td></td>
<td>Mr. D.C. Agrawal</td>
</tr>
<tr>
<td></td>
<td>Mr. Ian McAvoy</td>
</tr>
<tr>
<td></td>
<td>Mr. Gerald Francis</td>
</tr>
<tr>
<td></td>
<td>Mr. Mark Robinson</td>
</tr>
</tbody>
</table>
FIELD MEASUREMENTS
Measurement Locations

Reference position
(same for all 5 residences)

Indoor Noise and Vibration

Outdoor Noise and Vibration
FIELD MEASUREMENTS

Data Collection

• All data to be recorded
  (flash card recorder)
• Vibration – measure acceleration in field
  (seismic accelerometers)
• Sound – unweighted sound pressure
  (1/2” microphones)

• Raw waveforms to be recorded
• All recorders time synchronized
• Personnel to monitor and record event times
  in field
FIELD MEASUREMENTS
Data Processing

- Use MATLAB to
  - scale data
  - 1/3 octave band filters
  - create vibration/sound time histories
  - calculate event metrics
SOCIAL SURVEY
Design Considerations

- Overall goal of survey is to collect sufficient information about prevalence of adverse effects to support useful dosage-effect analyses.
- Observations needed under a reasonable range (at least 20 dB) of exposure conditions.
- Sufficient data required to yield 90% confidence intervals for sample proportions on the order of ±5% or smaller.
SOCIAL SURVEY
Design Considerations (cont’d)

• Sample size requirements imply need for ~ 200 completed interviews per site - with diverse exposure

• Sampling frame of ~1000+ households eligible for interview required at each site (assuming 70% completion rate)

• Sites with straight track alignments and reasonably homogeneous exposure/housing construction preferred
EXAMPLE: ANNOYANCE DUE TO RATTLE VS. DISTANCE FROM SOURCE

% HA = -.00855 (feet to centerline) + 50.1

\( r^2 = .93 \) (combined data)

\( r^2 = .98 \) (LAX)

\( r^2 = .64 \) (MSP)

---

<table>
<thead>
<tr>
<th>Sideline Distance from Closest Departure Runway Centerline, ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,500</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>100</td>
</tr>
</tbody>
</table>

---

Prevalence of High Annoyance Due to Rattle and Vibration, %

- Combined
- LAX
- MSP
SOCIAL SURVEY
Key Questionnaire Items

• ITEM 1: Can you please tell me how long you have lived at (street address)?

• ITEM 2: What do you like most about living conditions in your neighborhood?

• ITEM 3: What do you like least about living conditions in your neighborhood?
SOCIAL SURVEY
Key Questionnaire Items (cont’d)

• ITEM 5: While you’ve been at home over the past year, have you been bothered or annoyed by the sounds that San Francisco Muni trains make as they pass by outside your home?

• ITEM 6: Do you notice low rumbling sounds inside your home as San Francisco Muni trains pass by outside?

• ITEM 7: While you’ve been at home over the past year, have you ever been awakened by low rumbling sounds, rattling, shaking, or vibration inside your home when San Francisco Muni trains pass by?
SOCIAL SURVEY
Key Questionnaire Items (cont’d)

- ITEM 8: Do you ever hear rattling sounds from windows, doors, wall hangings, or other items in your home when San Francisco Muni trains pass by?

- ITEM 9: Do you ever feel your home shake or the floors, walls, counters, or furniture vibrate when San Francisco Muni trains pass by?
PILOT STUDY
San Francisco Muni Judah St. Line
PILOT STUDY
Ground View of Judah Street Line
PILOT STUDY UPDATE
San Francisco Muni

• June 16, Contact letters from APTA were sent out to 21 systems identified as candidates for field test

• Survey dates set for July 20-23

• July 20, Muni contacted Martin asking that the work be halted because of recent legal issues in the test area

• Data collection halted on 21 July (after 6 hours or interviewing)

• At present, no plans to pursue Muni further
PILOT STUDY – WHAT WE LEARNED

- Sampling frame of ~1100 residential households with listed telephone numbers prepared along 80 block faces of apartment buildings within 300 ft of Judah street frontage
- Computer-assisted telephone interviewing by experienced, trained, and centrally supervised personnel
- 94 interviews completed in approximately 6 hours
- Mean duration of interview slightly greater than 5 minutes
PILOT STUDY
Preliminary Findings

• Responses to questions about notice of adverse effects (airborne noise, rumble, rattle, and shaking) are orderly and interpretable

• 72% of all respondents noticed low rumbling sounds inside their homes as San Francisco Muni trains pass by outside

• About 37% of the respondents noticed rattling sounds in their homes as Muni trains passed by
PILOT STUDY
Preliminary Findings (cont’d)

• About 11% of all respondents considered rattling noises to be highly annoying

• About the same number of respondents who noticed rattle also reported feeling shaking or vibration in their homes as Muni trains pass by

• The frequency of notice and degree of annoyance due to shaking are similar to those of rattle
PILOT STUDY
Preliminary Findings (cont’d)

• Responses to questions about notice of adverse effects (airborne noise, rumble, rattle, and shaking) are orderly and interpretable

• 72% of all respondents noticed low rumbling sounds inside their homes as San Francisco Muni trains pass by outside

• About 37% of the respondents noticed rattling sounds in their homes as Muni trains passed by
IDEALIZED PERCENTAGES OF RESPONDENTS HEARING/NOT HEARING RATTLE vs. DISTANCE FROM TRACK
ACTUAL PERCENTAGES OF RESPONDENTS
HEARING/NOT HEARING RATTLE vs.
DISTANCE FROM TRACK

Distance from Track in Meters

Percent of Respondents

- don’t hear rattle
- do hear rattle
### MEAN DISTANCES FROM RIGHT OF WAY AT WHICH EFFECTS WERE NOTICED

<table>
<thead>
<tr>
<th>EFFECT</th>
<th>MEAN DISTANCE AT WHICH NOTICED (meters)</th>
<th>MEAN DISTANCE AT WHICH NOT NOTICED (meters)</th>
<th>( t_{df} )</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUMBLE</td>
<td>42</td>
<td>58</td>
<td>2.21\textsubscript{90}</td>
<td>.01</td>
</tr>
<tr>
<td>RATTLE</td>
<td>27</td>
<td>62</td>
<td>5.42\textsubscript{92}</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>SHAKE</td>
<td>32</td>
<td>59</td>
<td>3.84\textsubscript{88}</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>AWAKENING</td>
<td>40</td>
<td>43</td>
<td>0.38\textsubscript{51}</td>
<td>ns</td>
</tr>
</tbody>
</table>
## ROUGH ESTIMATES OF WIDTHS OF DOSAGE-EFFECT RELATIONSHIPS

<table>
<thead>
<tr>
<th>EFFECT</th>
<th>RATIO OF MEAN DISTANCES</th>
<th>20 LOG RATIO OF DISTANCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUMBLE</td>
<td>1.4</td>
<td>2.8 dB</td>
</tr>
<tr>
<td>RATTLE</td>
<td>2.3</td>
<td>9.8 dB</td>
</tr>
<tr>
<td>SHAKE</td>
<td>1.8</td>
<td>5.3 dB</td>
</tr>
</tbody>
</table>
PLANNED WAY AHEAD
Field Testing

• Proceed immediately with VTA (San Jose) as pilot test site #2

• Rank order remaining 19 agencies for testing.

• Proceed down list and test as many as possible within budgetary limits.

• Goals
  • 2000 completed interviews (10,000 contacts)
  • 120 in-residence measurements
# PROPOSED TEST ORDER

<table>
<thead>
<tr>
<th>LR</th>
<th>VTA San Jose</th>
<th>contact: Mark Robinson</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT</td>
<td>TTC (Toronto) - Rapid Transit</td>
<td>contact: Brian Longson</td>
</tr>
<tr>
<td>RT</td>
<td>NYCTA (New York)</td>
<td>contact: Tony Cabrera</td>
</tr>
<tr>
<td>RT</td>
<td>BART (SF/Oakland)</td>
<td></td>
</tr>
<tr>
<td>CR</td>
<td>Caltrain (SF to San Jose)</td>
<td>contact: Ian McAvoy</td>
</tr>
<tr>
<td>RT</td>
<td>MBTA Red/Orange/Blue</td>
<td>contact: Joe Oriolo</td>
</tr>
<tr>
<td>LR</td>
<td>Hudson Bergen (NJ)</td>
<td>contact: Mr. D.C. Agrawal</td>
</tr>
<tr>
<td>LR</td>
<td>Los Angeles Blue Line</td>
<td>contact: Gerald C. Francis</td>
</tr>
<tr>
<td>RT</td>
<td>CTA (Chicago)</td>
<td></td>
</tr>
<tr>
<td>CR</td>
<td>Long Island Railroad</td>
<td></td>
</tr>
<tr>
<td>CR</td>
<td>MBTA Commuter Rail</td>
<td></td>
</tr>
<tr>
<td>LR</td>
<td>MBTA Green Line</td>
<td>contact: Joe Oriolo</td>
</tr>
<tr>
<td>LR</td>
<td>DART (Dallas)</td>
<td></td>
</tr>
<tr>
<td>RT</td>
<td>Washington Metro</td>
<td></td>
</tr>
<tr>
<td>CR</td>
<td>GO Transit (metro Toronto)</td>
<td>contact: Greg Ashbee</td>
</tr>
<tr>
<td>CR</td>
<td>Metro North Railroad</td>
<td></td>
</tr>
<tr>
<td>RT</td>
<td>SEPTA</td>
<td></td>
</tr>
<tr>
<td>CR</td>
<td>Chicago METRA</td>
<td></td>
</tr>
<tr>
<td>LR</td>
<td>Sacramento</td>
<td></td>
</tr>
</tbody>
</table>