FINAL REPORT

On Project 25-34
Supplemental Guidance on the Application of FHWA's Traffic Noise Model (TNM)

APPENDIX G
Topography

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G.1 The Automated TNM Sensitivity Tool: Overview and Example

G.1.1 Introduction

This section describes the *Automated TNM Sensitivity Tool*, which has been built and tested on NCHRP 25-34 – for sensitivity-test usage in several topic areas.

In brief, the sensitivity tool is designed to investigate TNM's sensitivity to changes in one-or-more specific input parameters - for example, location of the right edge of pavement relative to the TNM roadway, barrier, intervening hills, and receivers. Such a test starts with a TNM case with:

- Simple "straight-line" geometries for all input objects, in this example: roadway, barrier and terrain lines
- A large field of receivers.

With this geometry, then (1) the position of the roadway edge is "inward offset" and "outward offset" by a small change in roadway width, (2) TNM is run with these two offsets, and (3) results of the two runs are subtracted, separately by receiver, to determine the resulting effect on sound levels, for example: 1.5dB change per 4-foot offset of roadway edge (at one specific receiver distance/height).

Such a test serves as guidance to the project team about how precisely TNM users need to model roadway widths say to hold TNM uncertainty down to plus/minus 1dB. The *Automated TNM Sensitivity Tool* allows automated computation of many hundreds of such tests, for very complete guidance to the project team. Finally, the project team needs to condense all those results into a form suitable for guidance about best TNM practice.

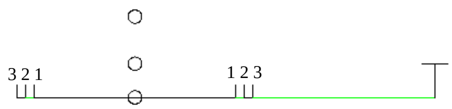
The remainder of this document describes the *Automated TNM Sensitivity Tool*, using this roadway-edge example to illustrate.

G.1.2 Overview of the sensitivity tool

Figure 1 provides a one-page overview of the *Automated TNM Sensitivity Tool*:

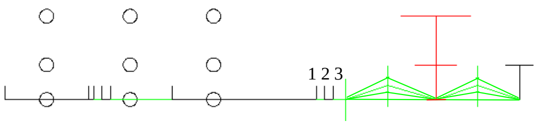
- At the top of the figure is a TNM section view of the roadway-width example, with one receiver to the right. Width[11] is the inward-offset width, while Width[33] is the outward-offset width. Two TNM runs with these respective widths allow subtraction, to obtain the change in sound level (ΔL_{eq}) due to the change in width ($\Delta Width$) yielding a sensitivity of ΔL_{eq} divided by $\Delta Width$.
- However, the next-lower figure section illustrates that the sensitivity depends upon other parameters, shown to the right. For example, if traffic consists only of automobiles, then sound propagation is close to the ground, where it is more likely to be affected by the right edge of pavement. The section view includes those additional parameters.
- The next section downwards adds additional receivers. Those further away, or higher off the ground, might be less affected.
- The next section downwards sums up all the various combinations of input values that are involved in this sensitivity test for a total of 432 TNM runs, producing 3,456 sensitivity computations of ΔL_{eq} due to $\Delta Width$.

How sensitive is Leq to position of roadway edge?



- Width [22] is actual roadway.
- Perturb width from [11] to [33].
- **What is ΔL_{eq} due to Δ*Width*?**

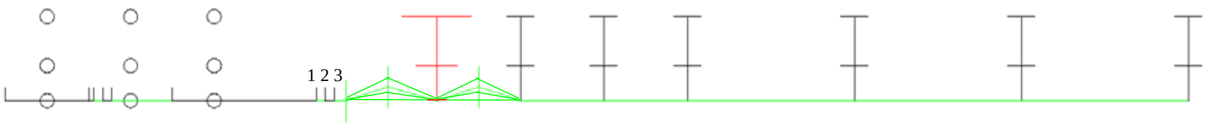
Answer depends upon other parameters.



Other parameters:

- All autos, or all MTs, or all HTs
- Alternative centerline locations, re the roadway edge
- Barrier or not, with different heights
- Rolling terrain or not, with different heights

Answer also depends upon receiver location.



In all:

- (3 vehicle types) **x** (3 centerline locations) **x** (3 barrier heights) **x** (4 "hill" heights) **x** (2 "hill locations") = **216 geometries**
- This means (216 geometries) **x** (width [11] and width [33]) = **432 TNM runs**
- Then will have (216 geometries) **x** (16 receivers) = **3,456 computations of ΔL_{eq} due to Δ*Width*** (and also 3,456 L_{eq}'s and 3,456 Noise Abatements)

How do we efficiently run TNM 432 times?

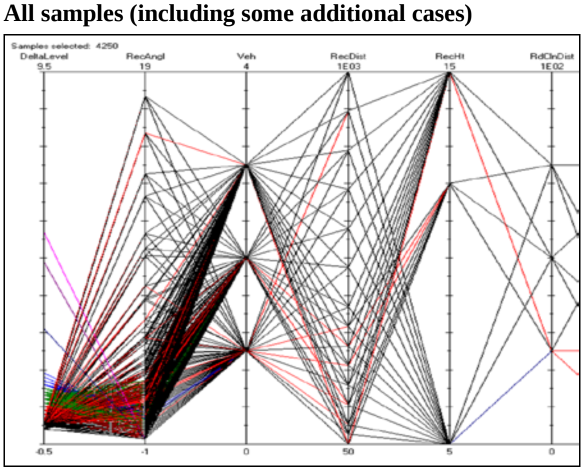
- Set up TNM input in Excel (one entry per input-parameter value), along with placeholders for all TNM output.
- Use *Excel* and *MacroExpress* to (1) automatically generate all 3,456 input combinations, (2) automatically transfer each run's input to TNM, (3) automatically run TNM, and (4) automatically transfer each run's output back to *Excel*, thereby preparing for Cobweb Plots.

How do we sort through all the output?

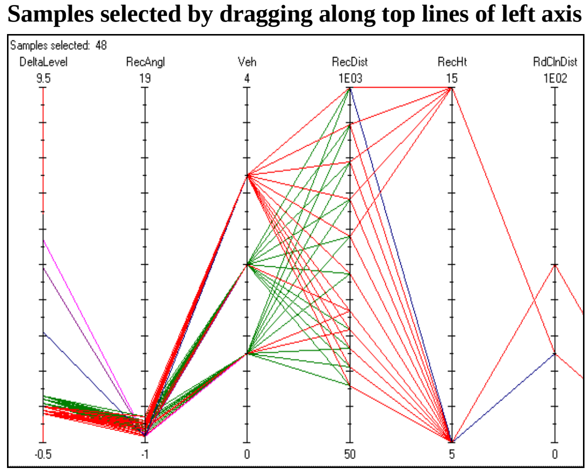
- Use **Cobweb Plots** Textbook: D. Kurowicka and R. Cooke, *Uncertainty Analysis*, Wiley, 2006
  Software: UNICORN at http://risk2.ewi.tudelft.nl/oursoftware/3-unicorn

Example plots:

All samples (including some additional cases)



Samples selected by dragging along top lines of left axis



Cobweb Plot allows us to find parameter values that generate "worst" sensitivity (or any other sensitivity range).

Figure 1 Overview of the Automated TNM Sensitivity Tool

- This huge number of TNM runs and sensitivity computations has a great advantage over smaller numbers: it is nearly certain to "find" the particular combinations of input parameters that produce the highest sensitivity values.
- The next section downwards in the figure then asks the obvious question: How do we efficiently run TNM 432 times? Here is the two-bullet answer from the figure.
  - Set up TNM input in Excel (one entry per input-parameter value), along with placeholders for all TNM output.
  - Use Excel and MacroExpress to (1) automatically generate all 3,456 input combinations, (2) automatically transfer each run's input to TNM, (3) automatically run TNM, and (4) automatically transfer each run's output back to Excel, thereby preparing for cobweb plots.

G.1.3 The sensitivity process: An Example

Crucial to the sensitivity process is a specially designed Excel spreadsheet, filled with specialized cell formulas (but no Visual Basic code), plus a specially designed set of MacroExpress macros to do all the automating. This spreadsheet and macro set comprise the *Automated TNM Sensitivity Tool*.

With that tool, the sensitivity process consists of the following steps:

1. **Clear spreadsheet remnants.** Invoke the script "Delete All TNM Tables in Excel" causing the tool to clear the Excel spreadsheet of all remnants from prior use.

2. **Import from TNM.** Enter the initial set of input into TNM, then calculate TNM, and then invoke the script "Transfer All Input Tables" causing the tool to import all TNM input tables into the spreadsheet.

3. **Specify input combinations.** In those imported TNM tables, find the input parameters of interest and type their Excel addresses into the spreadsheet's computation sheet. Also list the desired values for those input parameters, along with the input pairings that should be varied in synchrony (like the two end-point heights of a barrier that must vary up and down, both points in synchrony). Then enter the Plus/minus Offset Increment for the "offset" parameter(s) under investigation.

   Figure 2 shows this example input within Excel, but with reduced number of receivers and not showing the barrier and terrain-line input columns.

Combination Index (equal values force simultaneous changes):	1	2	3	3	3	4	4	4	4	4	4
Parameter (abbrev. OK):			Mainline Width	Mainline Pt1 Y	Mainline Pt2 Y	Auto Vol	MT Vol	HT Vol	Auto Spd	MT Spd	HT Spd
Input Sheet (exact):			TlnRoad	TlnRoad	TlnRoad	TlnTraf	TlnTraf	TlnTraf	TlnTraf	TlnTraf	TlnTraf
Input Cell (exact):			F21	K15	K16	I15	K15	M15	J15	L15	N15
Plus/minus Offset Increment:			5								
	Distance (or height)	Height (or distance)									
Values	50	5	50	-25	-25	100	0	0	50	0	0
	75	15	100	-50	-50	0	100	0	0	50	0
			150	-75	-75	0	0	100	0	0	50
	864	= number of input combinations from above (max = 5,000)									

Figure 2 Sample parameter input in Excel

   As shown in the figure, this input consists of (1) a Combination Index to show which parameter columns work in synchrony, (2) each parameter's Input Sheet and Input Cell, (3) the Plus/Minus Offset Increment for the parameter(s) being offset, and (4) the parameter values of interest—each entered just once.

From this information, the spreadsheet automatically constructs all input combinations, one line per combination (maximum of 5000 combinations in the current spreadsheet)—as shown in Figure 3.

InputSheet:	TInRec	TInRec	TInRoad	TInRoad	TInRoad	TInTraf	TInTraf	TInTraf	TInTraf	TInTraf	TInTraf
Variable:	Dist	Ht	Mainline Width	lainline Pt1 Y	inline Pt2 Y	Auto Vol	MT Vol	HT Vol	Auto Spd	MT Spd	HT Spd
Seq			CompLoopStart								
0	50	5	50	-25	-25	100	0	0	50	0	0
1	75	5	50	-25	-25	100	0	0	50	0	0
2	50	15	50	-25	-25	100	0	0	50	0	0
3	75	15	50	-25	-25	100	0	0	50	0	0
4	50	5	100	-50	-50	100	0	0	50	0	0
5	75	5	100	-50	-50	100	0	0	50	0	0
6	50	15	100	-50	-50	100	0	0	50	0	0
7	75	15	100	-50	-50	100	0	0	50	0	0
8	50	5	150	-75	-75	100	0	0	50	0	0
9	75	5	150	-75	-75	100	0	0	50	0	0
10	50	15	150	-75	-75	100	0	0	50	0	0
11	75	15	150	-75	-75	100	0	0	50	0	0
12	50	5	50	-25	-25	0	100	0	0	50	0
13	75	5	50	-25	-25	0	100	0	0	50	0
14	50	15	50	-25	-25	0	100	0	0	50	0
15	75	15	50	-25	-25	0	100	0	0	50	0
16	50	5	100	-50	-50	0	100	0	0	50	0
17	75	5	100	-50	-50	0	100	0	0	50	0
18	50	15	100	-50	-50	0	100	0	0	50	0
19	75	15	100	-50	-50	0	100	0	0	50	0
20	50	5	150	-75	-75	0	100	0	0	50	0
21	75	5	150	-75	-75	0	100	0	0	50	0
22	50	15	150	-75	-75	0	100	0	0	50	0
23	75	15	150	-75	-75	0	100	0	0	50	0
24	50	5	50	-25	-25	0	0	100	0	0	50
25	75	5	50	-25	-25	0	0	100	0	0	50
26	50	15	50	-25	-25	0	0	100	0	0	50

Figure 3 Resulting list of computation combinations (automatic)

In the second column of this figure, note that TInRecDist oscillates back and forth between the two distances, while in the next column, TInRecHt stays the same (5 ft) for one distance oscillation, then changes to 15 ft for the next oscillation. Each successive column follows that same oscillation-combination pattern. Also note that the three TInRoad columns all stay in synchrony during this process as do the six TInTraf columns.

Compute everything (in one stroke). Invoke the script "Comp Loop" causing the tool to loop over all the input combinations. For each combination, the tool transfers those input values to TNM, then runs TNM, and then transfers TNM's sound-level results back to Excel (for both the minus offset and the plus offset).

The Tool is able to do all this because it knows the exact place to paste each input from the Excel spreadsheet. That knowledge is built into the spreadsheet formulas, as illustrated in Figure 4.

In the lower-right in this figure is a small portion of the Traffic Input, which the macros paste here from TNM. Above each column is the specific location of that column's input within TNM. Those locations can reside permanently in the spreadsheet, because each input column always contains the same input parameter. To the left of the actual input are formulas that automatically derive the object number and segment number of each input object, for any number of objects and any number of segments per object.

The macros grab these values from the spreadsheet and use them to navigate to the proper TNM input location for each parameter.

				TNM Input Location													
			Input Type:					R	R	R	R	R	R	R	R	R	R
			Input Tab:					2	2	2	2	2	2	2	2	2	2
			To Name: #Ups					0	0	0	0	0	0	0	0	0	0
			#Dn:					0	0	0	0	0	0	0	0	0	0
			#Tabs:					0	0	0	0	0	0	0	0	0	0
			Header(H) or Spread(S):					S	S	S	S	S	S	S	S	S	S
			HeadTabSeq(#) or SpreadCol(#):					2	3	2	3	2	3	2	3	2	3
# Objects:	1		SpreadRow(#):					1	1	2	2	3	3	4	4	5	5
# Segs:		1															
	Obj #	Seg #		Roadway Name	xxx	Points Name	PointsNo.	Autos V	Autos S	MTrucks V	MTrucks S	HTrucks V	HTrucks S	Buses V	Buses S	Motorcycles V	Motorcycles S
	1	1	**TlnTraf:**	Mainline		West	1	100	50	0	0	0	0	0	0	0	0
	1	2				East	2										

Figure 4 Example Input Sheet (traffic) with Formula-derived TNM Input Locations

4. Excel then handles the rest of the arithmetic, to prepare for data mining of the resulting CSV file.

Figure 5 repeats the bottom portion of Figure 1, which shows a sample cobweb plot (on the left) and the result (on the right) of dragging the cursor along approximately the upper 4/5s of the cobweb plot's left-most axis (DelLev). Per that result, we learn that all the largest sensitivities on that axis derive from the very lowest values of RecAngl, the vertical angle subtended by the head/foot of the receiver. That angle (as well as other candidate parameters) was added to the CSV-generated spreadsheet, after mulling over the graphed results and thinking about the physics of the situation. Here is where the thinking comes in.

Different areas of the left axis can be swept with the cursor, to learn other patterns within the huge number of plot lines (more than 3,456 lines in this example). Similarly, the L_{eq} vertical axis (not shown here) can be swept to learn patterns connected with particular L_{eq} ranges. And successive sweeps can augment or replace prior sweeps.

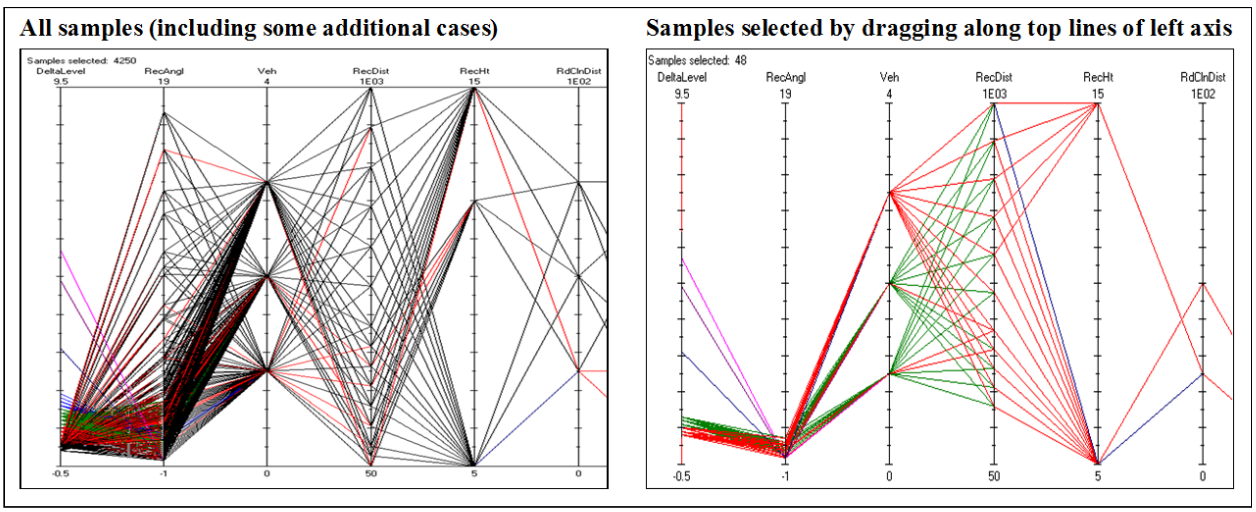


Figure 5 Cobweb plots, before/after left-axis selection of high-sensitivity lines

As is apparent from this overview of the *Automated TNM Sensitivity Tool*, a huge amount can be learned with relatively little effort.

G.2 Outside edge of pavement: Horizontal precision

The *Automated TNM Sensitivity Tool* (Section 1 of this appendix) was used to investigate the sensitivity of TNM computations to the exact modeled location of the outer edge of pavement. In brief, we wished to investigate how precisely the outer edge must be located, to achieve any particular precision in computed L_{eq}. Numerically, how does $\Delta Leq/\Delta Width$ depend upon all other TNM input?

G.2.1 Initial TNM sensitivity computations

G.2.1.1 The geometry

Figure 6 sketches the initial 3,456 sensitivity computations.

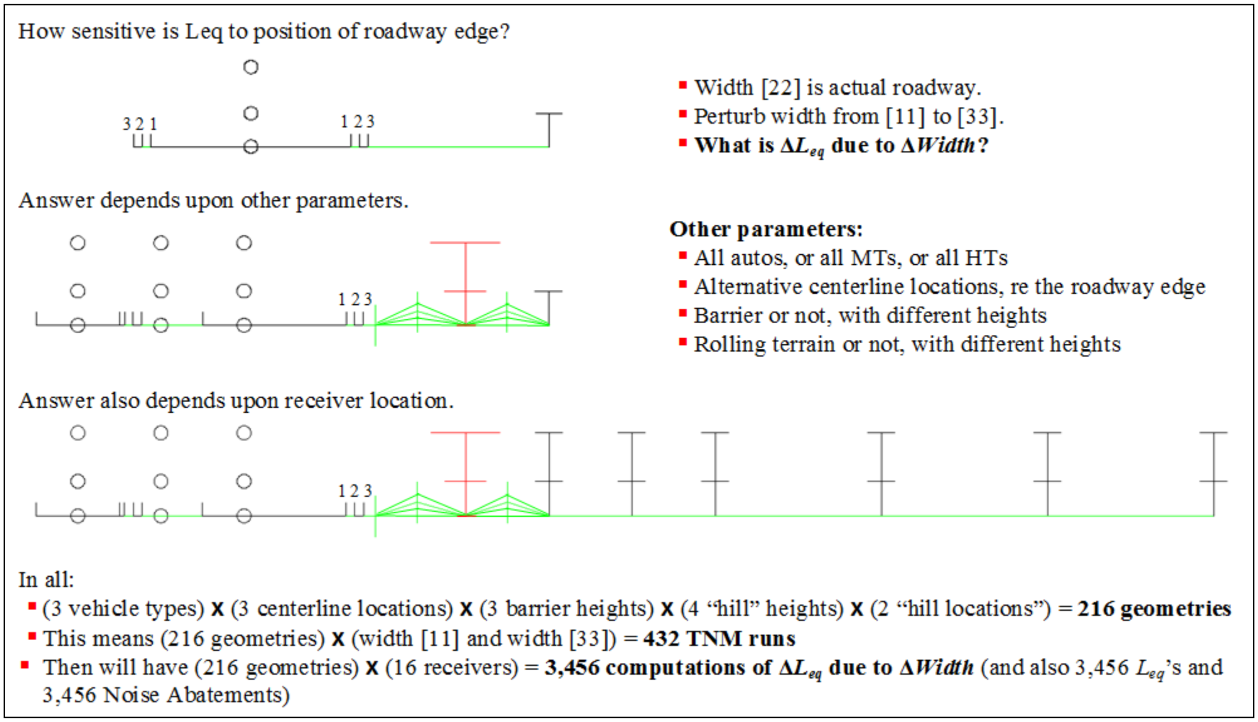


Figure 6 Initial TNM sensitivity computations

At the top of the figure is a TNM section view of a roadway, with one receiver to the right. In that section view, Width[11] is an inward-offset width, while Width[33] is an outward-offset width. Two TNM runs with these respective widths allow subtraction, to obtain the change in sound level (ΔL_{eq}) due to the change in width ($\Delta Width$) yielding a sensitivity of ΔL_{eq} divided by $\Delta Width$.

That sensitivity $\Delta Leq/\Delta Width$, shows how precisely the outer edge must be located, to achieve any particular precision in computed L_{eq}. And so it is the main subject of investigation here.

The next-lower part of Figure 6 anticipates that this sensitivity depends upon other parameters, shown to the right. For example, if traffic consists only of automobiles, then sound propagation is close to the ground, where it is more likely to be affected by the near edge of pavement. The section view includes those additional parameters. In particular, it shows:

- The three alternative positions of a single roadway. For each centerline position, the roadway's right edge is located at position 2 in the figure.
- The two alternative locations of an intervening hill, each with four heights (0, 1, 2 and 3 feet).
- The intervening barrier, with three alternative heights (0, 5 and 12 feet).
- Twelve of the sixteen receivers located 5 and 12 feet above the terrain. The other four receivers are off the view to the right.

The next section downwards in the figure sums up all the various combinations of input values that are involved in this sensitivity computation for a total of **432 TNM runs**, producing **3,456 sensitivity computations of ΔL_{eq} due to $\Delta Width$**.

G.2.1.2 The spreadsheet input combinations

Figure 7 shows the corresponding TNM input combinations within Excel's Sensitivity spreadsheet. As seen in the figure:

- Columns 1 and 2 contain the receiver distances and heights. TNM input includes all combinations of those: two receivers at each of eight distances from the roadway's near edge.
- Columns 3 first contain the multi-valued roadway points 1 and 2. These two points vary in synchrony, because their column index number is the same. For the same reason, roadway width also varies in synchrony with the roadway point locations, to keep the near roadway edge unmoved.
- Columns 4 contain synchronized traffic volumes and speeds. As a result of this input, each TNM run contains only one vehicle type, always at the same speed—while the other vehicle types are zeroed out.
- Columns 5 contain heights of the two barrier points, again synchronized with each other.
- Columns 6 and 7 contain the multi-valued terrain-line input. Even though Figure 6 appears to show two terrain lines, each TNM run contain but one of them. Column 6 varies the location of that terrain line between two values, while Column 7 varies the height among four values (including zero). Because these columns are numbered differently, the two terrain-line locations are paired separately with each of the four terrain-line heights.

	Receivers: Check that Cols B,C on Comps sheet reproduce TNM's receiver order.		Multi-valued parameters															
Combination Index (equal values force simultaneous changes):	1	2	3	3	3	4	4	4	4	4	4	5	5	6	6	7	7
Parameter (abbrev. OK):			RoadPt1	RoadPt2	RoadWidth	TraffAVol	TraffASp	TraffMTVol	TraffMTSp	TraffHTVol	TraffHTSp	BarrHtPt1	BarrHtPt2	TLPt1	TLPt2	TLHt1	TLHt2
InputSheet (exact):			TInRoad	TInRoad	TInRoad	TInTraf	TInTraf	TInTraf	TInTraf	TInTraf	TInTraf	TInBarr	TInBarr	TInTerr	TInTerr	TInTerr	TInTerr
Input Cell (exact):			K12	K13	F12	I12	J12	K12	L12	M12	N12	T12	T13	I12	I13	J12	J13
Plus/minus Offset Increment:					2												
	Distance (or height)	Height (or distance)															
Values	50	5	-25	-25	50	1000	50	0	0	0	0	0	0	12.5	12.5	0	0
	75	12	-50	-50	100	0	0	1000	50	0	0	5	5	37.5	37.5	1	1
	100		-75	-75	150	0	0	0	0	1000	50	12	12			2	2
	150															3	3
	200																
	250																
	300																
	350																
	3,456	= number of input combinations from above (max = 5,000)															
	216	= number of computation loops (ignores number of receivers)															

Figure 7 TNM Input combinations within Excel

In addition, the figure shows the offset parameter (roadway width), which offsets by plus/minus 2 feet during the sensitivity computations. As a result, the ΔLeq from that offset corresponds to a ΔWidth of 4 feet.

Figure 8 and Figure 9 contain the corresponding geometry within TNM.

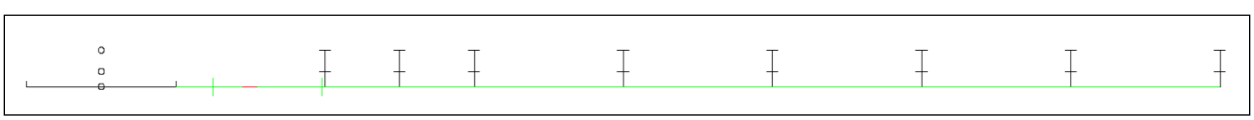


Figure 8 TNM skew section

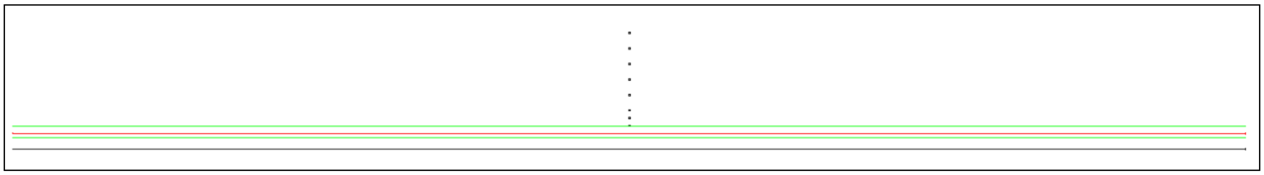


Figure 9 TNM plan view

In the TNM skew section, the alternative objects are shown at their starting locations and heights that is:

- The closest roadway location
- The hill location between the roadway and the barrier, with the hill at zero height
- The barrier at zero height (faint, horizontal red line).

In addition:

- The terrain is flat and consists of "lawn."
- Another terrain line appears just in front of the first receiver, and at zero height to fix the terrain at that distance and height, for receivers further away from the roadway.

With this Excel input and TNM geometry, we investigate the sensitivity to near-edge location, as a function of:

- Centerline location (three distances to edge of pavement: 25, 50 and 75 ft with these roadway widths to enforce that: 50, 100 and 150ft)
- Traffic on that single roadway: All automobiles, or all medium trucks, or all heavy trucks
- Barrier height (three heights: 0, 5 and 12 feet)
- Hill height (four hill heights: 0, 1, 2 and 3 feet)
- Hill location (two locations: (1) roadway side of barrier, midway between roadway edge and barrier, as well as (2) symmetrically on the opposite side of the barrier).

G.2.1.3 Computation results

Figure 10 shows the initial cobweb plot,[1, 2] which contains a left-to-right line for each of the combined 3,456 input combinations. Each line's intersection with a vertical axis shows that combination's value for that axis parameter. For example, note that all lines pass through one of only three points on the RdWidth (roadway width) axis. In contrast, the lines spread out among the eleven computed values of DeltaLevel, to the right in the plot.

In addition, the figure contains a "minimum" and a "maximum" line, to fix the vertical-scale limits at convenient values and thereby make the line-intersection values easier to read from each axis scale.

[1] UNICORN at http://risk2.ewi.tudelft.nl/oursoftware/3-unicorn or its update.
[2] Kurowicka, D. and R. Cooke, *Uncertainty Analysis*, Wiley (2006).

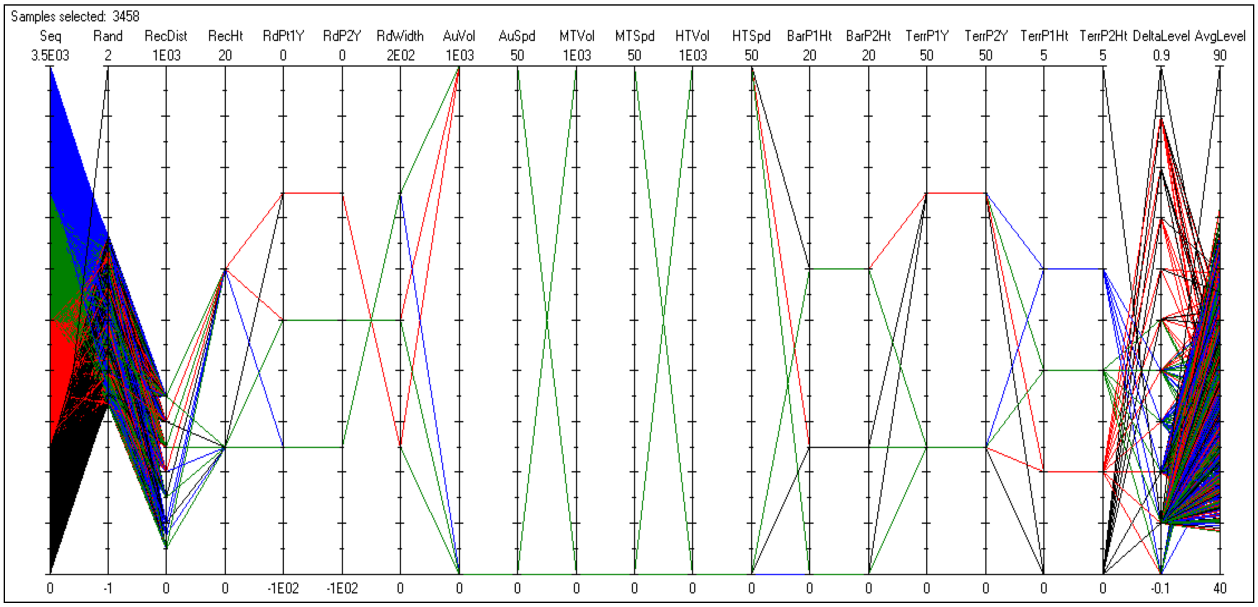


Figure 10 All TNM results: First analysis phase

In this figure:

- **Seq** is a sequence number.
- **Rand** is a random number (used briefly during analysis but not discussed below).
- **RecDist** is the receiver distance (in feet) from the near edge of pavement.
- **RecHt** is the receiver height (in feet).
- **RdPt1Y** is roadway point 1's centerline distance (in feet) from the near edge of pavement; similarly for **RdPt2Y**.
- **RdWidth** is the roadway width (in feet).
- **AuVol** and **AuSpd** are the automobile volume (in vehicles per hour) and speed (in miles per hour), respectively; similarly for the corresponding medium-truck and heavy-truck parameters.
- **BarrP1Ht** is barrier point 1's height (in feet); similarly for BarrP2Ht.
- **TerrPt1Y** is terrain-line point 1's distance from the near edge of pavement (in feet); similarly for **TerrPt2Y**.
- **TerrPt1Ht** is terrain-line point 1's height (in feet); similarly for **TerrPt2Ht**.
- **DeltaLevel** is the change in sound level (in dB) due to the offset roadway width.
- **AvgLevel** is the sound level (in dB), averaged over the two values of the offset parameter.

Figure 11 contains the same information as the prior plot, but with "condensed" parameters for example, six traffic parameters condensed down to one (Automobiles = 1, Medium trucks = 2, Heavy trucks =3). In addition, the all-important DeltaLevel axis is now at the far left.

This second plot contains an additional computed parameter: "apparent" SrcHt (source height). We computed this new parameter from the others, in Excel, using *a priori* knowledge about what parameters might influence sensitivity. In particular for SrcHt, we drew a line from the receiver to the edge of pavement, and then reflected it specularly upward to the left (angle of reflection equal to angle of incidence). Then SrcHt is the height at which this reflected line crosses the roadway centerline.

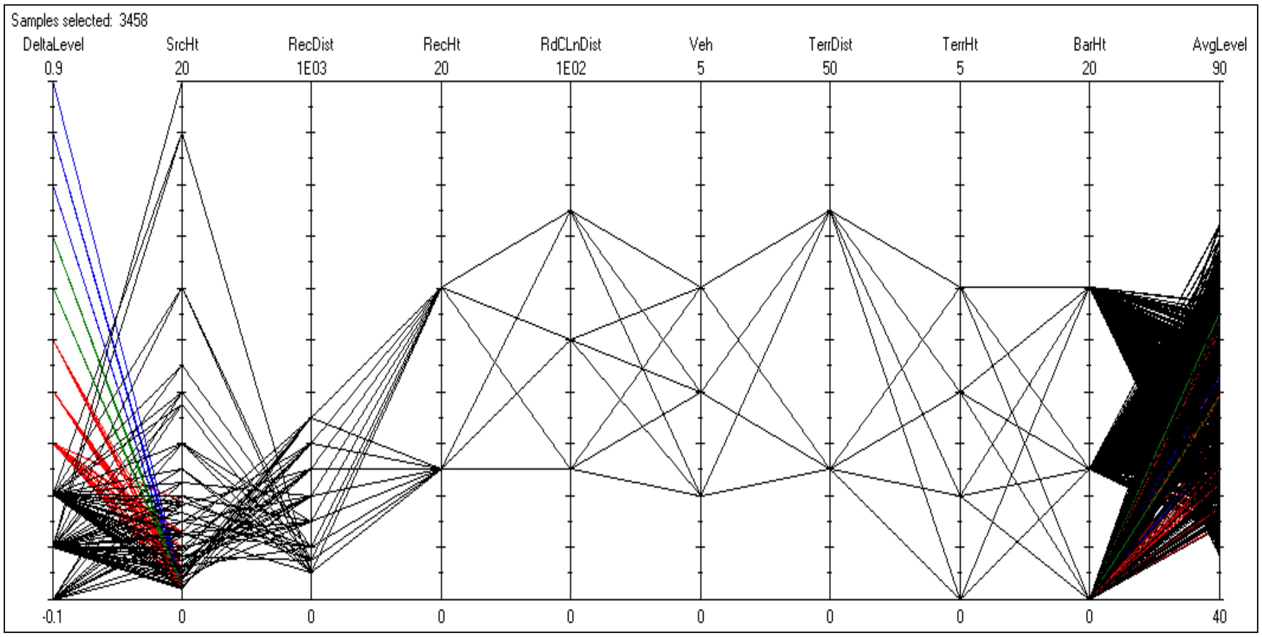


Figure 11 Same, but simplified axes

- Next we used a very convenient ability of cobweb plots. By sweeping the cursor along the upper portion of the DeltaLevel axis, we selected the lines with DeltaLevel values 0.45 dB (0.5 dB after rounding) and higher—resulting in Figure 12.

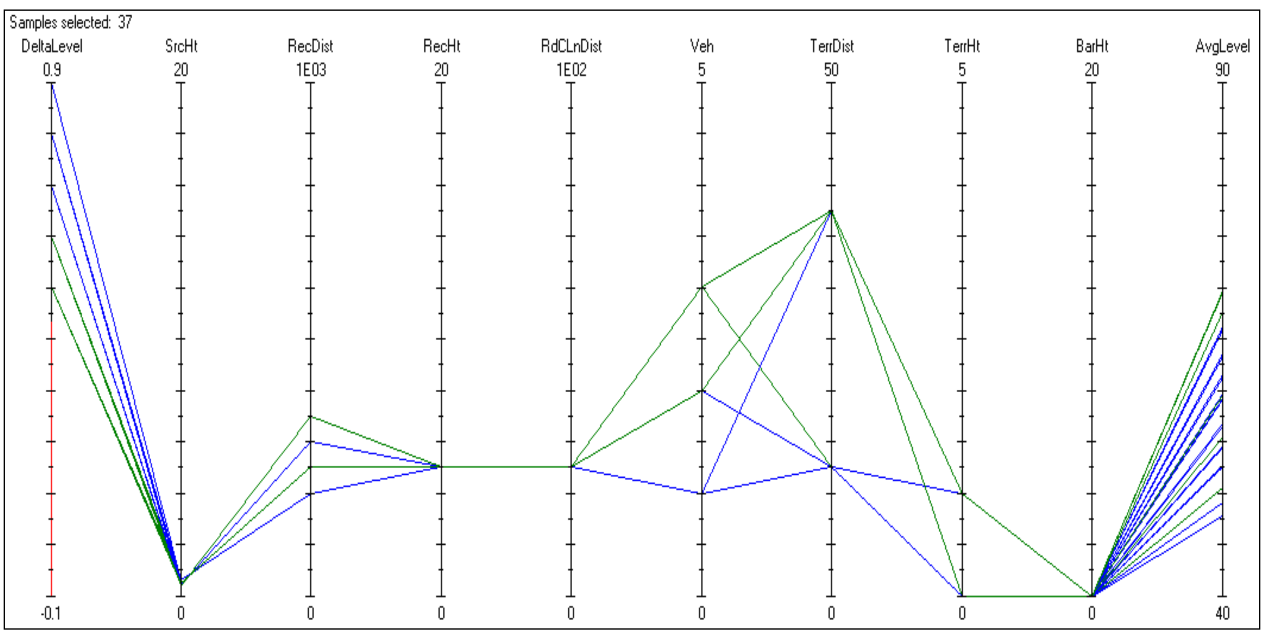


Figure 12 Subset of phase-1 TNM results: DeltaLevel rounds to 0.5 dB or higher

From these, we learned that these highest values of DeltaLevel are restricted to:

- Very low "apparent" source heights (less than 1 foot)
- Larger receiver distances (greater or equal to 200 feet)
- Only 5-foot receivers
- Lowest centerline distances (25 feet)
- Lowest terrain perturbations (less than or equal to 1 foot)
- The no-barrier condition.

We were somewhat surprised that these "worst" apparent source heights were so low, even for heavy trucks. This seems to indicate that the incoming grazing angle to the road-edge diffraction is not particularly important or more likely that tire noise always dominates DeltaLevel. This means that this pavement-edge effect is likely independent of vehicle type.

Hence our conclusions for this analysis phase:

- Vehicle type is probably not important.
- Distance of rolling terrain is not important, as long as it is low (less than 1.3 feet, or so).
- Barrier cannot be present.
- No excessive shoulder width, since the remaining lines in the figure are restricted to the 25-foot centerline distance.

G.2.2 Additional receivers and ground slopes

The next analysis phase involved additional receivers out to 1000 feet from the roadway edge. Figure 13 contains those additional input combinations for flat-ground receivers.

Furthermore, we decided to examine results if the ground dropped away slightly, or rose slightly, with increasing distance to the edge of pavement. Figure 14 contains those additional input combinations, which was used with two different baseline TNM cases: (1) receivers on ground that sloped uniformly upwards by 1 degree, and (2) the same, but sloped uniformly downwards by 1 degree. Notice that several input complexities were omitted from these additional TNM runs.

	Receivers: Check that Cols B,C on Comps sheet reproduce TNM's receiver order.		Multi-valued parameters															
Combination Index (equal values force simultaneous changes):	1	2	3	3	3	4	4	4	4	4	4	5	5	6	6	7	7
Parameter (abbrev. OK):			RoadPt1	RoadPt2	RoadWidth	TraffAVol	TraffASp	TraffMTVol	TraffMTSp	TraffHTVol	TraffHTSp	BarrHtPt1	BarrHtPt2	TLPt1	TLPt2	TLHt1	TLHt2
InputSheet (exact):			TlnRoad	TlnRoad	TlnRoad	TlnTraf	TlnTraf	TlnTraf	TlnTraf	TlnTraf	TlnTraf	TlnBarr	TlnBarr	TlnTerr	TlnTerr	TlnTerr	TlnTerr
Input Cell (exact):			K12	K13	F12	I12	J12	K12	L12	M12	N12	T12	T13	I12	I13	J12	J13
Plus/minus Offset Increment:					2												
	Distance (or height)	Height (or distance)															
Values	400	5	-25	-25	50	1000	50	0	0	0	0	0	0	12.5	12.5	0	0
	500	15	-50	-50	100	0	0	1000	50	0	0					1	1
	600		-75	-75	150	0	0	0	0	1000	50						
	700																
	800																
	900																
	1000																
	252	= number of input combinations from above (max = 5,000)															
	18	= number of computation loops (ignores number of receivers)															

Figure 13 Additional input combinations: Receivers on flat, horizontal ground

	Receivers: Check that Cols B,C on Comps sheet reproduce TNM's receiver order.		**Multi-valued parameters ---**								
Combination Index (equal values force simultaneous changes):	1	2	3	3	3	4	4	4	4	4	4
Parameter (abbrev. OK):			RoadPt1	RoadPt2	RoadWidth	TraffAVol	TraffASp	TraffMTVol	TraffMTSp	TraffHTVol	TraffHTSp
InputSheet (exact):			TInRoad	TInRoad	TInRoad	TInTraf	TInTraf	TInTraf	TInTraf	TInTraf	TInTraf
Input Cell (exact):			K12	K13	F12	I12	J12	K12	L12	M12	N12
Plus/minus Offset Increment:					2						
	Distance (or height)	**Height (or distance)**									
Values	50	5	-25	-25	50	1000	50	0	0	0	0
	75	15	-50	-50	100	0	0	1000	50	0	0
	100		-75	-75	150	0	0	0	0	1000	50
	150										
	200										
	250										
	300										
	350										
	400										
	500										
	600										
	700										
	800										
	900										
	1000										
	270	**= number of input combinations from above (max = 5,000)**									
	9	**= number of computation loops (ignores number of receivers)**									

Figure 14 Additional input combinations: Receivers on sloped ground (up and down)

Figure 15 contains the results for these additional receivers, combined with the results for the initial receivers.

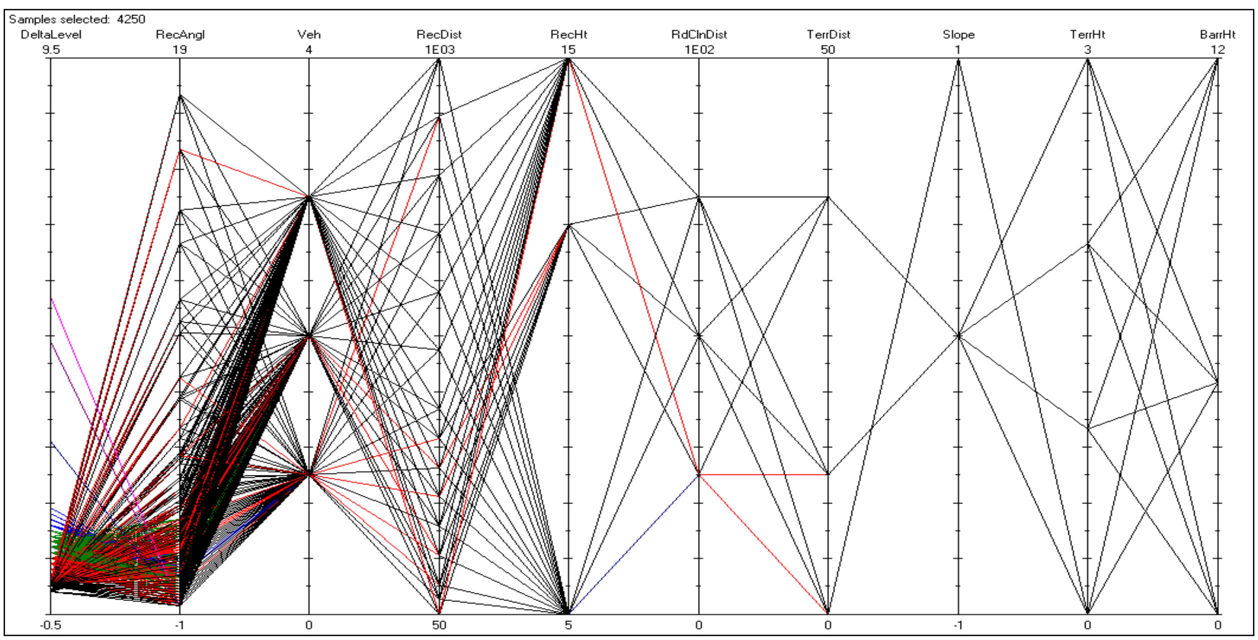


Figure 15 All TNM results for both analysis phases, combined

In this plot, the variable names have been simplified to the following:

- **DeltaLevel** is the change in sound level (in dB) due to the offset roadway width.
- **Veh** is the vehicle type (Automobiles = 1, Medium trucks = 2, Heavy trucks = 3).
- **RecDist** is the receiver distance (in feet) to the roadway centerline.
- **RecHt** is the receiver height (in feet)
- **TerrDist** is the terrain-line's distance (in feet) from the near edge of pavement.
- **Slope** is the terrain slope away from the roadway (in degrees), either +1 (up) or –1 (down).
- **TerrHt** is the terrain-line's height (in feet).
- **BarrHt** is the barrier's height (in feet).

In addition, we defined a new variable:

- **RecAngl** (receiver angle) is the vertical angle (in degrees) subtended by the receiver (measured at the edge of roadway):

$$RecAngl = \left(\frac{180}{\pi}\right)\tan^{-1}\left(\frac{RecHt}{RecDist}\right) + Slope. \qquad (1)$$

Next we filtered on DeltaLevel, to examine the input parameters that result in various amounts of DeltaLevel (taking rounding into account). Filtering resulted in the following figures.

- Figure 16: DeltaLevel rounds above 1.5 dB
- Figure 17: DeltaLevel rounds to 1.5 dB
- Figure 18: DeltaLevel rounds to 1.0 dB
- Figure 19: DeltaLevel rounds to 0.5 dB.

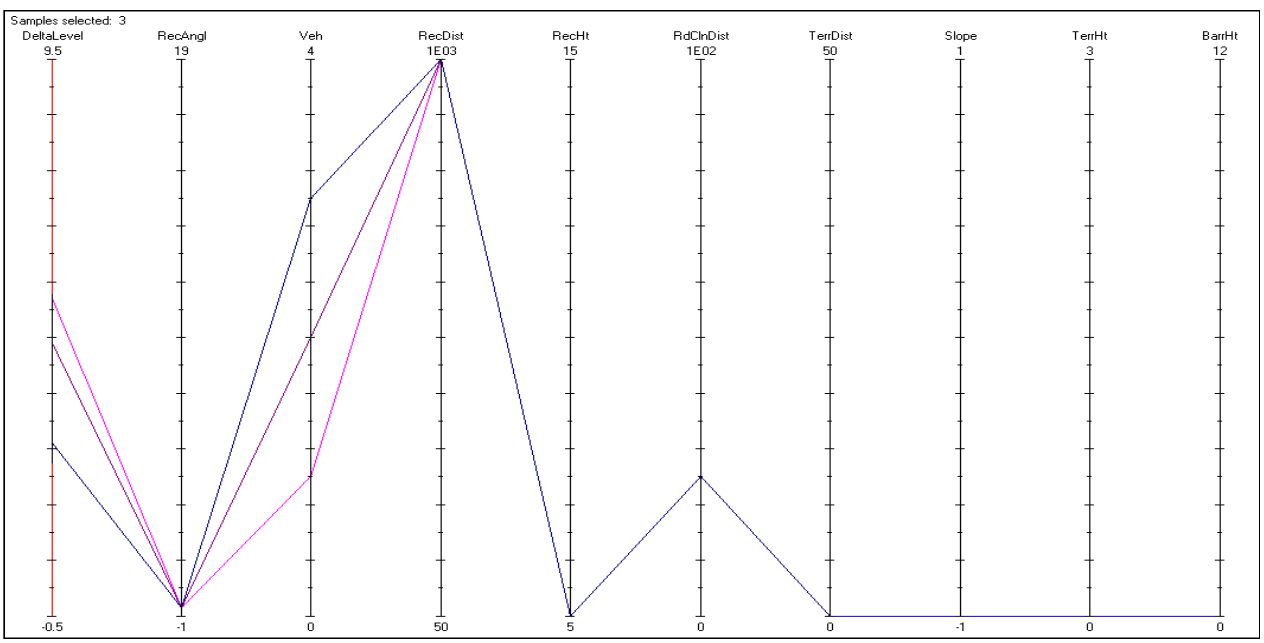


Figure 16 All TNM results: DeltaLevel rounds above 1.5 dB

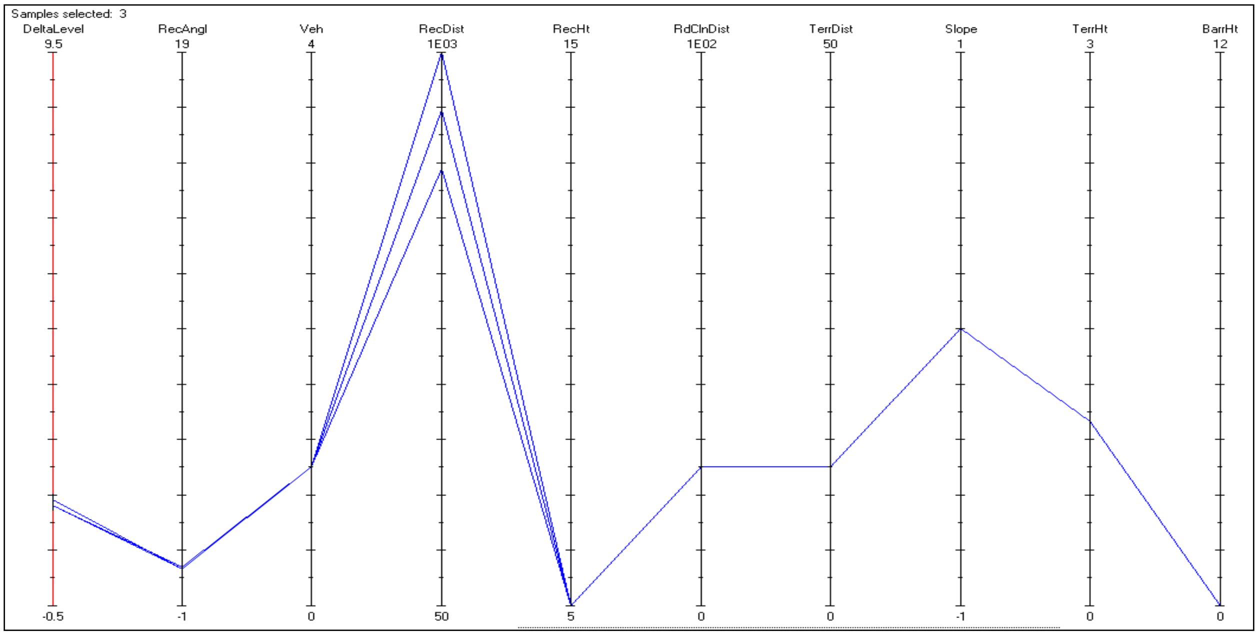


Figure 17 All TNM results: DeltaLevel rounds to 1.5 dB

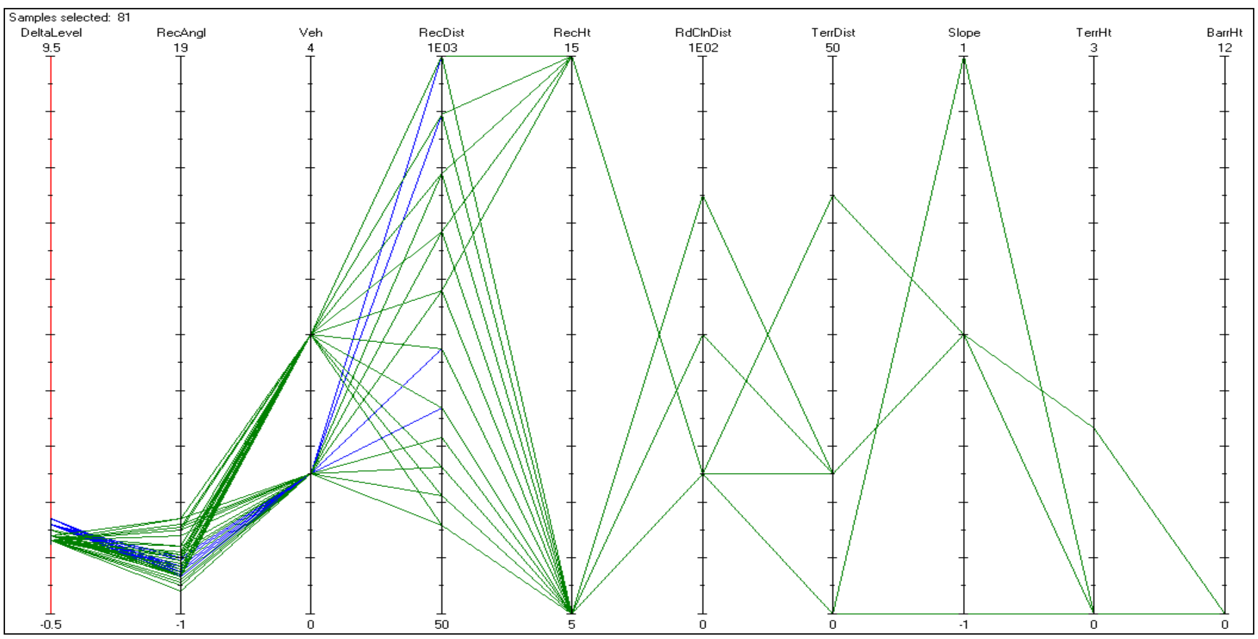


Figure 18 All TNM results: DeltaLevel rounds to 1.0 dB

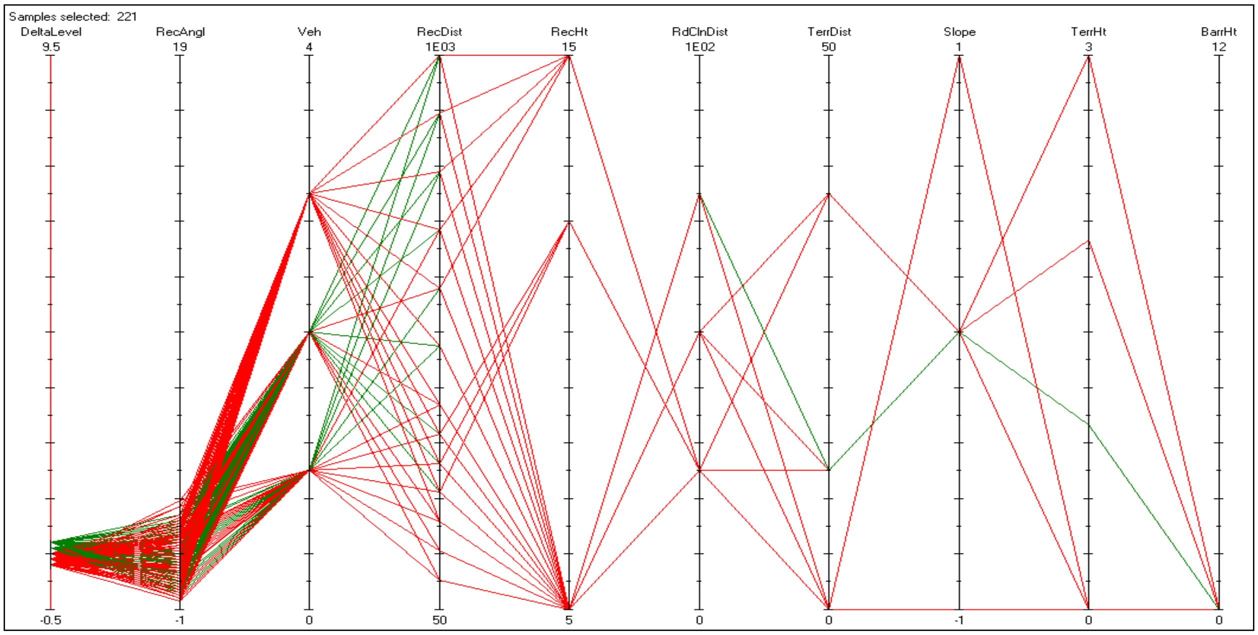


Figure 19. All TNM results: DeltaLevel rounds to 0.5 dB

In addition, we plotted results separately for the three slopes:

- Figure 20: 0 degree slope
- Figure 21: +1 degree slope
- Figure 22: –1 degree slope

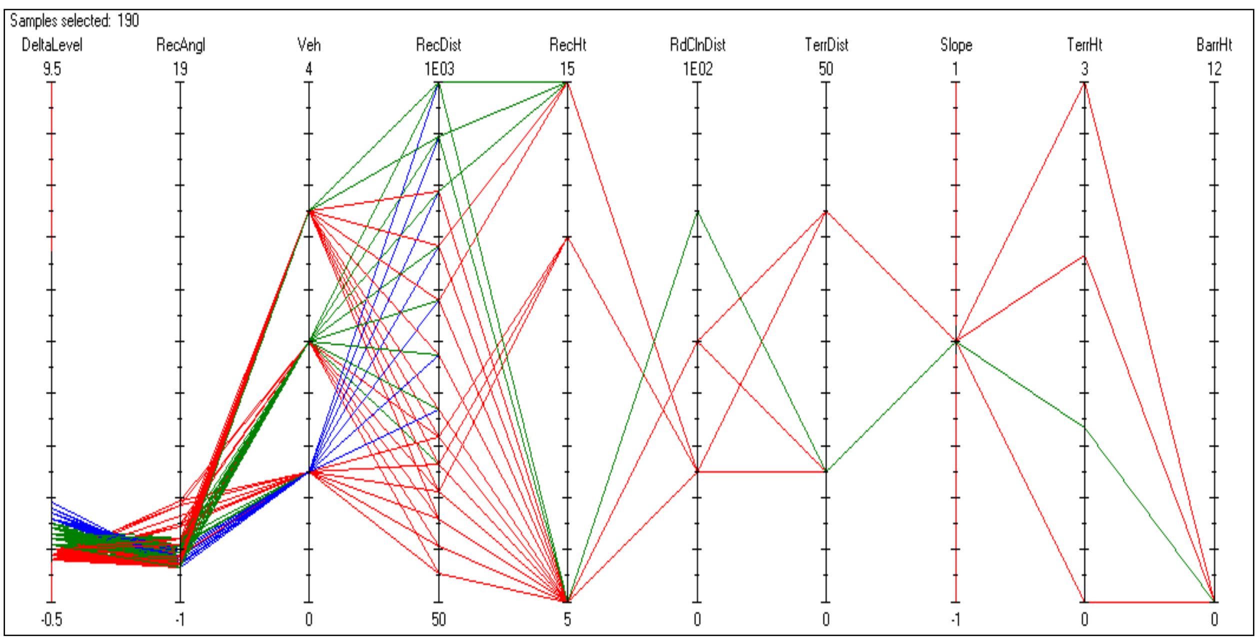


Figure 20 All TNM results: 0 degree slope

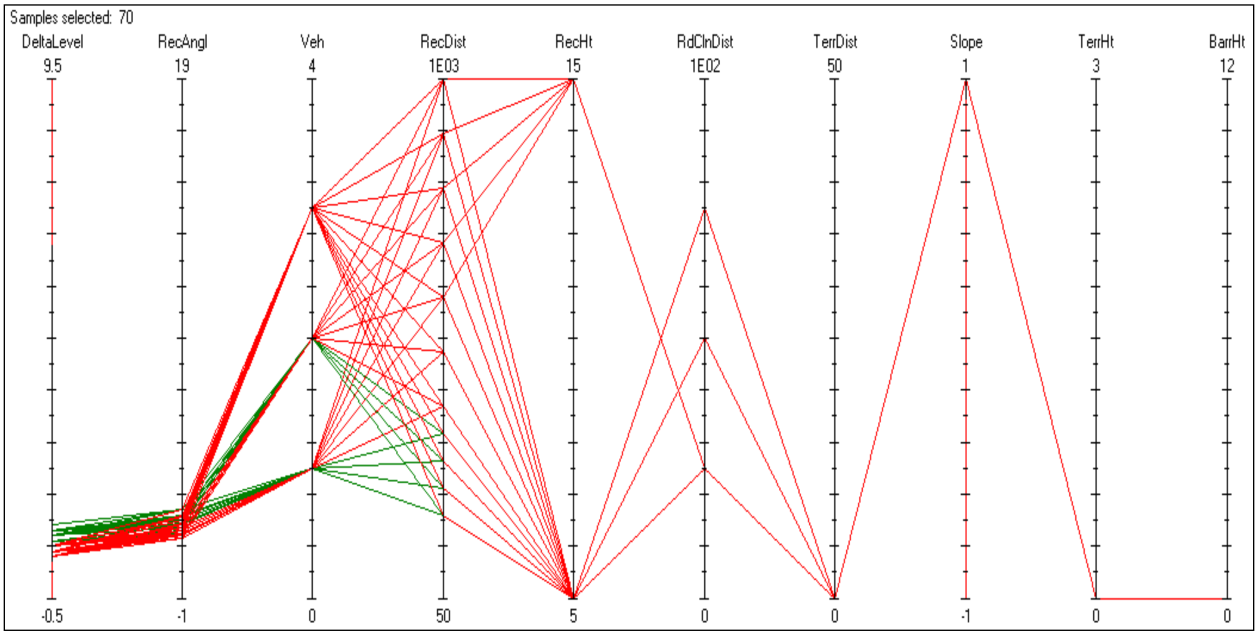


Figure 21 All TNM results: +1 degree slope

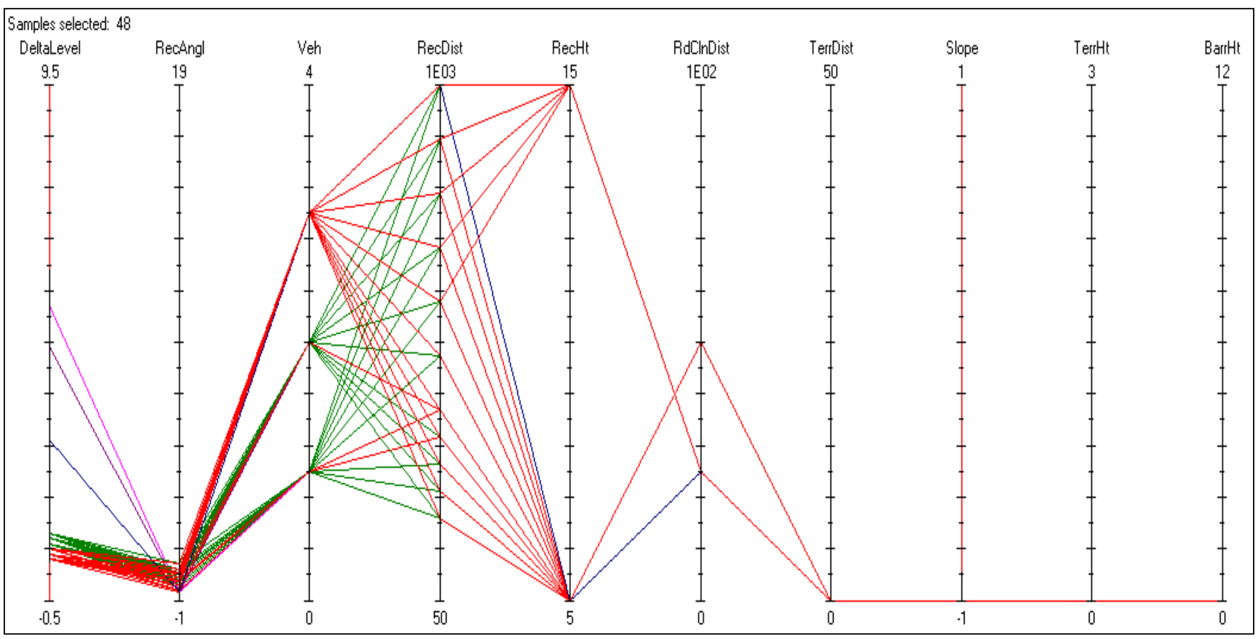


Figure 22 All TNM results: –1 degree slope

From these cobweb plots, we concluded that RecAngl is by far the most influential parameter in determining DeltaLevel.

To determine the functional dependence of DeltaLevel upon RecAngl, we examined a series of two-dimensional scatterplots searching for a plot to illuminate the essence of our sensitivity results. Figure 23 shows the most revealing plot we found, while Figure 24 zooms into the lower part of the same data points.

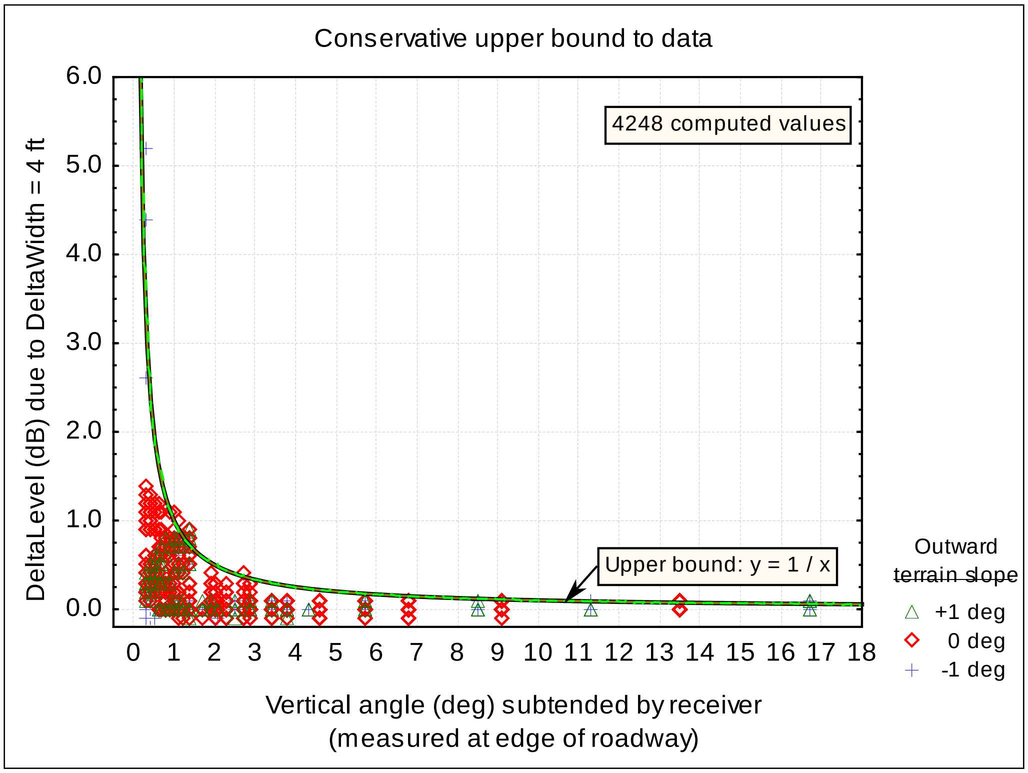


Figure 23 Conservative upper bound to TNM results: All points

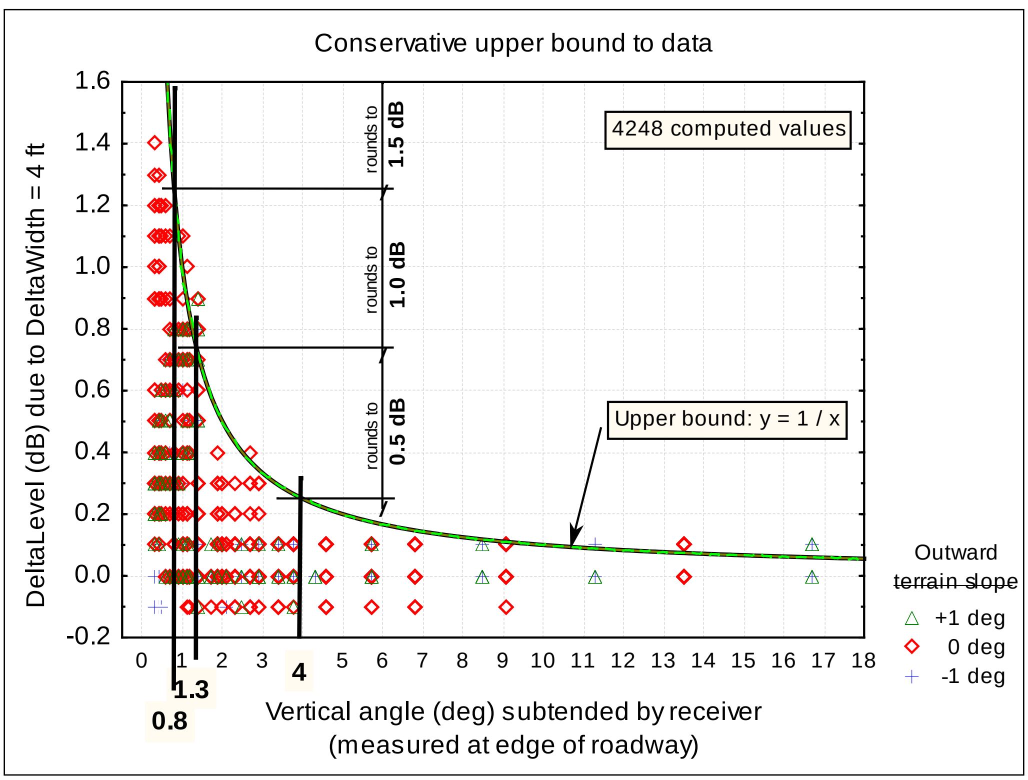


Figure 24 Conservative upper bound to TNM results: Zoomed in and annotated

Each of these two figures contains a hyperbola, with the equation $y = 1/x$. In terms of our variables, that equation assumes this functional form:

$$\left(\frac{\Delta L_{eq}}{\Delta Width}\right)_{maximum} = \left(\frac{DeltaLevel}{\text{dBA}/\text{4-ft near-edge shift}}\right)_{maximum} = \frac{1\text{ deg}}{RecAngl}. \qquad (2)$$

This equation provides a conservative upper bound to the maximum DeltaLevel expected, for a 4-foot shift in the near-edge position. This is the major quantitative result of our analysis.

G.2.3 Generalizations

For the guidance just below, we have augmented our actual analysis beyond the exact cases computed to other "equivalent" situations (based upon our understanding of roadway-noise acoustics). In particular, our augmentation takes the following into account:

- Our belief that an "equivalent" terrain line, that is, one located somewhat outside the roadway pavement and at pavement height would experience the same location sensitivity as the near edge of pavement actually computed. We base this equivalence upon our belief that the highly sensitive TNM behavior, uncovered above, is due to very small grazing angles when sound diffracts from the near edge of pavement towards the receiver.
- Our belief that this same sensitivity would accrue when an "equivalent" barrier substitutes for the computed receivers. In this situation, the sensitivity "trigger" is the barrier top. The resulting sensitivity would likely accrue to most receivers in the barrier's shadow zone.

G.2.4 Resulting Guidance for TNM input

We recommend the following best practice for entering the near edge of pavement (or "equivalent" terrain line) into TNM:

- First, be on the lookout for intervening ground that is either flat and level (no intervening hills or ridges) out to the nearest receivers (or "equivalent" barrier) or that slopes gently up or down (±1-to-2 degrees or so) towards them.
- Where such situations exist, determine the vertical angle in degrees, at the near edge of roadway (or "equivalent" terrain line), subtended by the receiver (or "equivalent" barrier) height.
- Take the reciprocal of that angle. That value is an upper bound on the L_{eq} change produced by a 4-foot horizontal shift in the position of the edge of pavement (or "equivalent" terrain line).
- If that sound-level uncertainty is too large for your modeling purposes, then spend extra input effort to model that edge with more horizontal precision.
  - For edge of pavement: Recommended is a "shoulder" roadway, overlapping the nearest travel lane, that weaves left and right to precisely position the edge of shoulder.
  - For "equivalent" terrain line: Recommended is a closer look at roadway plans, to more precisely locate the terrain line.

This guidance applies to (1) traffic of all mixes, (2) roadways of all widths, (3) receiver distances out to 1000 feet, (3) receivers or "equivalent" barriers up to 15 feet above the terrain.

<u>Pavement ground zones</u>

- Do not model the near edge of pavement with a pavement ground zone. Instead, model it with a "shoulder" roadway that is, a roadway without traffic that weaves right/left to best match the near edge of pavement.

G.3 Required terrain lines along elevated roadways

When roadways are elevated, best accuracy requires a terrain line along the roadway - either (1) along the toe of slope for roadways on fill, or (2) at ground level just off the edge of structure, for roadways on structure. That terrain line serves to pull the ground downward to its proper elevation, thereby properly modeling the height of lines-of-sight above the ground.

G.3.1 The problem when the toe-of-slope terrain line is left out

Figure 25 shows the cross-sectional geometry with and without a toe-of-slope terrain line.

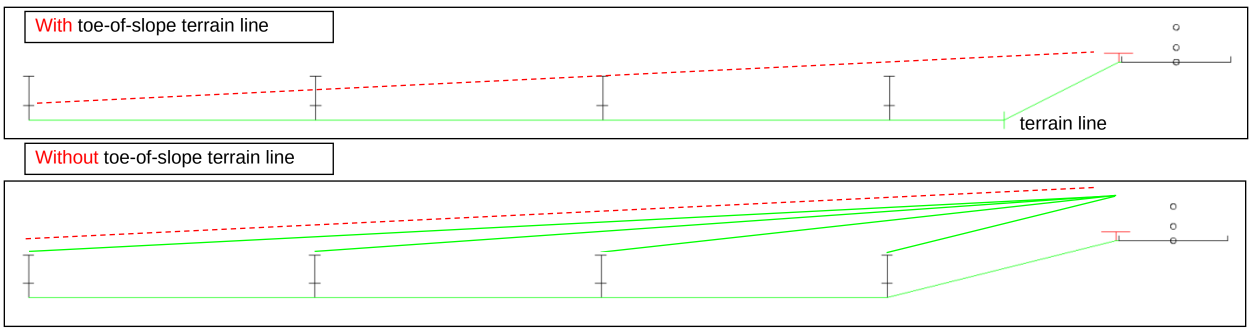


Figure 25 TNM cross-section with and without toe-of-slope terrain line

With toe-of-slope terrain line. The top panel of the figure is the skew section drawn by TNM. Its green ground line connects the bases of successive TNM input, from right to left: (1) the Jersey barrier base, (2) the terrain line, and (3) each receiver base in turn. This top panel also contains a red dashed line-of-sight, across the barrier top to the most distant 5-foot receiver.

Without toe-of-slope terrain line. The bottom panel of the figure, in contrast, is a *modified* TNM skew section. As modification, the ground line drawn by TNM has been replaced with the varying ground lines that TNM *actually uses to compute*. Note that these "computation" ground lines are different for each receiver stack. For example, when computing for the most distant 5-foot receiver, TNM completely ignores all other receivers. Therefore for computation, TNM uses a ground line that connects that receiver's base directly to the barrier's base, as shown. This ground line is obviously unrealistic. In fact, the actual ground passes through the bases of the other receiver stacks, as shown in the upper panel. But TNM does not take this actual geometry into account.[3]

For the most distant 5-foot receiver, notice how closely proximate the computed ground line is to the receiver's line-of-sight to the barrier top. That proximity is completely artificial. The actual propagation situation appears in the figure's top panel, not the bottom panel. In turn, this artificial proximity results in artificially high ground attenuation for distant receivers.

Note that the modeled conditions are even more artificial without the Jersey barrier, since then the line-of-sight attaches to the roadway edge, which is even lower towards the ground.

[3] Proper terrain lines through the bases of all receivers would mostly correct the situation for the more distant receivers (but not for the closest receiver stack). However, the single terrain line at the toe-of-slope is simpler to input.

G.3.2 Sensitivity tests

In summary, omission of a toe-of-slope terrain line can bias TNM sound levels downwards, especially for distant receivers. We investigated that bias with the *Automated TNM Sensitivity Tool* (Section 1 of this appendix), for many combinations of input parameters.

For simplicity, we confined our computations to roadways approximately 20 feet above the terrain - both on fill and on structure. For roadways on structure, the toe-of-slope terrain line is replaced by a terrain line very near the structure's edge - call it a "near-edge" terrain line located down at ground level.

In comparison with other uses of the sensitivity tool, here we are not seeking the sound-level sensitivity to small changes in input. Instead, we are seeking the sound-level change with and without the toe-of-slope (or near-edge) terrain line. This we do by specifying a specifically chosen plus/minus offset increment. We choose this offset so that the horizontal terrain-line position with the *minus* offset is exactly where we wish it to be, whereas with the *plus* offset it is placed where it will not influence sound levels.

G.3.2.1 The geometry

Figure 26 contains the TNM cross-sectional geometry for the sensitivity computations (roadway on fill).

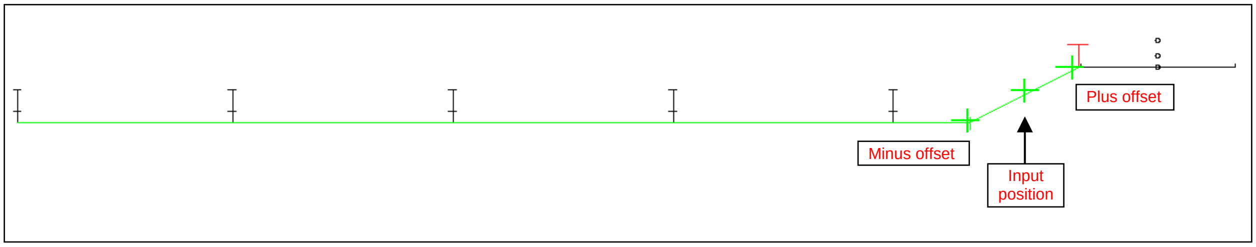


Figure 26 Cross section for sensitivity tests (roadway on fill)

In the figure, to the right is a TNM roadway on fill, along with its adjacent Jersey barrier. To their left are several terrain-line symbols (green plus signs), then five stacks of 5-foot and 15-foot receivers. Further stacks are off the figure to the left.

In actual fact, the TNM case has only one terrain line, input half-way up the fill slope. Then for the sensitivity computations, the "minus offset" moves that terrain line to the left and downward, to the "minus offset" position in the figure. Therefore, the minus-offset computation is "with" the toe-of-slope terrain line.

In contrast, the "plus offset" moves the input terrain line to the right and upward, to the "plus offset" position in the figure. In this position, it essentially duplicates the baseline of the barrier and therefore has no influence on the computed sound level. Therefore, the plus-offset computation is "without" the toe-of-slope terrain line.

For the on-structure roadway, the situation is somewhat simpler. The terrain line has only to be offset vertically from the plus offset position in the figure ("without") to the ground directly below that point ("with").

In all, we ran these sensitivity tests for the following receivers:

- 5 receiver distances from the barrier: 100, 200, 300, 400 and 500 feet
- 2 receiver heights at each distance: 5 and 15 feet—for a total of 10 receivers.

For the sensitivity computations, we included:

- 1 roadway height: 20 feet above the terrain
- 3 traffic conditions: All automobiles, then all medium trucks, then all heavy trucks.
- 4 barrier heights: 0, 3, 7, and 10 feet
- 3 roadway widths: 30, 50 and 70 feet in synchrony with 3 corresponding roadway centerline positions: 0, 10 and 20 feet from the barrier (all to account for different shoulder widths)
- 2 "minus-offset" terrain-line distances from the barrier, corresponding to the on-fill and on-structure roadway cases.

These input values led to 72 distinct geometries, each run twice "with" and "without" the terrain line in the propagation path. In turn, these 72 geometries combined with the 10 receivers to produce 720 computation combinations.

G.3.2.2 The spreadsheet input combinations

For the roadway on fill and on structure, respectively, Figure 27 and Figure 28 show the TNM input combinations within Excel's Sensitivity Spreadsheet.

As seen in these two figures:

- Columns 1 and 2 contain the receiver distances and heights. TNM input includes all combinations of those: two receivers at each of five distances from the roadway's near edge.
- Columns 3 contain the position of the two terrain-line end points. These end points vary in synchrony, because their column index is the same. Per this input, the geometry shifts between:
  - o "With" toe-of-slope line: Y = –41 – 24 = –65 feet; Z = 12.5 – 12.5 = 0 feet
  - o "Without" condition: Y = –41 + 24 = –17 feet; Z = 12.5 + 12.5 = 25 feet.
- Columns 4 contain the roadway barrier heights for the two end points, also varying in synchrony.
- Columns 5 contain the roadway parameters: end-point positions and corresponding width in synchrony.
- Columns 6 contain the synchronous traffic.

In addition, the default terrain is "lawn."

Receivers: Check that Cols B,C on Comps sheet reproduce TNM's receiver order.		Ground Zone Types and Flow Control Devices: If you are entering these here, see the notes below the yellow cells.														
1	2	3	3	3	3	4	4	5	5	5	6	6	6	6	6	6
		TLnY1	TLnZ1	TLnY2	TLnZ2	BarrHt1	BarrHt2	RdY1	RdY1	RdWidth	AUVol	AUSpd	MTVol	MTSpd	HTVol	HTSpd
		TInTerr	TInTerr	TInTerr	TInTerr	TInBarr	TInBarr	TInRoad	TInRoad	TInRoad	TInTraf	TInTraf	TInTraf	TInTraf	TInTraf	TInTraf
		I12	J12	I13	J13	T12	T13	K12	K13	F12	I12	J12	K12	L12	M12	N12
		24	12.5	24	12.5											
Distance or Height (#s, only)	Height or Distance (#s, only)															
-100	5	-41	12.5	-41	12.5	0	0	0	0	30	100	50	0	0	0	0
-200	15					3	3	10	10	50	0	0	100	50	0	0
-300						7	7	20	20	70	0	0	0	0	100	50
-400						10	10									
-500																
360	= number of input combinations from above (max = 5,000)															
36	= number of computation loops (ignores number of receivers)															

Figure 27 TNM Input combinations within Excel: On fill

Receivers: Check that Cols B,C on Comps sheet reproduce TNM's receiver order.		**Ground Zone Types and Flow Control Devices: If you are entering these here, see the notes below the yellow cells.**														
1	2	3	3	3	3	4	4	5	5	5	6	6	6	6	6	6
		TLnY1	TLnZ1	TLnY2	TLnZ2	BarrHt1	BarrHt2	RdY1	RdY1	RdWidth	AUVol	AUSpd	MTVol	MTSpd	HTVol	HTSpd
		TlnTerr	TlnTerr	TlnTerr	TlnTerr	TlnBarr	TlnBarr	TlnRoad	TlnRoad	TlnRoad	TlnTraf	TlnTraf	TlnTraf	TlnTraf	TlnTraf	TlnTraf
		I12	J12	I13	J13	T12	T13	K12	K13	F12	I12	J12	K12	L12	M12	N12
			12.5		12.5											
Distance or Height (#s, only)	**Height or Distance (#s, only)**															
-100	5	-17	12.5	-17	12.5	0	0	0	0	30	100	50	0	0	0	0
-200	15					3	3	10	10	50	0	0	100	50	0	0
-300						7	7	20	20	70	0	0	0	0	100	50
-400						10	10									
-500																
360	**= number of input combinations from above (max = 5,000)**															
36	**= number of computation loops (ignores number of receivers)**															

Figure 28 TNM Input combinations within Excel: On structure

G.3.3 Graphics investigation of the TNM results

Figure 29 shows the initial cobweb plot,[4, 5] which contains a left-to-right line for each of the 720 sensitivity combinations. Each line's intersection with a vertical axis shows that combination's value for that axis parameter. For example, note that all lines pass through one of only five points on the RecDist (receiver distance) axis. In contrast, the lines spread out among the many computed values of DelLev.

In addition, the figure contains a "minimum" and a "maximum" line, to fix the vertical-scale limits at convenient values and thereby make the line-intersection values easier to read from each axis scale.

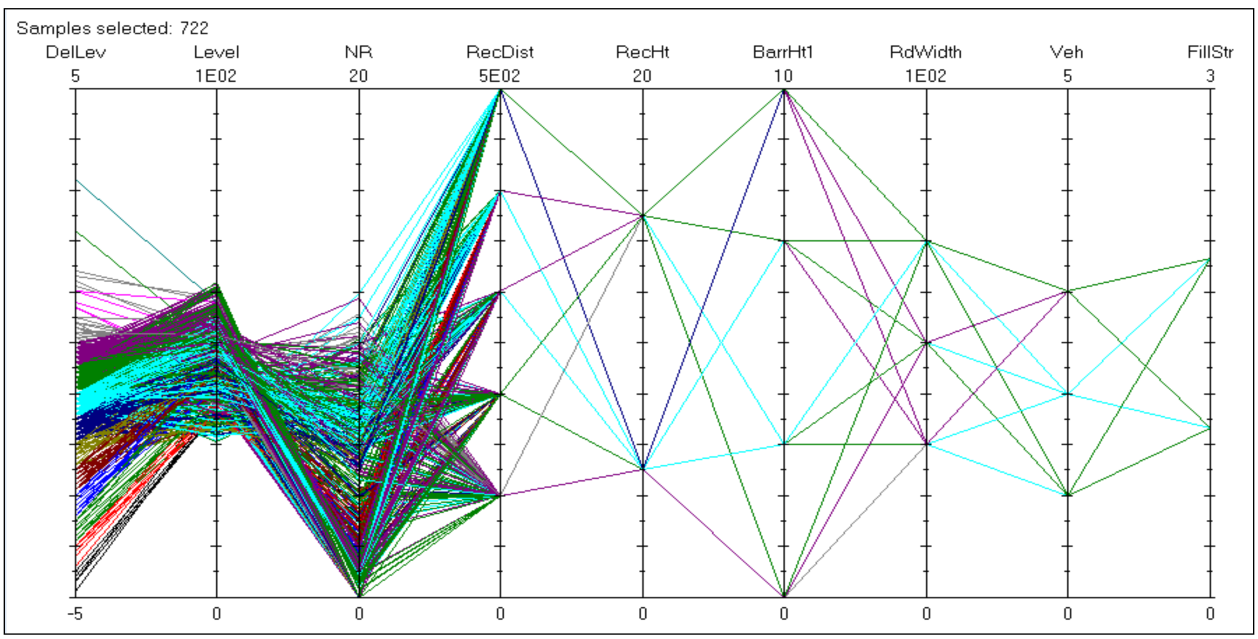


Figure 29 Cobweb plot of all input and output

The vertical axes in this plot show TNM input and results. From left to right, these are:

[4] UNICORN at http://risk2.ewi.tudelft.nl/oursoftware/3-unicorn or its update.
[5] Kurowicka, D. and R. Cooke, *Uncertainty Analysis*, Wiley (2006).

- **DelLev** is the computed DeltaLevel (in dBA) that is, the bias in A-weighted sound level produced by leaving out the terrain line along the roadway (essentially all values are less than zero, indicating an under-computation of L_{eq} without the terrain line).
- **Level** and **NR** are the average sound level (in dB) and average barrier noise reduction (in dB), respectively, with and without the terrain line (of use here only for filtering purposes).
- **RecDist** and **RecHt** are the receiver distance (in feet) and receiver height (in feet), respectively.
- **BarrHt1** is the barrier height (in feet).
- **RdWidth** is the roadway width (in feet).
- **Veh** is the vehicle type: Automobiles = 1, Medium Trucks = 2, Heavy Trucks = 3.
- **FillStr** denotes whether the computation was for the roadway on fill (value = 1) or on structure (value = 2).

Figure 30 through Figure 36 contain various DelLev subsets of these 720 input combinations. Included are only those plots, chosen from many others, that showed interesting behaviors. Our conclusions follow each of these figures.

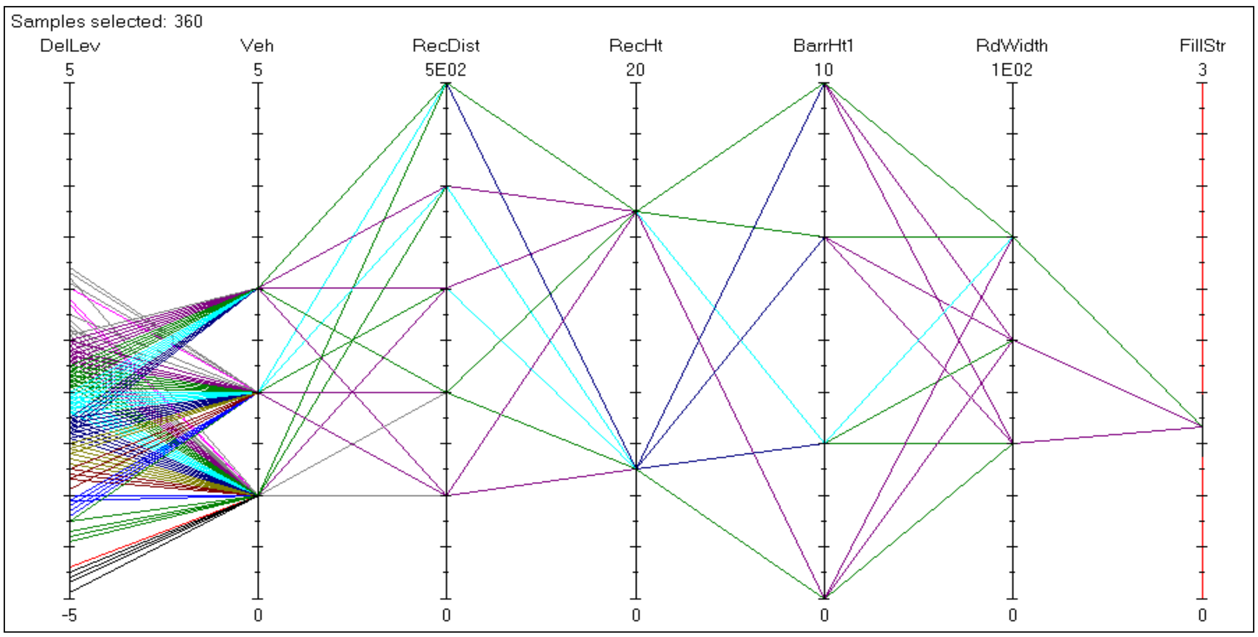


Figure 30 Only roadway on fill (filtered by right-most axis)

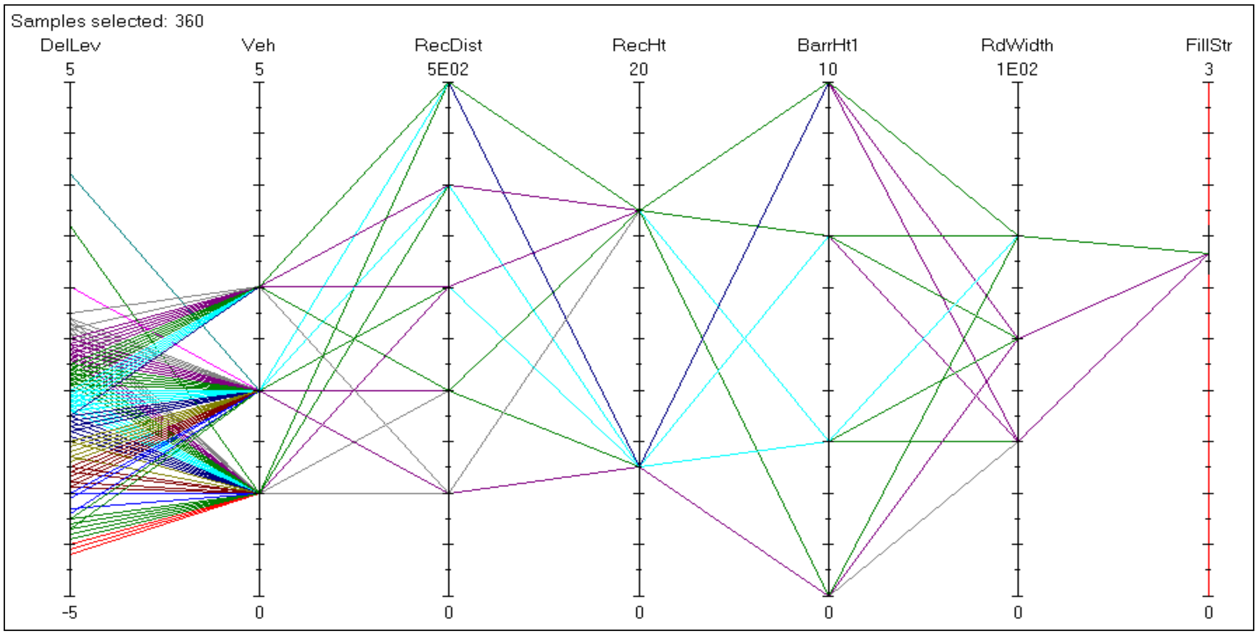


Figure 31 Only roadway on structure (filtered by right-most axis)

Overall, maximum effects are somewhat larger for roadways on fill than for roadways on structure.

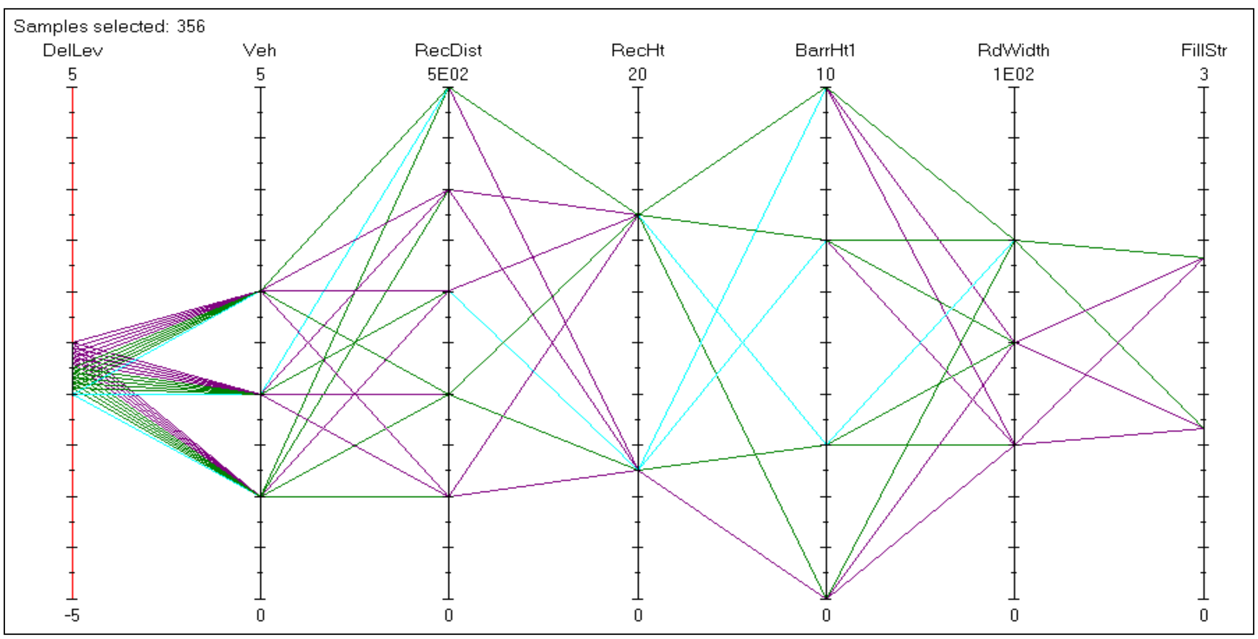


Figure 32 Terrain-line effect between 0 and –1 dB (filtered by left-most axis)

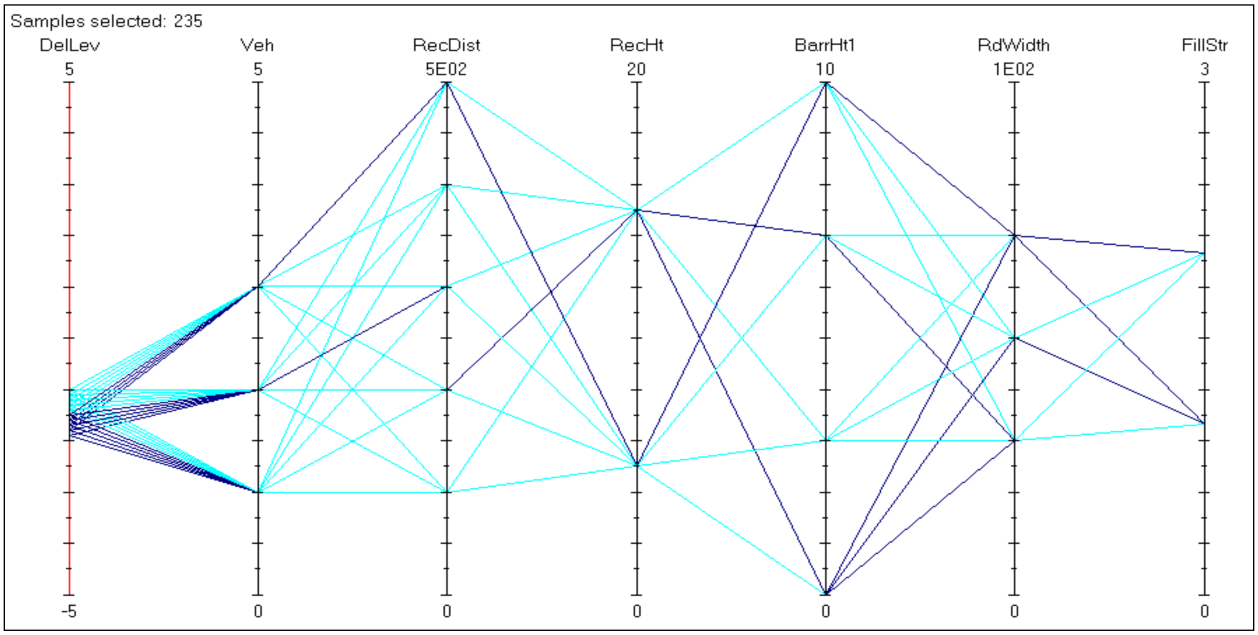


Figure 33 Terrain-line effect between –1 and –2 dB (filtered by left-most axis)

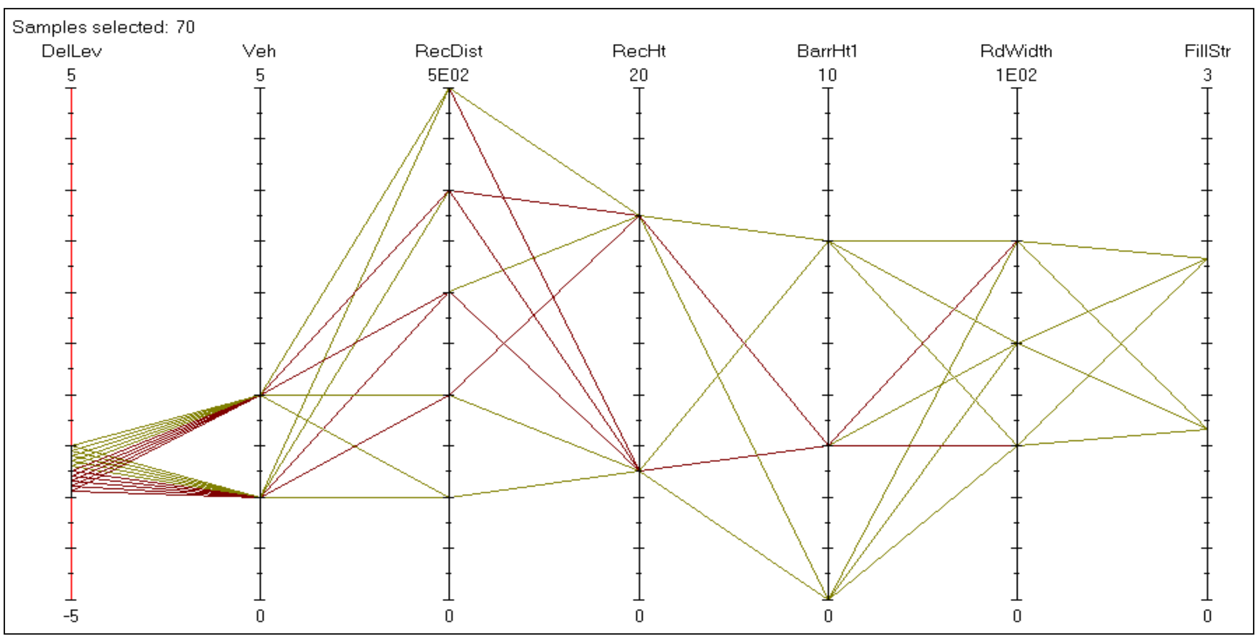


Figure 34 Terrain-line effect between –2 and –3 dB (filtered by left-most axis)

Effects greater than 2 dB are achieved only for autos and medium trucks, in combination with barriers 7 feet or less in height (or no barrier). In other words, effects greater than 2 dB require lines-of-sight lower to the ground than is the case for heavy trucks and tall barriers.

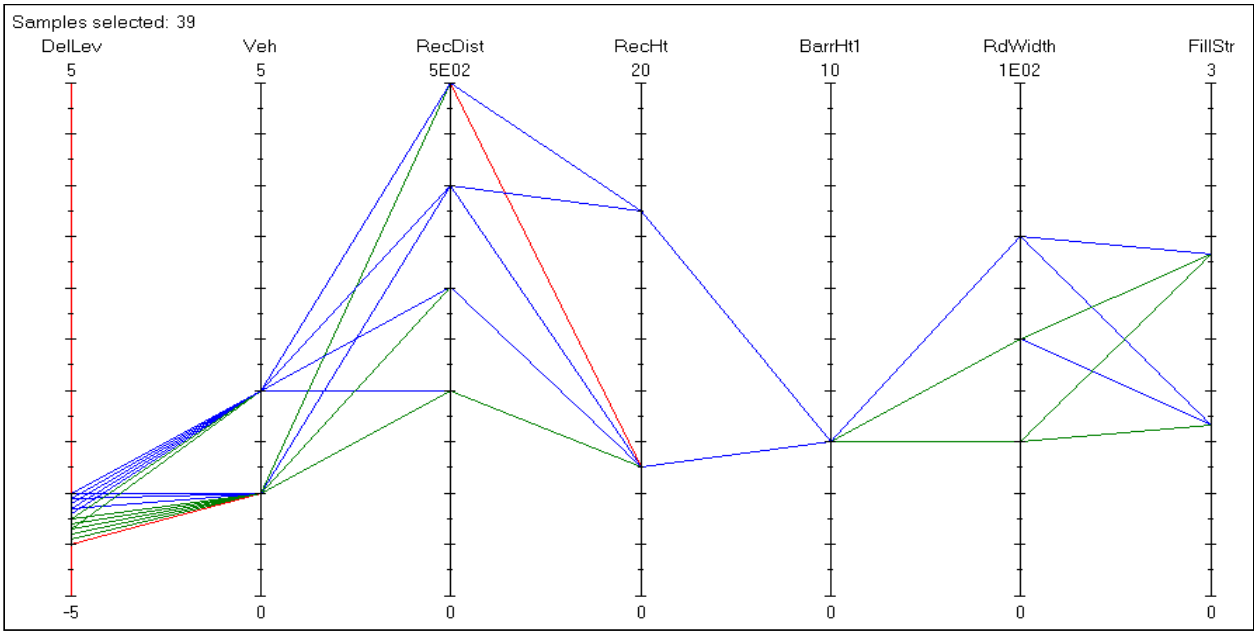


Figure 35 Terrain-line effect between –3 and –4 dB (filtered by left-most axis)

In addition, effects greater than 3 dB are achieved only with 3-foot barriers but not for the closest receivers (100 feet).

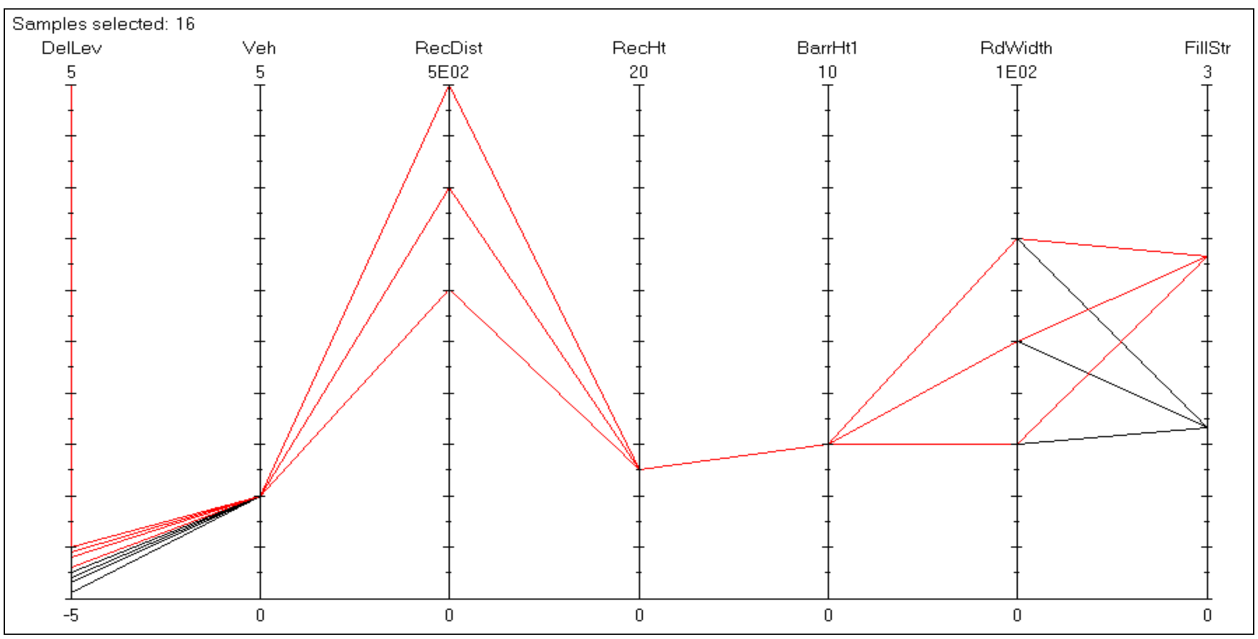


Figure 36 Terrain-line effect between –4 and –5 dB (filtered by left-most axis)

In addition, effects greater than 4 dB are achieved only for automobiles and distant receivers (300, 400 and 500 feet), and only for receivers at 5 feet.

Note that all these conclusions are independent of the roadway width or whether the roadway is on fill or on structure.

G.3.4   Introduction to Guidance

When roadways are elevated, best accuracy requires a terrain line along the roadway either (1) along the toe of slope for roadways on fill, or (2) at ground level just off the edge of structure, for roadways on structure. That terrain line serves to pull the ground downward to its proper elevation, thereby properly modeling the height of lines-of-sight above the ground.

For example, with a roadway on 20-foot fill or on 20-foot structure, omission of such a terrain line can result in underprediction of sound levels by the amounts shown in Table 1.

Table 1 Approximate underpredictions with omitted Terrain Line

Underprediction	Conditions			
	Receiver height	Receiver distance	Predominant vehicle(s)	Height of roadway-edge barrier
2 to 3 dB	5 and 15 feet	100 feet and greater	Autos and medium trucks	7 feet or less, or no barrier
3 to 4 dB	5 and 15 feet	200 feet and greater	Autos and medium trucks	3 feet or less
4 to 5 dB	5 feet	300 feet and greater	Autos	3 feet or less

G.3.5   Guidance for TNM input

When modeling roadways on fill, always include a terrain line along the toe of slope of the roadway fill. Similarly, when modeling roadways on structure, always include a terrain line at ground level just off the edge of structure.

G.4   Minimum terrain-line spacing

The diffraction mathematics within TNM assumes that sound waves are spherically shaped when approaching a diffraction edge. This is normally true, of course. However, when two diffracting edges are spaced very close together, the first of these edges distorts that wave shape so it is no longer spherical when it approaches the second edge.

Does this non-spherical wave front at the second edge produce anomalies in the resulting sound level at the receiver? To investigate this question, we ran a series of TNM cases with two diffracting edges, spaced initially far apart, but then brought closer and closer together in a search for abrupt changes in receiver sound level.

G.4.1   Input

Figure 37 shows the TNM skew section through the resulting terrain, for the widest separation (25 feet) between the two terrain lines at the top of the intervening hill.

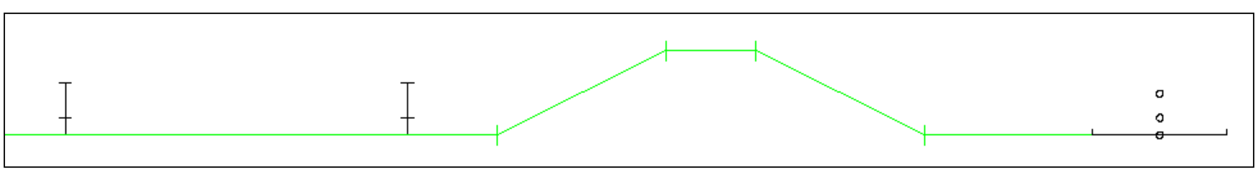


Figure 37 TNM skew section, showing only first two receiver stacks (out of nine)

In all, we want to compute this geometry for 17 top widths (from 25 feet down to 0.1 foot), combined with 3 roadway positions (and corresponding widths), combined with 3 traffic conditions: all autos, all medium trucks and all heavy trucks. To compute these 153 input combinations efficiently, we used the *Automated TNM Sensitivity Tool* (Section 1 of this appendix) with the input in Figure 38.

Receivers: Check that Cols B,C on Comps sheet reproduce TNM's receiver order.		Ground Zone Types and Flow Control Devices: If you are entering these here, see the notes below the yellow cells.										
1	2	3	3	4	4	4	5	5	5	5	5	5
		TLnY1	TLnY2	Road1Y	Road2Y	RoadWidth	AUVol	AUSpd	MTVol	MTSpd	HTVol	HTSpd
		TInTerr	TInTerr	TInRoad	TInRoad	TInRoad	TInTraf	TInTraf	TInTraf	TInTraf	TInTraf	TInTraf
		I16	I17				I12	J12	K12	L12	M12	N12
Distance or Height (#s, only)	Height or Distance (#s, only)											
-200.00	5	-125	-125	20	20	40	100	50	0	0	0	0
-300.00	15	-112	-112	25	25	50	0	0	100	50	0	0
-400.00		-106	-106	30	30	60	0	0	0	0	100	50
-500.00		-105	-105									
-600.00		-104	-104									
-700.00		-103	-103									
-800.00		-102	-102									
-900.00		-101	-101									
-1000.00		-100.9	-100.9									
		-100.8	-100.8									
		-100.7	-100.7									
		-100.6	-100.6									
		-100.5	-100.5									
		-100.4	-100.4									
		-100.3	-100.3									
		-100.2	-100.2									
		-100.1	-100.1									
2,754	= number of input combinations from above (max = 5,000)											
153	= number of computation loops (ignores number of receivers)											

Figure 38 Sensitivity spreadsheet input

G.4.2 Results

Figure 39 shows the entire set of results from the 2,754 TNM computations. Plotted vertically in the figure is each receiver's L_{eq} (in dB). Plotted horizontally is the horizontal separation between the two top-width terrain lines of Figure 37.

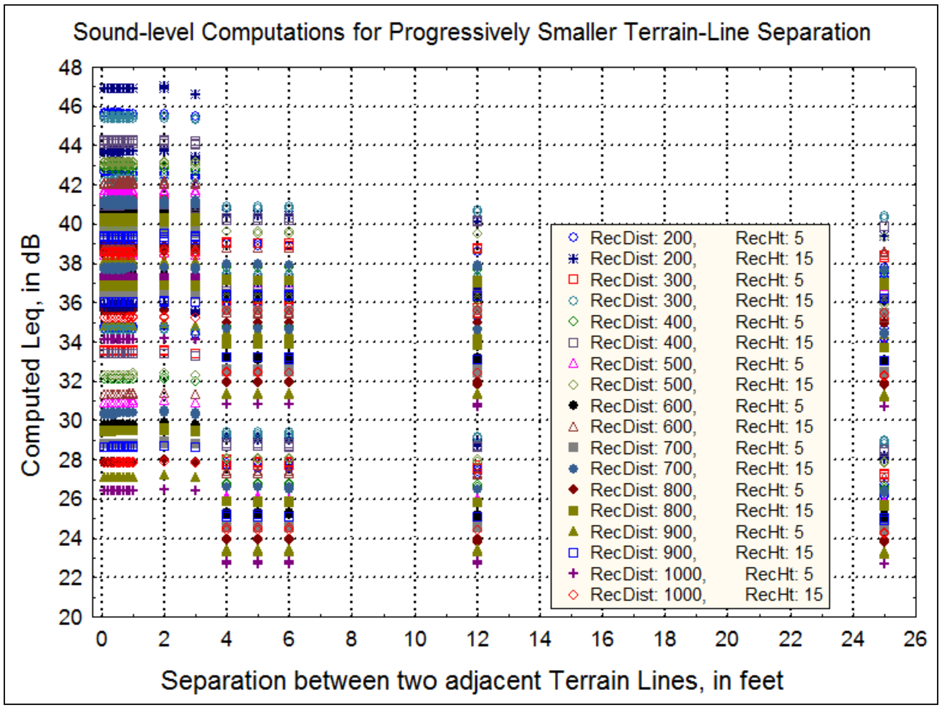


Figure 39 Sound-level computations for progressively smaller Terrain-Line separation

As is apparent from this figure, as the terrain-line separation decreases (from right to left in the figure), the computed L_{eq} increases abruptly at a separation of 3-to-4 feet by approximately 6 dB. Because nothing else changes except terrain-line separation, we consider this abrupt sound-level increase to be "anomalous."

So the answer is "yes": The non-spherical wave front at the second diffracting edge produces anomalies in the resulting sound level at the receiver. Moreover, these anomalies occur for separations of 4 feet and less.

Note that our computations used terrain lines on top of an intervening hill or berm. We computed this particular geometry rather than flat or gully geometry because we expected the hill geometry to show the most effect. From our knowledge of the TNM code and of acoustic propagation, we expect that:

- Intervening flat terrain might produce a discontinuity smaller than 6 dB.
- Intervening gullies might be immune to this difficulty.

G.4.3 Introduction to Guidance

The diffraction mathematics within TNM assumes that sound waves are spherically shaped when approaching a diffraction edge. This is normally true, of course. However, when two diffracting edges are spaced very close together, the first of these edges distorts the wave shape so it is no longer spherical when it approaches the second edge.

As a result, terrain-line spacing less than 4 feet produces an abrupt, anomalous increase in sound level of:

- Approximately 6 dB, when the terrain lines are near the top of an intervening hill or berm
- Perhaps as large as 6 dB, when the terrain lines are on intervening flat ground
- Somewhere between 0 and 6 dB, when the terrain lines lie in an intervening gully.

Digital terrain models

When digital terrain models approximate undulating terrain, they often divide that terrain into a large collection of triangles. If the edges of those triangles are used as terrain lines within TNM, then the terrain-line spacing would reduce to zero feet near the vertex of all those triangles. Although not tested here, we believe such a set of terrain lines would produce these 6-dB anomalies throughout.

G.4.4 Resulting Guidance for TNM input

Never input terrain lines closer than 4 feet apart, especially on an intervening hill or intervening flat ground.

In addition, never input terrain lines to duplicate the triangular topography regions that are produced by digital terrain models.

G.5 Terrain lines: Vertical precision

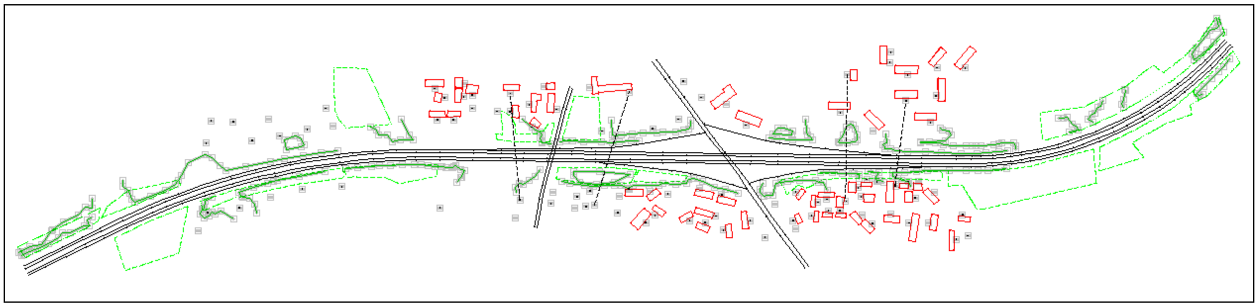
As part of this NCHRP project, we solicited and received a number of noise studies and/or TNM runs for actual highway projects around the country. Input for two of these included an interesting assortment of terrain lines.

Of concern to this NCHRP project is TNM's sensitivity to the input Z-coordinates of these modeled terrain lines. To that end, we re-ran those two TNM cases with all the terrain lines moved upwards by 2 feet. This appendix describes the results of those increased terrain-line elevations, along with our conclusions about their need for vertical precision.

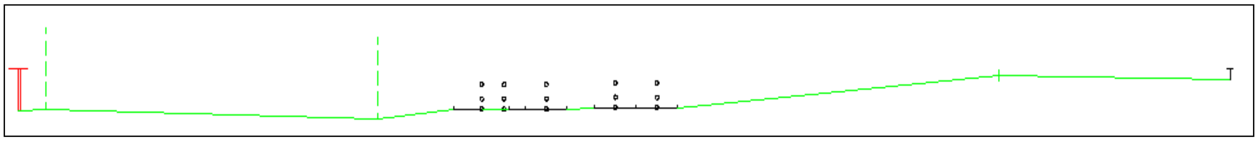
G.5.1 The TNM cases

Figure 40 and Figure 41 show TNM plan views for these two cases. Highlighted in each plan view are the case's terrain lines and receivers. Underneath each plan view are several skew sections across the roadway (located by dashed lines in the plan view).

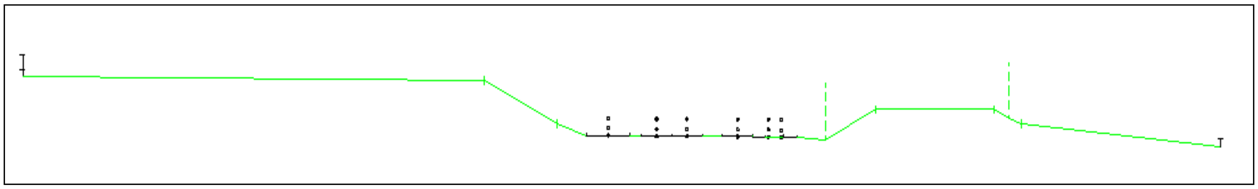
Plan view



Left section



Left-center section



Right section

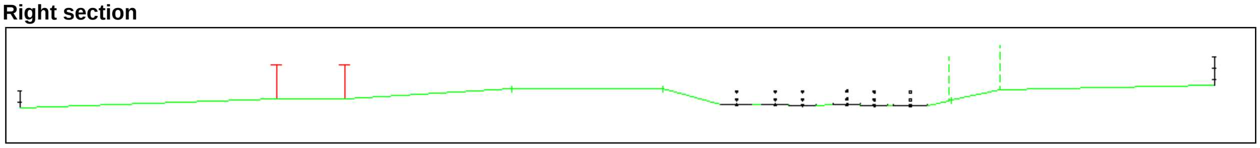


Figure 40 TNM plan view and sections (left to right) for Georgia I-285: Panthersville Interchange

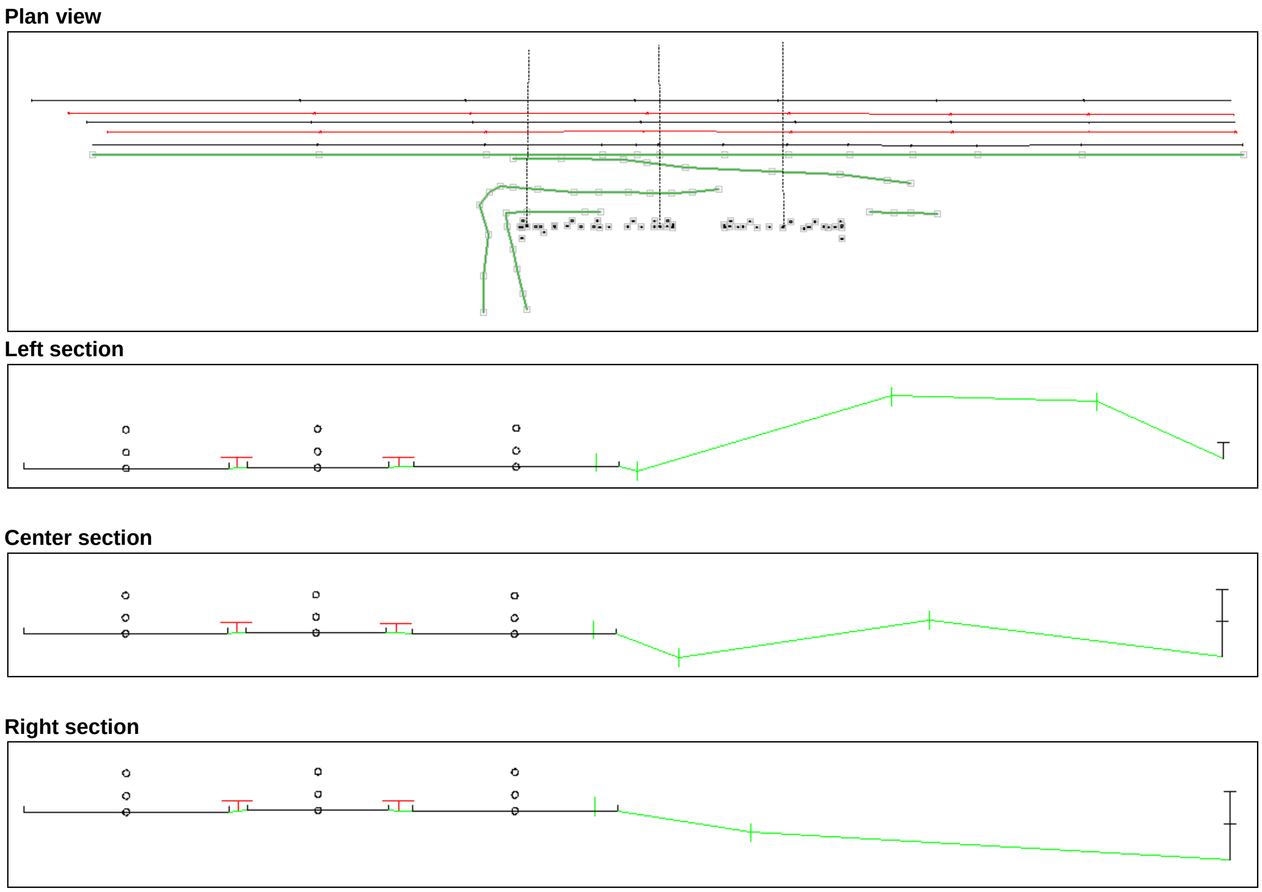


Figure 41 TNM plan view and sections (left to right) for Lorton Valley, Fairfax Cty VA

G.5.1.1 The effect of increased terrain-line elevation

For these two TNM cases, Figure 42 shows the effect of elevating all terrain lines by 2 feet. In particular, the figures contain histograms of the resulting change in L_{eq}. As shown, those L_{eq} increases are as large as 4 or 5 dB, depending upon receiver location.

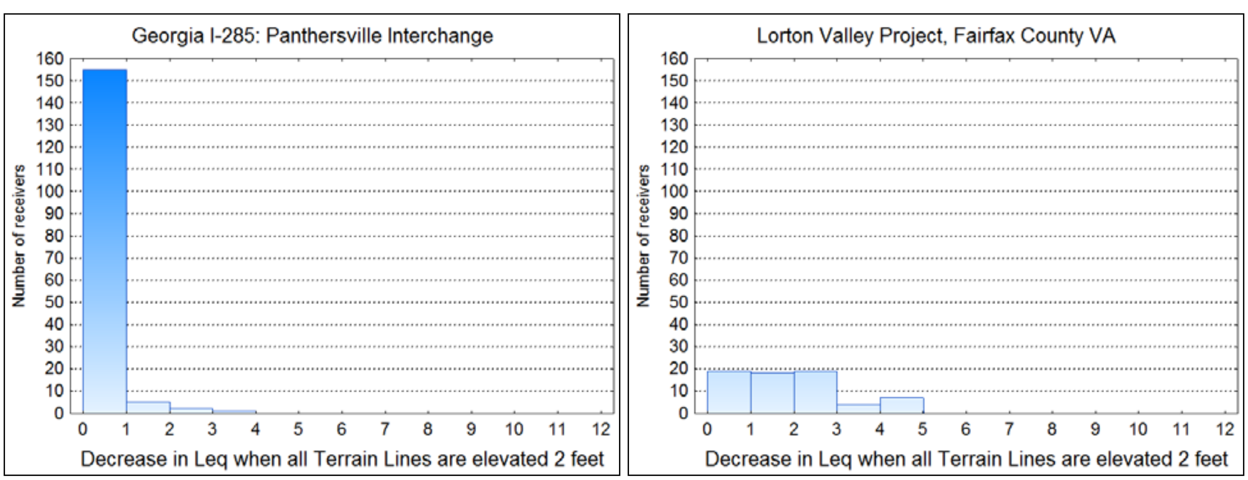


Figure 42 Decrease in L_{eq} when all terrain lines are elevated by 2 feet

The histogram to the left (Georgia I-285) shows nearly all changes to be less than 1 dB. The 10-or-so exceptions are limited to 4 dB. This is likely typical of a limited-access highway, mostly on grade, as it passes under a local cross street.

In contrast, the histogram to the right shows the majority of changes to be greater than 1 dB, ranging up to 5 dB. This is likely typical of a roadway that is coming up out of a cut section.

G.5.2 Additional sensitivity testing

We further investigated TNM sensitivity to terrain-line elevation with the *Automated TNM Sensitivity Tool* (Section 1 of this appendix). As with other uses of this tool, we computed for many combinations of input parameters. For those various input combinations, we thereby investigated how precisely terrain-line elevation must be input, to achieve any particular L_{eq} precision. Numerically, how does $\Delta Leq/\Delta z_{TL}$ depend upon all other TNM input?

G.5.3 The geometry

Figure 43 shows TNM's cross-sectional geometry for this study, for three separate types of intervening terrain.

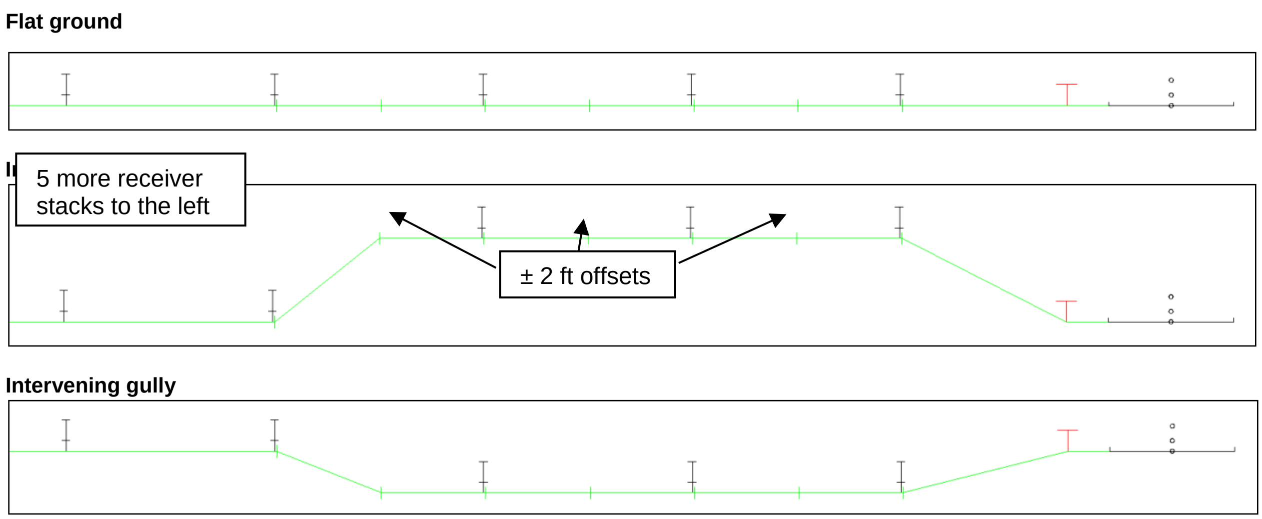


Figure 43 TNM sensitivity geometries: flat, hill, gully

Receivers included in all three phases:

- 10 receiver distances from the near edge of pavement: 100 , 200, ..., 900 and 1000 feet
- 2 receiver heights at each distance: 5 and 15 feet for a total of 20 receivers

Then for these receivers:

- 4 barrier heights: 0, 3, 10 and 15 feet
- 3 roadway widths: 40, 50 and 60 feet including the three corresponding roadway positions to leave the near edge of shoulder unchanged.
- 3 traffic conditions: All automobiles, then all medium trucks, then all heavy trucks.

These input values led to (4)(3)(3) = 36 distinct source-barrier geometries for each phase, each run twice for terrain-line Z coordinate *reduced*, and then *increased*, by 2 foot. In turn, these 36 geometries combined with the 20 receivers to produce 720 total input combinations for each of the three phases that is, **(**3)(720) = 2,160 sensitivity computations of ΔL_{eq} due to $\Delta z_{TerrainLine}$ in all.

Figure 44 shows the corresponding TNM input combinations within Excel's Sensitivity Spreadsheet. As seen in the figure:

- Columns 1 and 2 contain the receiver distances and heights. TNM input includes all combinations of those: two receivers at each of ten distances from the roadway's near edge.
- Columns 3 contain the elevations for the three terrain lines that have offset elevations (both end points of each).
- Columns 4 contain the height of the two barrier end points.
- Columns 5 contain the roadway distances to the barrier, plus the synchronous roadway width.
- Columns 6 contain the synchronous roadway traffic.

Receivers: Check that Cols B,C on Comps sheet reproduce TNM's receiver order.

Ground Zone Types and Flow Control Devices: If you are entering these here, see the notes below the yellow cells.

1	2	3	3	3	3	3	3	4	4	5	5	5	6	6	6	6	6	6
		TLn2Z1	TLn2Z2	TLn4Z1	TLn4Z2	TLn6Z1	TLn6Z2	Height1	Height2	Road1Y	Road2Y	RoadWidth	AUVol	AUSpd	MTVol	MTSpd	HTVol	HTSpd
		TlnTerr	TlnTerr	TlnTerr	TlnTerr	TlnTerr	TlnTerr	TlnBarr	TlnBarr	TlnRoad	TlnRoad	TlnRoad	TlnTraf	TlnTraf	TlnTraf	TlnTraf	TlnTraf	TlnTraf
		J16	J17	J20	J21	J12	J13	S12	S13	K12	K13	F12	I12	J12	K12	L12	M12	N12
		2	2	2	2	2	2											
Distance or Height (#s, only)	**Height or Distance (#s, only)**																	
-100.00	5	0	0	0	0	0	0	0	0	20	20	40	100	50	0	0	0	0
-200.00	15							3	3	25	25	50	0	0	100	50	0	0
-300.00								10	10	30	30	60	0	0	0	0	100	50
-400.00								15	15									
-500.00																		
-600.00																		
-700.00																		
-800.00																		
-900.00																		
-1000.00																		

720 = number of input combinations from above (max = 5,000)
36 = number of computation loops (ignores number of receivers)

Figure 44. TNM Input combinations within Excel, for flat ground

In addition, Figure 44 shows the offset parameter (Z-coordinate for the three terrain lines), which offsets by plus/minus 2 feet during the sensitivity computations. Note that these terrain lines have only one value for their Z-coordinate. Therefore, they do not increase the number of TNM runs. They are only in the figure because Excel needs to "offset" them.

Also note that the three types of intervening terrain cannot be combined into a single sensitivity operation, because the receiver Z-coordinates differ for flat ground, intervening 20-foot gully and intervening 40-foot hill. For the gully and hill terrain, the "0" values for terrain-line Z in Figure 44 all change to –20 and +40, respectively.

G.5.4 Computation results

G.5.4.1 All data

Figure 45 shows the initial cobweb plot,[6, 7] which contains a left-to-right line for each of the 2,160 variable combinations. Each line's intersection with a vertical axis shows that combination's value for

[6] UNICORN at http://risk2.ewi.tudelft.nl/oursoftware/3-unicorn or its update.
[7] Kurowicka, D. and R. Cooke, *Uncertainty Analysis*, Wiley (2006).

that axis parameter. For example, note that all lines pass through one of only two points on the RecHt (receiver height) axis. In contrast, the lines spread out among the many computed values of DelLev.

In addition, the figure contains a "minimum" and a "maximum" line, to fix the vertical-scale limits at convenient values and thereby make the line-intersection values easier to read from each axis scale.

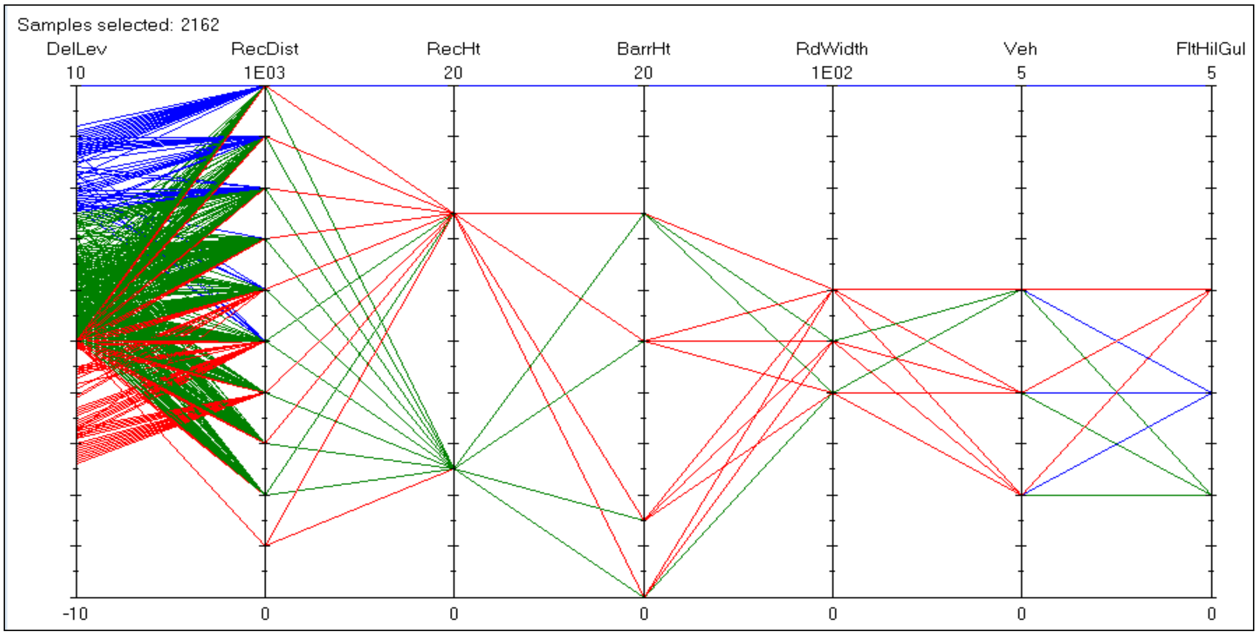


Figure 45. Initial cobweb plot: All variables, all data points

In this cobweb plot:

- **DelLev** is the computed DeltaLevel (in dBA) that is, the change in sound level produced by the plus/minus offset in the three terrain lines of Figure 43.
- **RecDist** and **RecHt** are the receiver distance (in feet) and receiver height (in feet), respectively.
- **BarrHt** is the barrier height (in feet).
- **RdWidth** is the roadway width (in feet).
- **Veh** is the vehicle type: Automobiles = 1, Medium Trucks = 2, Heavy Trucks = 3.
- **FltHilGul** denotes whether the intervening terrain was flat (value = 1), hill (value = 2), or gully (value = 3).

G.5.4.2 Results: Intervening flat ground

For intervening flat ground, Figure 46 through Figure 50 contain several filtered cobweb plots that show particular aspects of the data relationships. Following each figure are various implications about how DelLev relates to the other variables in these plots.

For these plots, various vertical axes are relocated next to the DelLev axis, to best show the relation between DelLev and that relocated variable. To restrict each of these cobweb plots to flat ground, we swiped the cursor through FltHilGul = 1 on the right-most vertical axis.

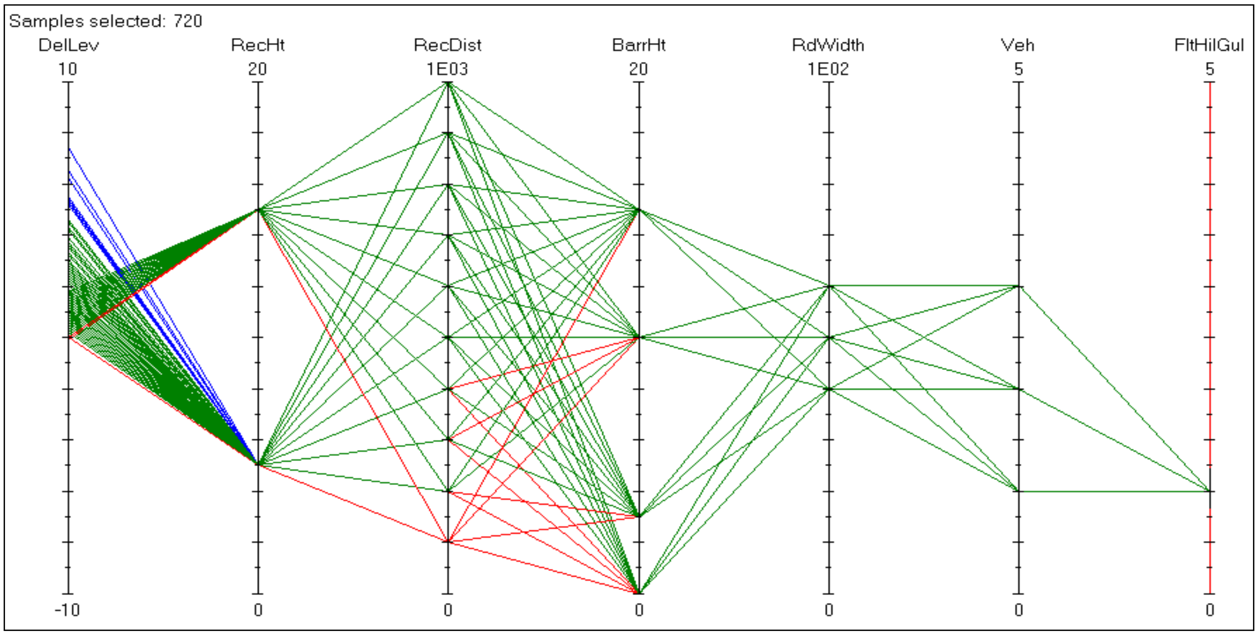


Figure 46 Only flat ground (FltHilGul = 1)

From this plot, only five-foot receivers are significantly affected (effect > 1 dB). So the next plot retains just these receivers (on its fourth vertical axis).

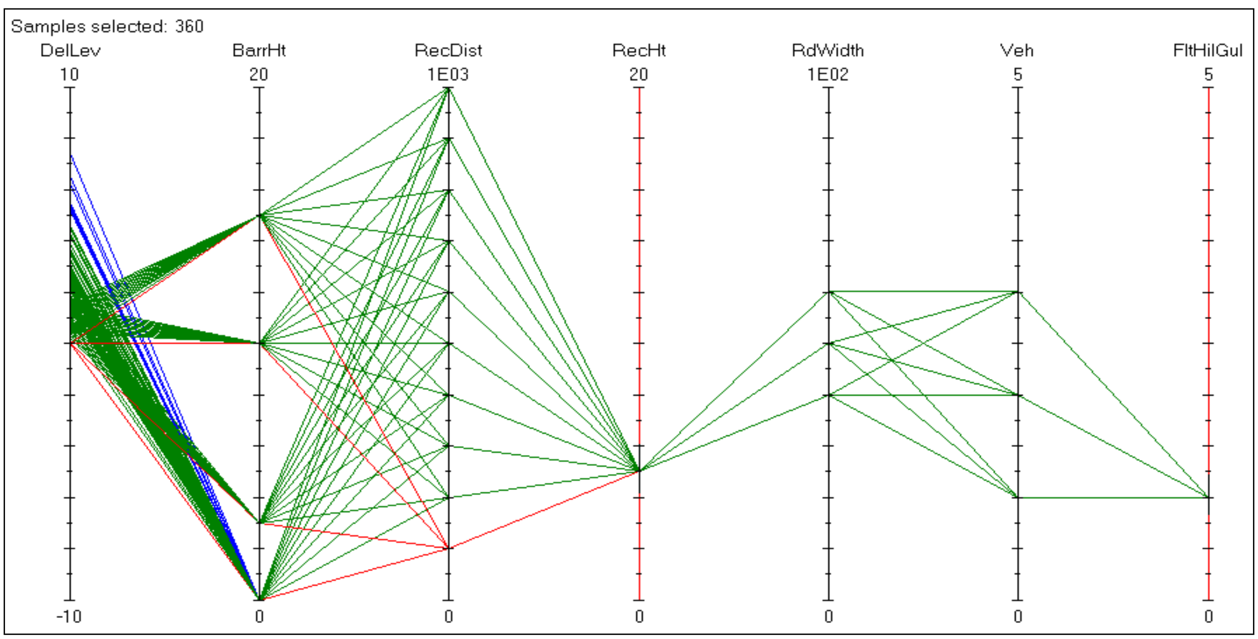


Figure 47 Only flat ground and 5-foot receivers

From this plot, only no-barrier geometries are significantly affected. So the next three plots retain just the no-barrier geometries (on their third vertical axis). These next plots differ by which axis is relocated next to DelLev.

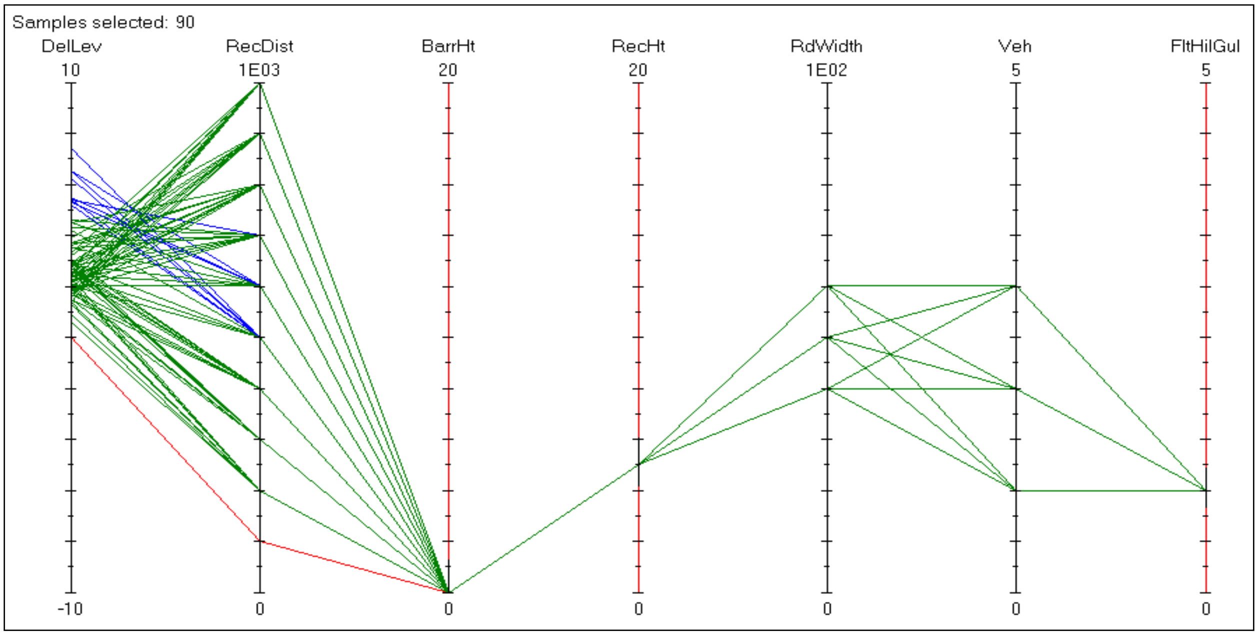


Figure 48 Flat ground, 5-foot receivers, no barrier—investigating receiver distance

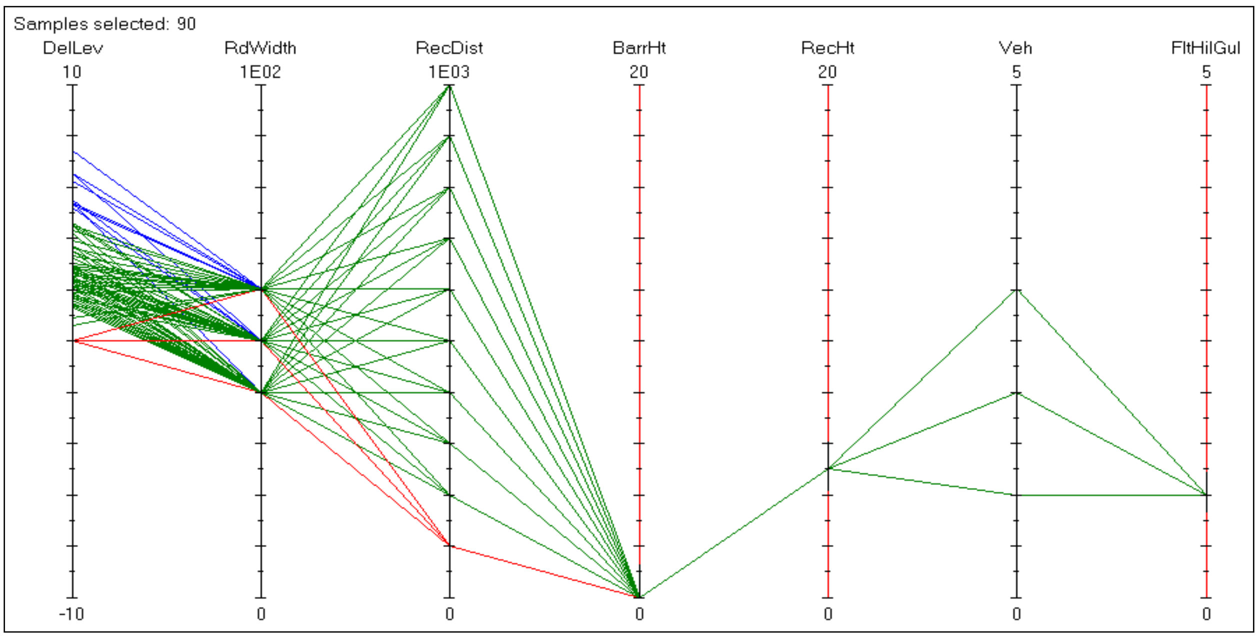


Figure 49 Flat ground, 5-foot receivers, no barrier—investigating roadway width

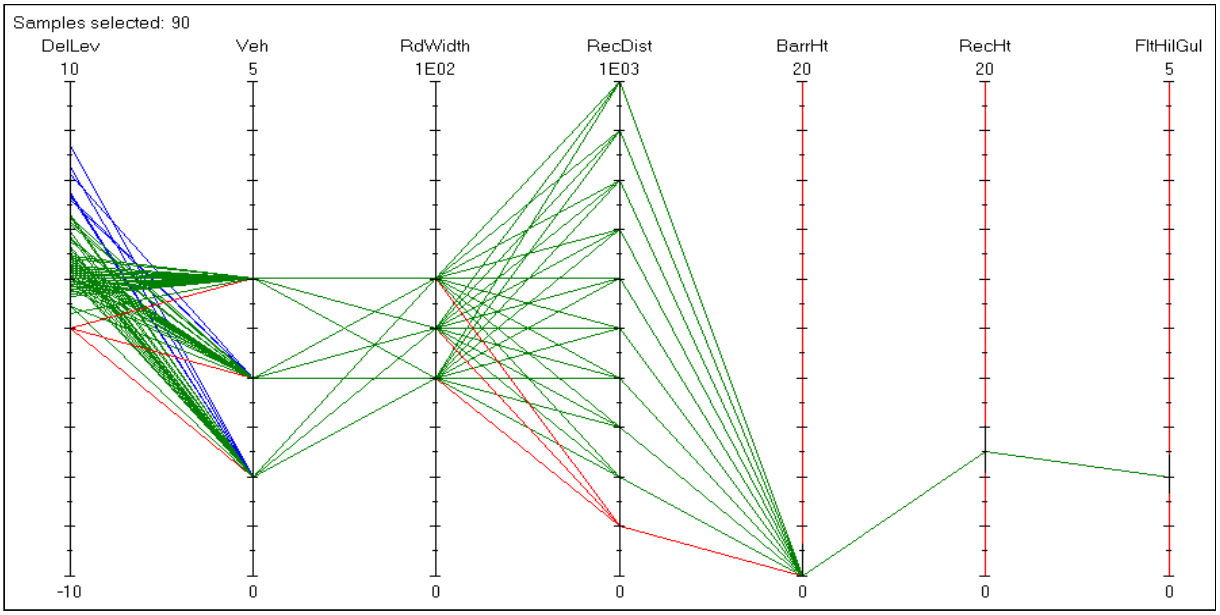


Figure 50 Flat ground, 5-foot receivers, no barrier—investigating vehicle type

The third of these plots shows that TNM's sensitivity to terrain-line elevation is significantly less for heavy trucks than for automobiles or medium trucks. Other than that relationship, however, none of these last three figures shows much pattern between DelLev and receiver distance, roadway width, and/or vehicle type.

To examine matters further, Figure 51 and Figure 52 contain categorized scatterplots of DelLev (vertically) against receiver distance. The first of these labels the points with their value of roadway width, while the second labels them with vehicle type.

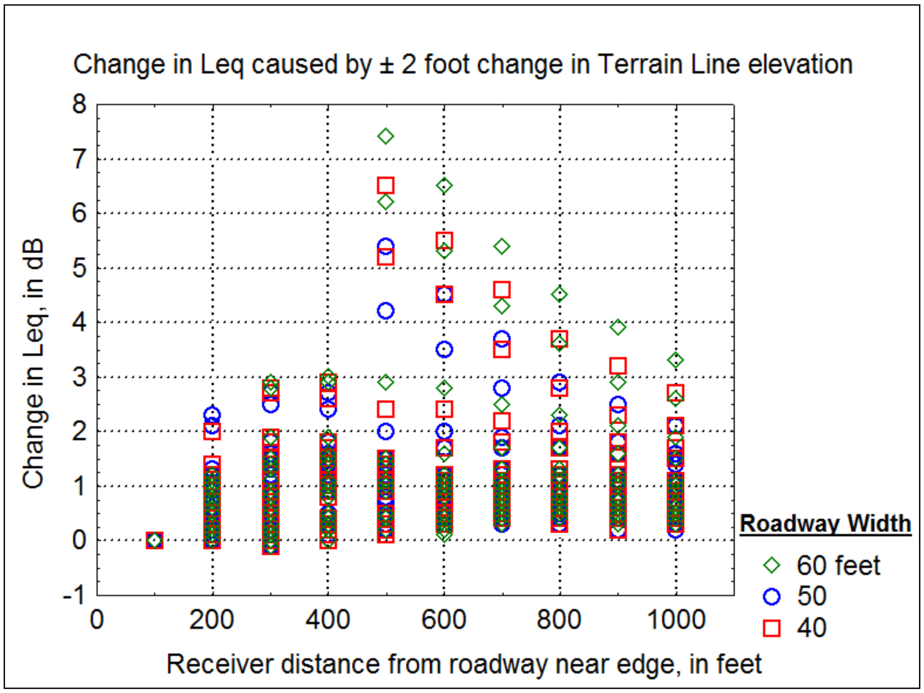


Figure 51 Relation between DelLev and RecDist, for the three values of RdWidth

This plot shows that mid-distance receivers (500-to-700 feet) experience the highest sensitivity to terrain-line offsets. That sensitivity is as large as 7.5 dB for the vertical terrain offset of ± 2 feet. Possible explanations:

- Receivers closer than 500 feet have fewer intervening terrain lines that "offset," which might explain their lower sensitivity. In fact, the closest receiver (100 feet) has no such terrain lines.
- At larger distances, sensitivity diminishes, per this plot.

In addition, the plot shows that increasing roadway widths increase the sensitivity—as is most apparent at mid-distances.

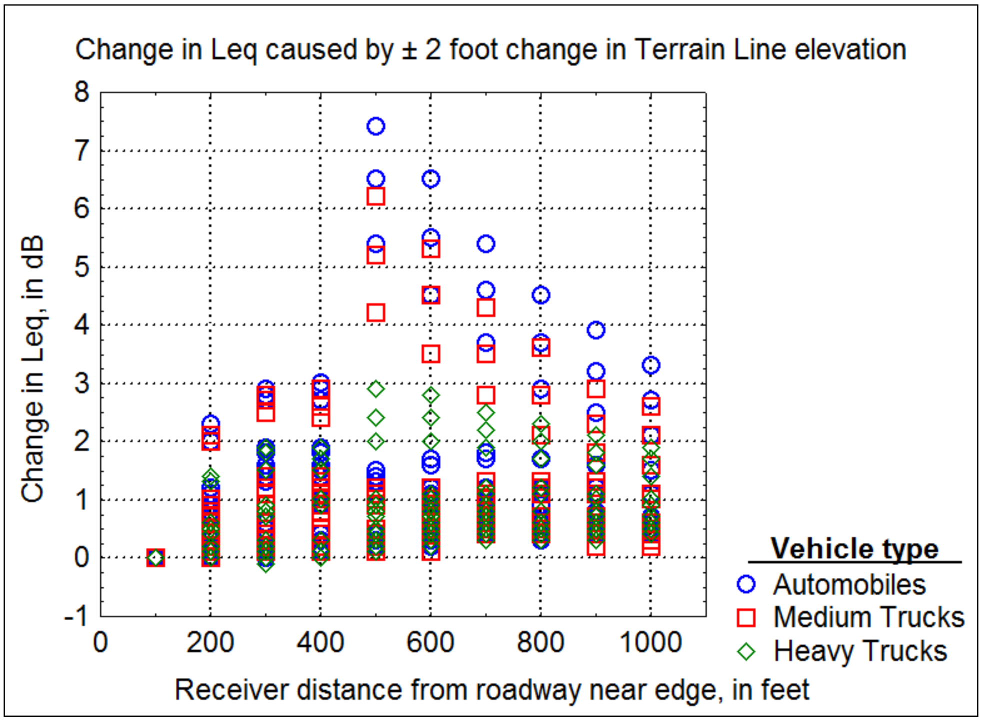


Figure 52 Relation between DelLev and RecDist, for the three values of Vehicle Type

This plot shows that sensitivity is greatest for automobile traffic, intermediate for medium-truck traffic, and least for heavy-truck traffic, again most apparent at mid-distances.

Finally, Figure 53 shows another view of the dependence on RdWidth and Vehicle type. In this figure, the three scatter plots show DelLev vertically, plotted separately (from left to right) against receiver distance, roadway width and vehicle type.

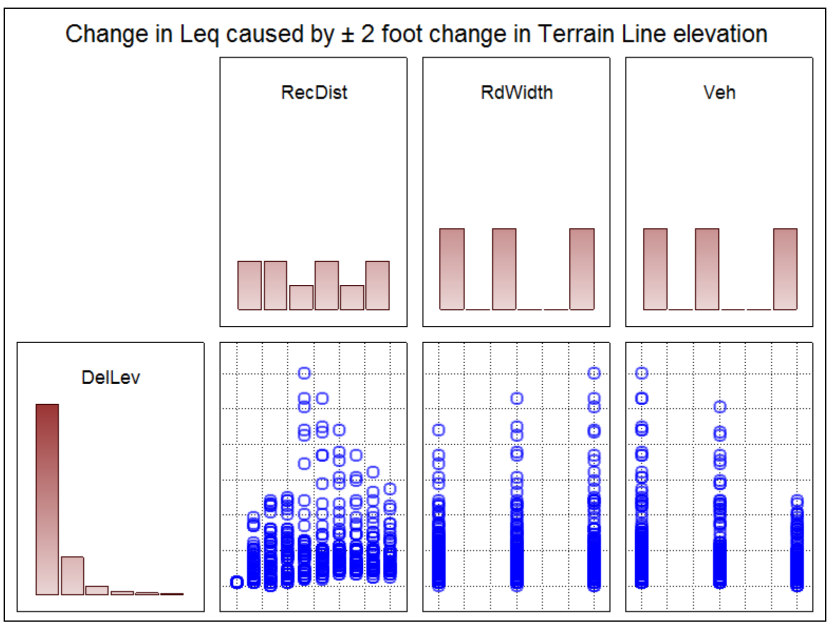


Figure 53 Relation between DelLev and RecDist, RdWidth, Vehicle type

The sensitivity dependence on RdWidth and Vehicle type (mentioned above) are very apparent from this figure.

Effects larger than 3 dB

As these figures show, a modest number of computed points have effects larger than 3 dB. Figure 54 investigates these further.

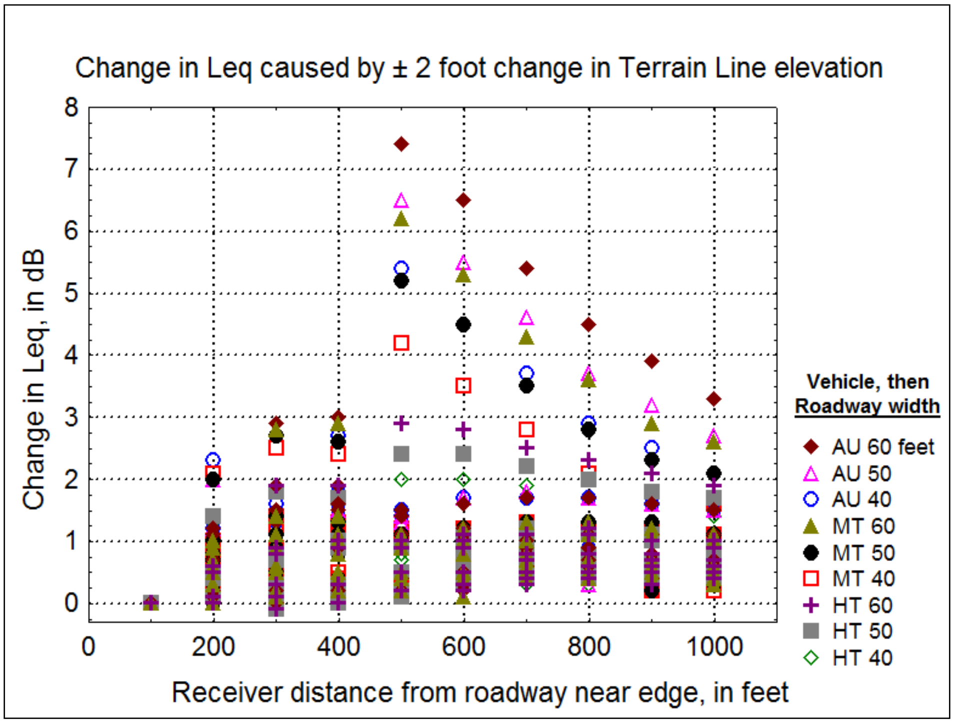


Figure 54 More detailed view of changes above 3 dB

This figure shows:

- Effects larger than 3B (flat ground) only for automobiles (up to 7.5dB) and medium trucks (up to 6.2 dB). Lower source heights produce larger effects.
- Effects 1 dB greater for each 10-foot increase in roadway width (and therefore source-receiver distance).
- No effects larger than 3B for receivers at 400 feet or less.
- Maximum effects at 500 feet, then decreasing approximately 1 dB per 100 feet and disappearing below 3dB at 1000 feet.

G.5.4.3 Results: Intervening Hill

For an intervening 40-foot hill, Figure 55 contains a filtered cobweb plot that shows the relation between DelLev and receiver height.

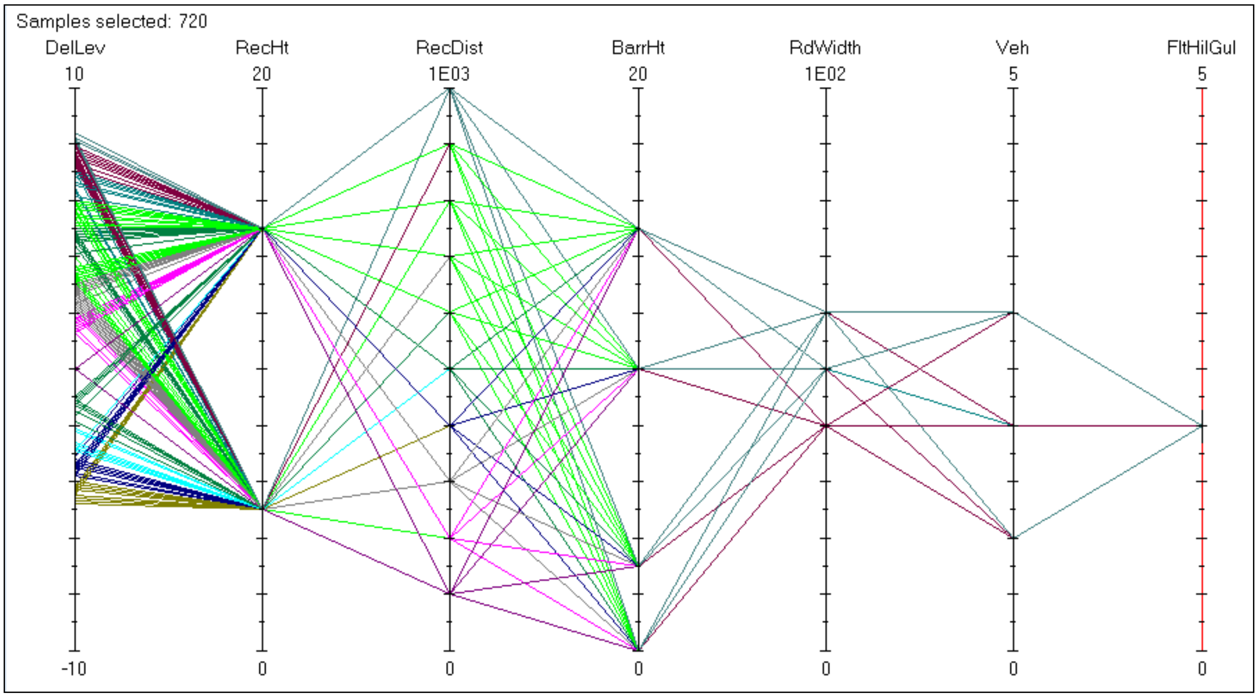


Figure 55 Only intervening hill (FltHilGul = 2)

This plot shows essentially no functional relation between DelLev (the left-most axis) and receiver height (the next axis to the right). Graphically, for each of the two receiver heights, the set of lines to the DelLev axis subtend the entire range of DelLevs. In shorter terms, each receiver height is associated with all values of DelLev.

Similar cobweb plots were constructed with the other parameters adjacent to DelLev. With one exception, each of these showed the same association with DelLev. In words, there appears to be no functional dependence of DelLev on receiver height, barrier height, roadway width, or vehicle type with an intervening hill.

In contrast, however, Figure 56 shows an interesting relation between DelLev and receiver distance.

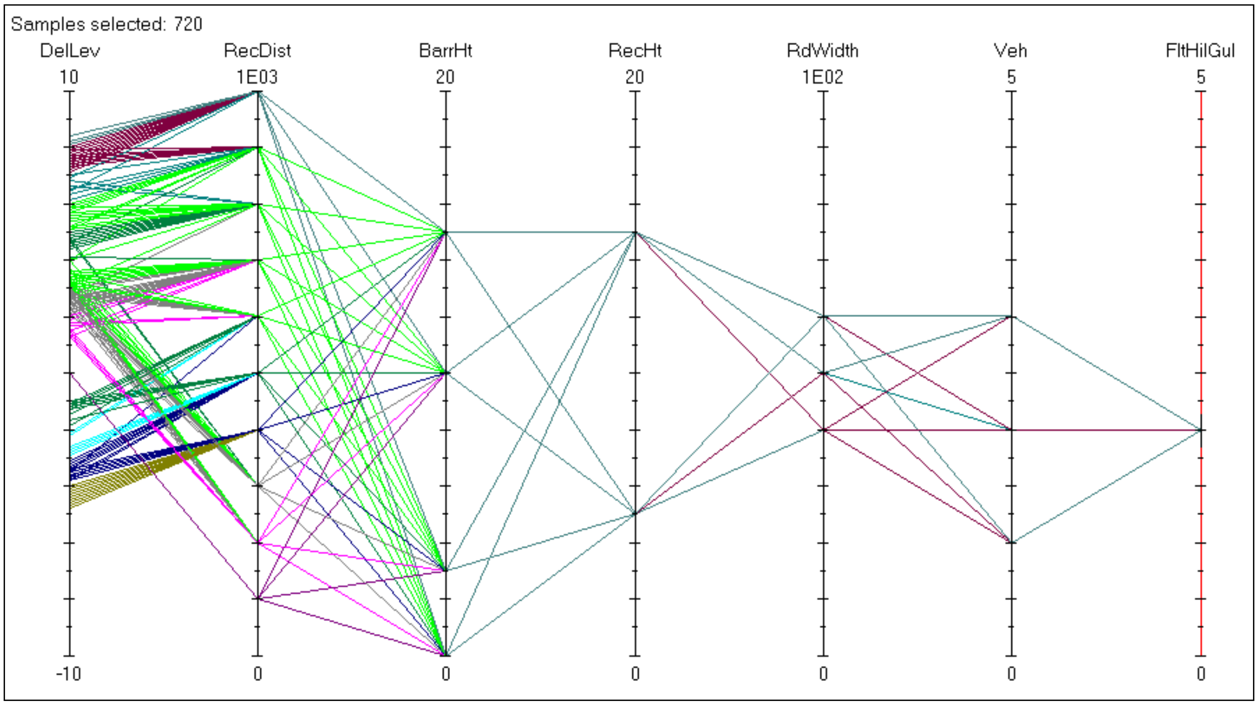


Figure 56 Intervening hill—investigating receiver distance

To examine this relation more closely, Figure 57 plots these two variables against one another.

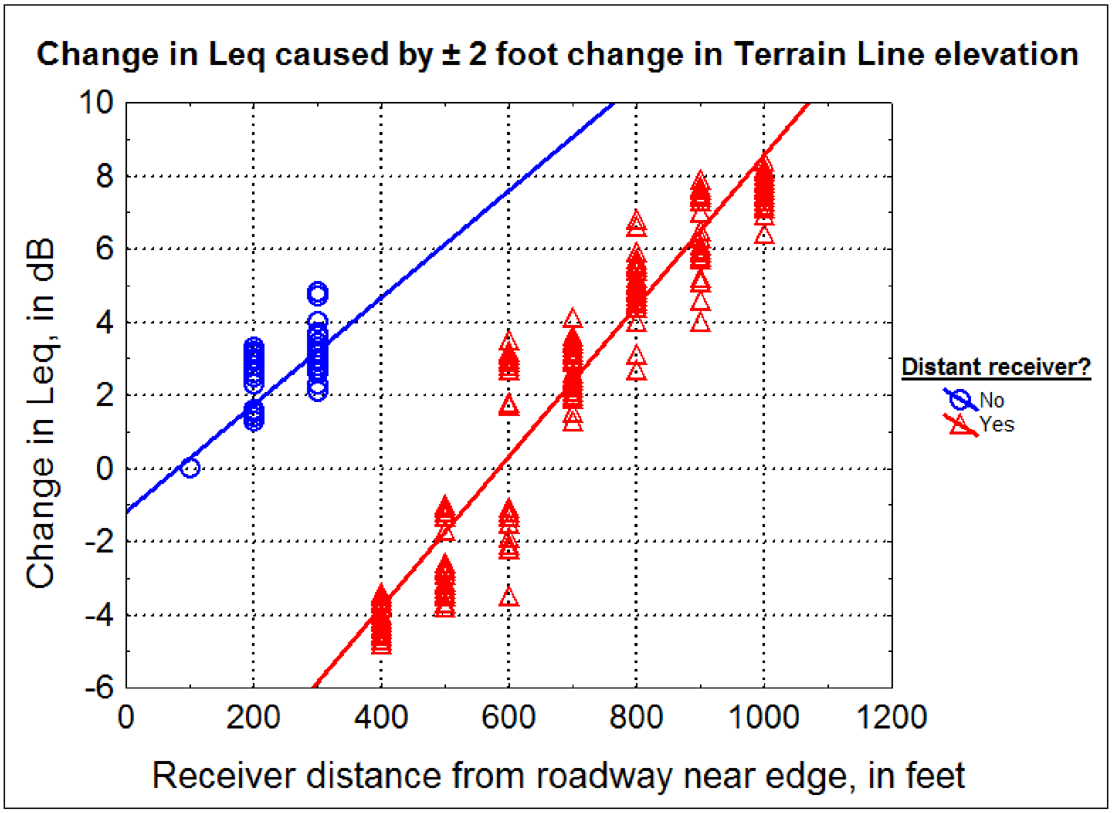


Figure 57 Relation between DelLev and receiver distance: Intervening hill

This figure clearly shows the receiver distances for which this effect is greatest. Note the locations of these receivers from Figure 43 (on page G-33).

Table 2 shows the implications of this figure in particular the sound-level effect of increasing terrain-line elevation by 4 feet.

Table 2 Sound-level effect of increased terrain-line elevation: Intervening hill

Receiver category	Particular receiver distance(s) in these computations	Sound-level effect
Receivers closer than the intervening terrain lines	100 feet	None
Receivers on the intervening hill	200 feet 300 feet	Increase of 2-to-4 decibels
Receivers just behind the intervening hill	400 feet 500 feet	Decrease of 2-to 5 decibels
Receivers very far behind the intervening hill	700 feet and greater	Increase of 2-to-8 decibels, with some indication that the effect is flattening out at 8 decibels

Effects larger than 4 dB

Figure 58 is a matrix plot of DelLev (vertical coordinate) against these separate horizontal parameters: receiver distance, receiver height, barrier height, road width and vehicle type.

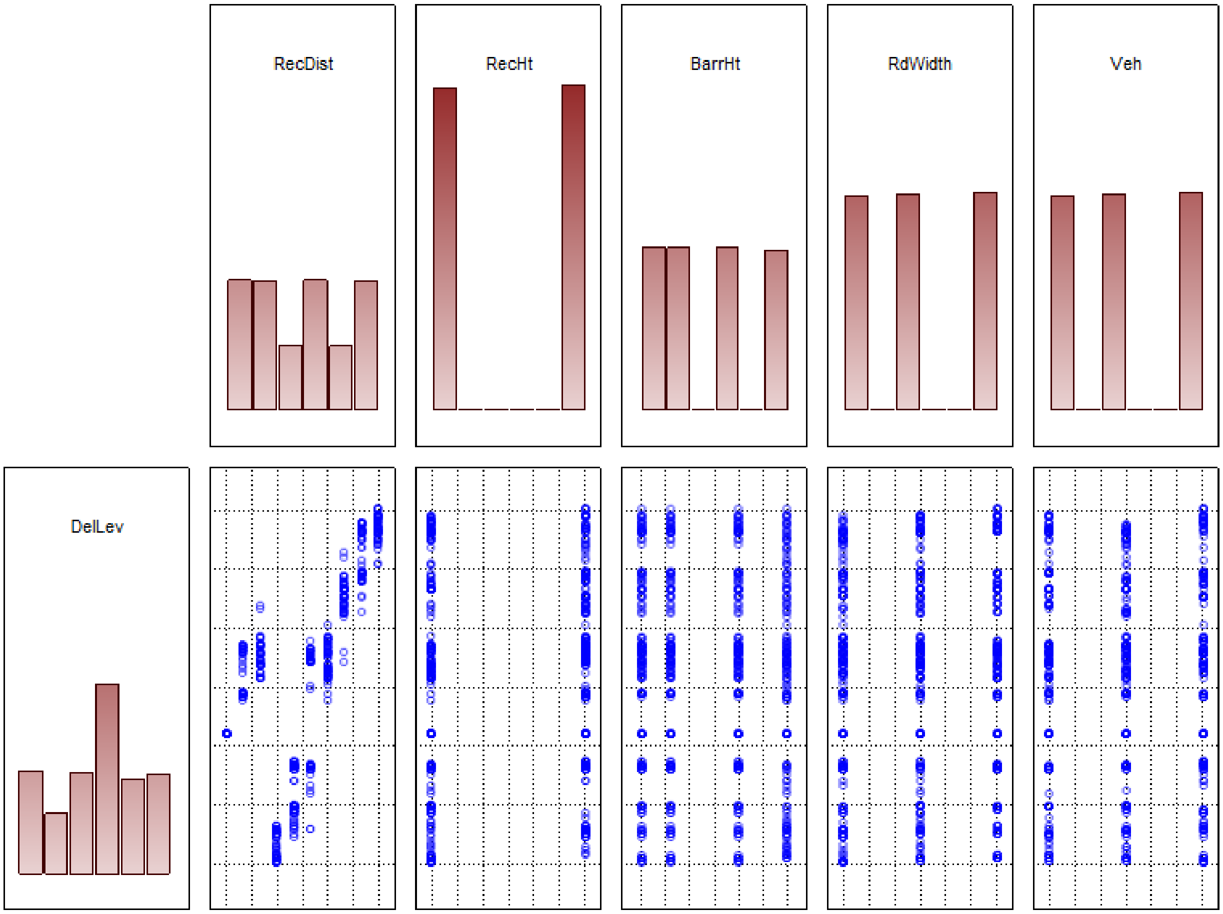


Figure 58 Effects larger than 4 dB: Intervening hill

The left-most plot is a repeat of Figure 57, but without the explicit scales. As the other four plots clearly show, DelLev has essentially no dependence upon the other variables that were investigated. Hence the conclusions are valid for all values of receiver height (5 and 15 feet), barrier height (0, 3, 10 and 15 feet), roadway width (40, 50 and 60 feet), and vehicle type.

G.5.4.4 Results: Intervening Gully

For an intervening 20-foot gully, Figure 59 contains a filtered cobweb plot for only the cases involving that gully. As is obvious from this plot, the terrain-line offsets do not influence sound levels when they lie within an intervening gully.

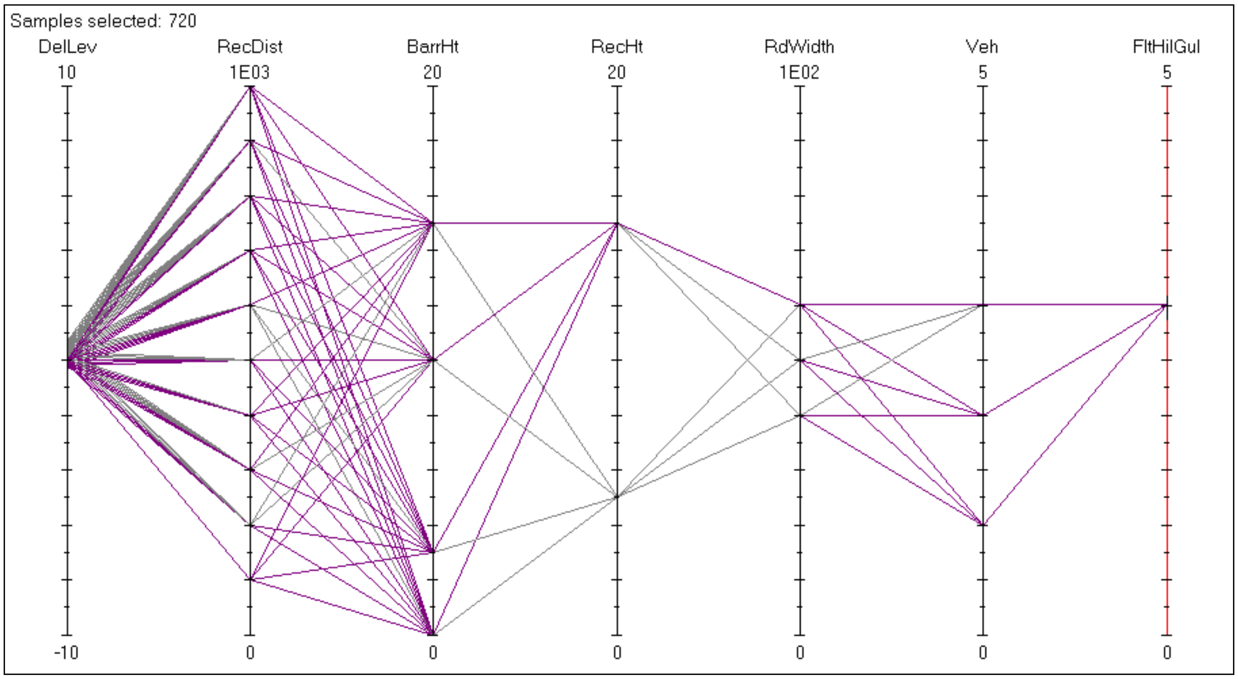


Figure 59 Only intervening gully (FltHilGul = 3)

G.5.5 Introduction to Guidance

As part of this NCHRP project, we solicited and received a number of noise studies and/or TNM runs for actual highway projects around the country. Input for two of these included an interesting assortment of terrain lines. Of concern to this NCHRP project is TNM's sensitivity to the input Z-coordinates of these modeled terrain lines. To that end, we re-ran these two TNM cases with all the terrain lines moved upwards by 2 feet.

In addition, we performed a sensitivity analysis with offset terrain-line elevations under three geometries: (1) intervening flat ground, (2) intervening 40-foot hill, and (3) intervening 20-foot gully.

G.5.6 Resulting Guidance for TNM input

From the highway projects: Keep the vertical precision of all terrain lines to plus/minus 1 foot especially for barrier-design projects, for which plus/minus 1-to-2 decibel accuracy is generally the goal.

From the sensitivity analysis: Follow the guidance in Table 3. No guidance is needed for situations not in this table. In particular, no guidance is needed when the terrain lines are in intervening gullies of significant depth.

Table 3 Guidance for elevation of intervening terrain lines

Intervening terrain	Dominant vehicle type	Receiver heights	Receiver distances	Roadway width	Guidance: Match actual terrain elevation within this amount
Flat within ± 10 feet Gullies less than 10 feet deep	Heavy trucks	5 feet	All	All	± 2 feet
	Medium trucks Automobiles	5 feet	Less than 450 feet	All	± 2 feet
			450 to 750 feet	More than 50 feet	± 0.5 feet
				30 to 50 feet	± 1 foot
				Less than 30 feet	± 2 feet
			750 feet to 1000 feet	More than 50 feet	± 1 foot
				Less than 50 feet	± 2 foot

			More than 1000 feet	All	± 2 feet
Hills more than 10 feet high	All	All	Actually on the hill	All	± 2 feet
			Within 100 feet behind the hill	All	± 1.5 feet
			Further than 100 feet behind the hill	All	± 1 foot

G.6 Barrier tops: Vertical precision

Section G.2 of this appendix showed strong TNM sensitivity to location of the outer edge of pavement. In that section, we suspected that strong sensitivity might actually reside within TNM's *diffraction* algorithm especially when the diffracting edge just grazes the source-receiver line of sight.

That suspicion led us to look for similar sensitivity when sound diffracts over wall barriers. In this current study, we found that same sensitivity also restricted to near-grazing conditions. This section summarizes our barrier study and its conclusions.

As with the study in Section G.2, we investigated barrier attenuation with the *Automated TNM Sensitivity Tool* (Section 1 of this appendix). Rather than confine this study *a priori* to near-grazing conditions, we computed for many combinations of input parameters. For those various input combinations, we thereby investigated how precisely barrier height must be input, to achieve any particular L_{eq} precision. Numerically, how does $\Delta Leq/\Delta BarrHeight$ depend upon all other TNM input?

G.6.1 The geometry

Figure 60 shows TNM's cross-sectional geometry for this sensitivity study.

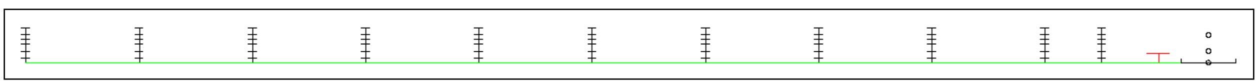


Figure 60 Initial TNM sensitivity computations

In the figure, to the right are a TNM roadway and an adjacent noise barrier. To their left is a large array of TNM receivers:

- 11 receiver distances from the barrier: 25 feet to 500 feet
- 6 receiver heights at each distance: 2, 5, 8, 10, 12 and 15 feet—for a total of 66 receivers.

For the sensitivity computations, we included:

- 3 traffic conditions: All automobiles, then all medium trucks, then all heavy trucks.
- 4 barrier heights: 8, 10, 15 and 20 feet
- 3 roadway widths: 20, 30 and 40 feet
- 6 distances between the roadway edge and the barrier: 22, 27, 32, 37, 42 and 47 feet.

These input values led to 216 distinct source-barrier geometries, each run twice for barrier height *reduced*, and then *increased*, by 1 foot. In turn, these 216 geometries combined with the 66 receivers to produce 14,256 source-barrier-receiver combinations [8] that is, **14,256 sensitivity computations of ΔL_{eq} due to Δ*BarrHeight***.

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[8] Since 14,256 combinations exceed the Sensitivity Spreadsheet's capability, that spreadsheet was used separately three times (once per vehicle type) and then the results were combined into one CSV file for graphing and analysis.

G.6.2 The spreadsheet input combinations

Figure 61 shows the corresponding TNM input combinations within Excel's Sensitivity Spreadsheet. As seen in the figure:

- Columns 1 and 2 contain the receiver distances and heights. TNM input includes all combinations of those: six receivers at each of eleven distances from the roadway's near edge.
- Columns 3 contain the height of the two barrier end points. These end points vary in synchrony, because their column index is the same.
- Column 4 contains the roadway width.
- Columns 5 contain the roadway distances to the barrier, also varying in synchrony.

Input							
	Receivers: Check that Cols B,C on Comps sheet reproduce TNM's receiver order.		Multi-valued parameters: (1) Code Lawn as LL. (2) Flo				
Combination Index (equal values force simultaneous changes):	1	2	3	3	4	5	5
Parameter (abbrev. OK):			BarrHt1	BarrHt2	RoadW	RoadDist1	RoadDist2
InputSheet (exact):			TInBarr	TInBarr	TInRoad	TInRoad	TInRoad
InputCell (exact):			T12	T13	F12	K12	K13
Plus/minus Offset Increment:			1	1			
	Distance or Height (#s, only)	Height or Distance (#s, only)					
Values	25	2	8	8	20	-22	-22
	50	5	10	10	30	-27	-27
	100	8	15	15	40	-32	-32
	150	10	20	20		-37	-37
	200	12				-42	-42
	250	15				-47	-47
	300						
	350						
	400						
	450						
	500						
Insert additional rows above this line, if needed.							
	4,752 = number of input combinations from above (max = 5,000)						

Figure 61 TNM Input combinations within Excel

In addition, the figure shows the offset parameter (barrier height), which offsets by plus/minus 1 foot during the sensitivity computations. As a result, the ΔL_{eq} from that offset corresponds to a $\Delta BarrHeight$ of 2 feet. In addition, the terrain is flat and consists of "lawn."

G.6.3 Computation results

Figure 62 shows the initial cobweb plot,[9, 10] which contains a left-to-right line for each of the combined 14,256 input combinations. Each line's intersection with a vertical axis shows that combination's value for that axis parameter. For example, note that all lines pass through one of only four points on the hBarr (barrier height) axis. In contrast, the lines spread out among the (rounded) sixteen computed values of DelLev.

In addition, the figure contains a "minimum" and a "maximum" line, to fix the vertical-scale limits at convenient values and thereby make the line-intersection values easier to read from each axis scale.

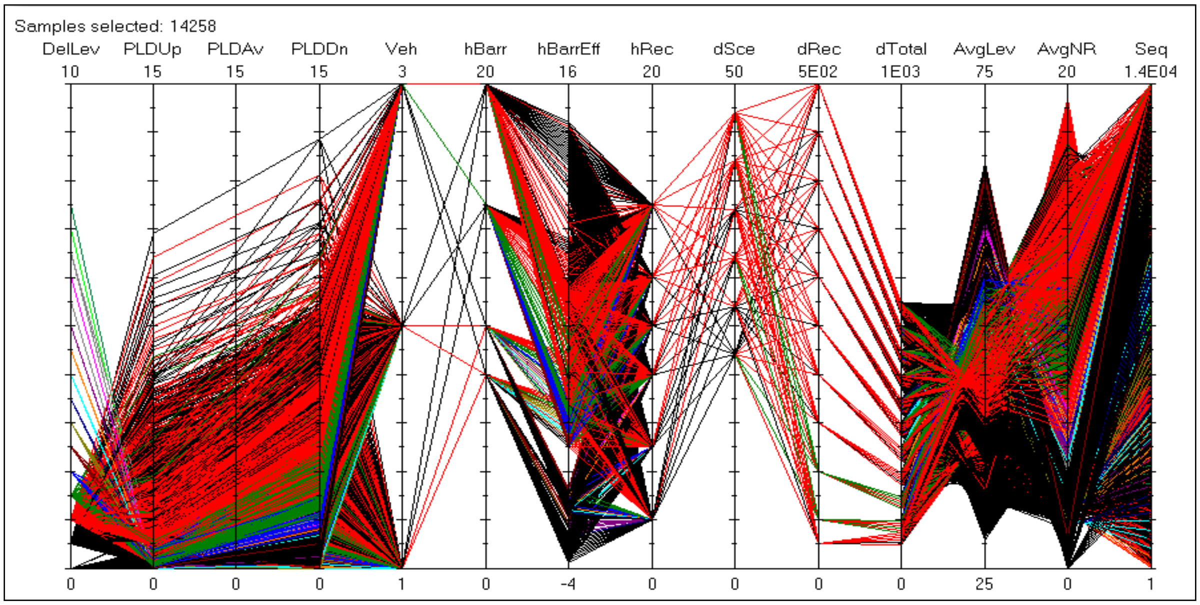

Figure 62 Cobweb plot of all input and output

Most of the vertical axes in this plot show TNM input and results. From left to right, these input/results axes are:

- **DelLev** is the computed DeltaLevel (in dB)—that is, the change in A-weighted sound level produced by the 2-foot change in barrier height (twice its offset increment).
- **Veh** is the vehicle type: Automobiles = 1, Medium Trucks = 2, Heavy Trucks = 3.
- **hBarr** is the barrier height (in feet).
- **hRec** is the receiver height (in feet).
- **dSce** is the source (roadway) distance (in feet) from the barrier.
- **dRec** is the receiver distance (in feet) from the barrier.
- **AvgLev** is the computed A-weighted sound level (in dBA) an average of the plus-1foot and the minus-1foot results.
- **AvgNR** is the computed noise reduction—an average of the plus1-foot and the minus-1ft results.

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[9] UNICORN at http://risk2.ewi.tudelft.nl/oursoftware/3-unicorn or its update.
[10] Kurowicka, D. and R. Cooke, *Uncertainty Analysis,* Wiley (2006).

The remaining vertical axes plot the following additional parameters (all computed in Excel from the input parameters):

- **PLDUp** is the barrier's path length difference from the *upper* subsource to the receiver. That path length difference equals the path length up and over the barrier, minus the path length when the barrier is absent.
- **PLDAv** is the average of PLDUp and PLDDn.
- **PLDDn** is the same as PLDUp, except from the *lower* subsource (0.328 feet for all vehicle types).
- **hBarrEff** is the "effective" barrier height (in feet) that is, the amount by which the barrier protrudes vertically through the source-receiver line of sight (see the green arrow in Figure 63).
- **dTotal** is the total source-to-receiver distance (in feet).
- **Seq** is a sequence number.

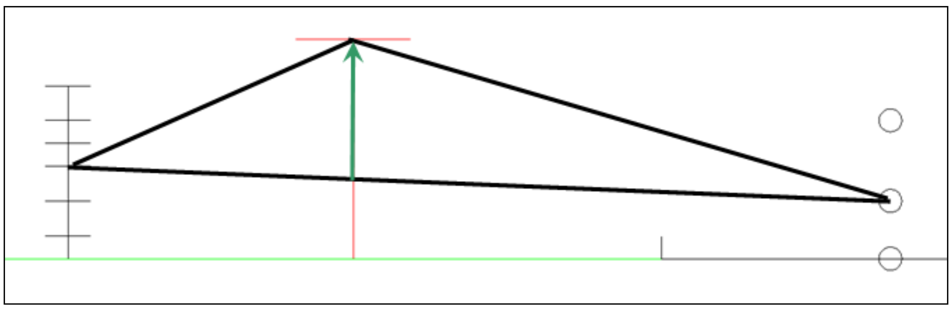

Figure 63 Sketch of effective barrier height (in green)

G.6.4   Graphics investigation of the TNM results

Starting with Figure 62 above, we investigated the parameter combinations that led to various ranges of DelLev. Figure 64 through Figure 67 show the four chosen ranges of DelLev.

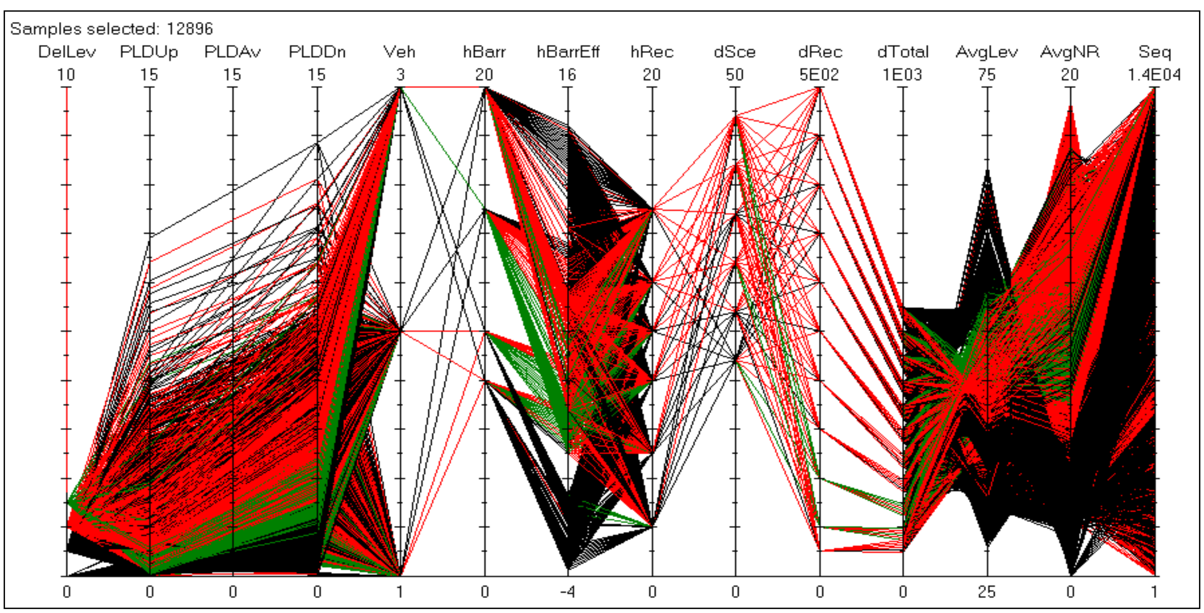

Figure 64 Filter DelLev to include only these rounded values: 0.0, 0.5, 1.0 and 1.5 dB

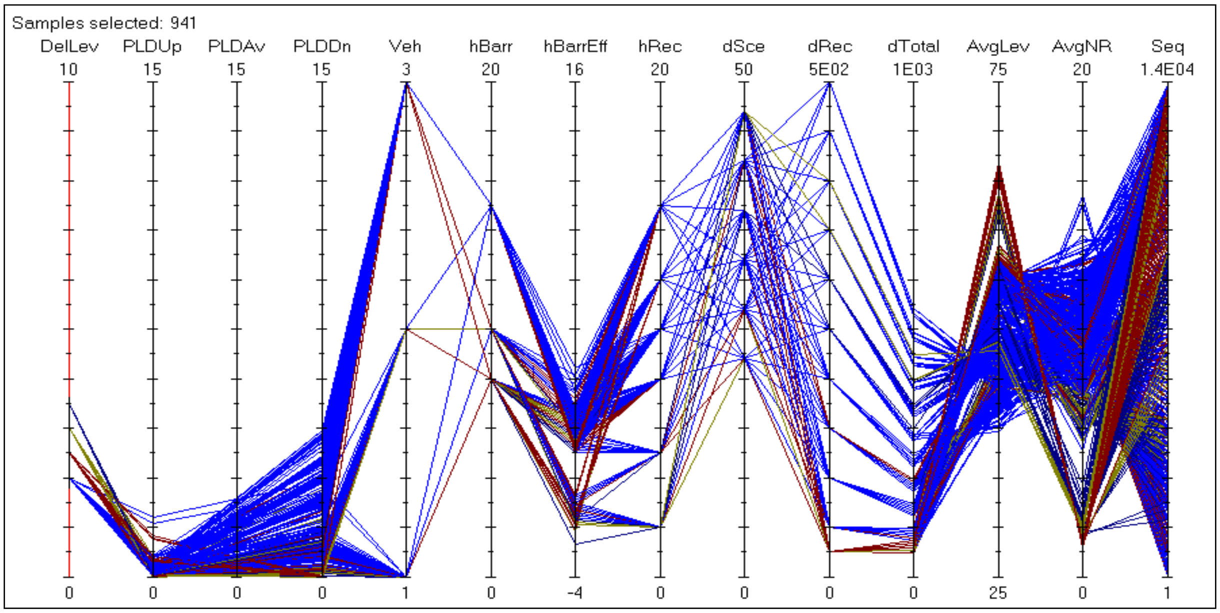

Figure 65 Filter DelLev to include only these rounded values: 2.0, 2.5, 3.0 and 3.5 dB

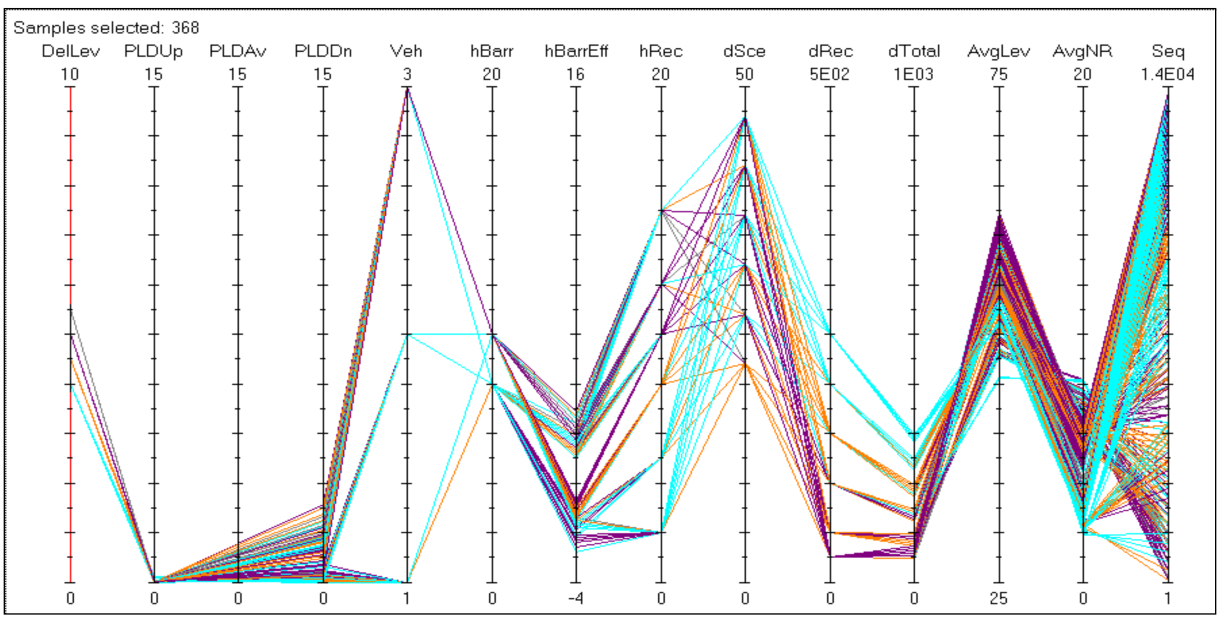

Figure 66 Filter DelLev to include only these rounded values: 4.0, 4.5, 5.0 and 5.5 dB

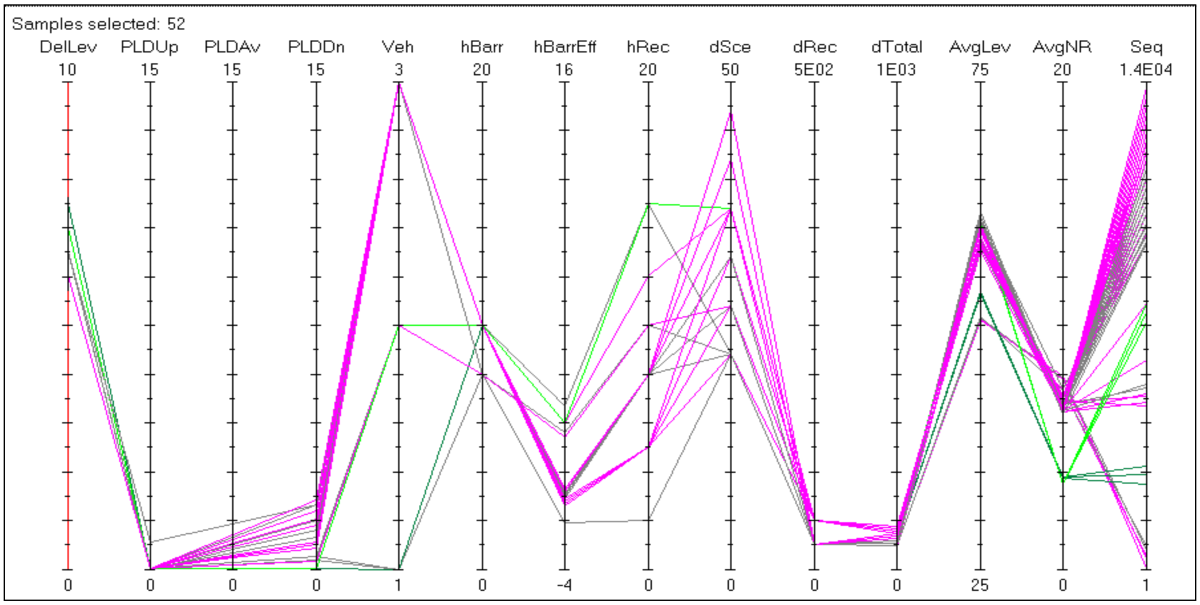

Figure 67 Filter DelLev to include only these rounded values: 6.0, 6.5, 7.0 and 7.5 dB

As is apparent from this filtering, the large values of DelLev (2.5 dB and higher) all match up with extremely small values of PLDUp that is, the path length difference over the barrier, starting from the upper subsource height.

Figure 68 shows those two parameters plotted against each other, along with a vertical line that roughly separates the highly sensitive results (DelLev generally > 2.5 dB) from those less sensitive. As the figure shows, the majority of highly sensitive results are for PLDUp less than 0.04 feet.

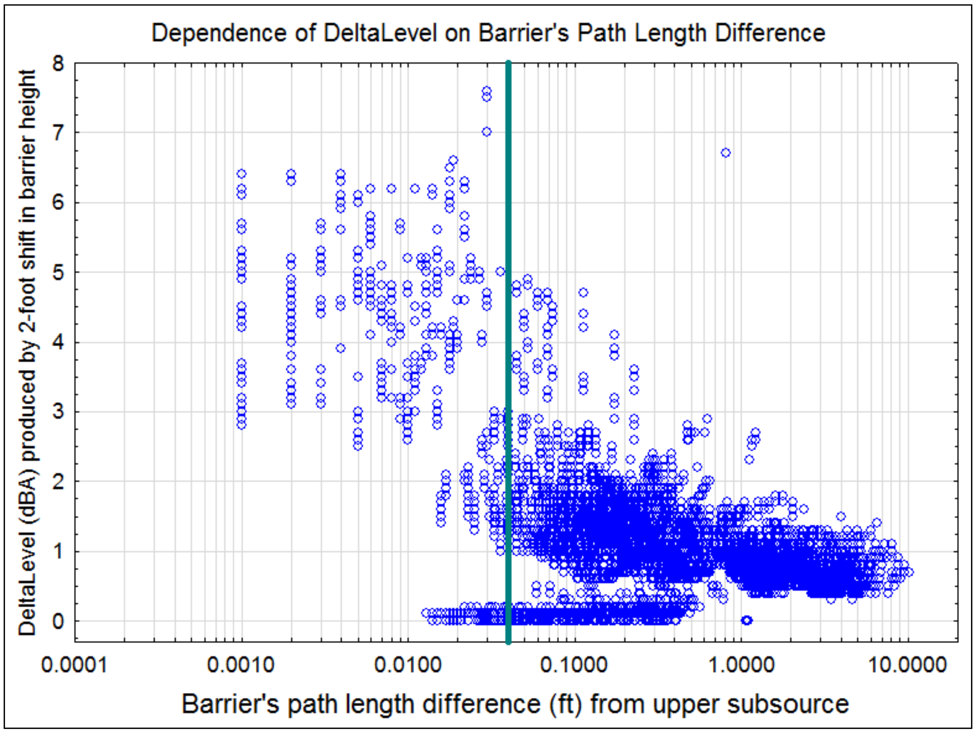

Figure 68 Dependence of DelLev on barrier's Path Length Difference

The series of "filtered" cobweb plots also shows that DelLev increases with decreasing source-receiver distance (dTotal). Figure 69 shows that dependence more explicitly. In particular, the very largest DelLevs happen only for the lowest source-receiver distances:

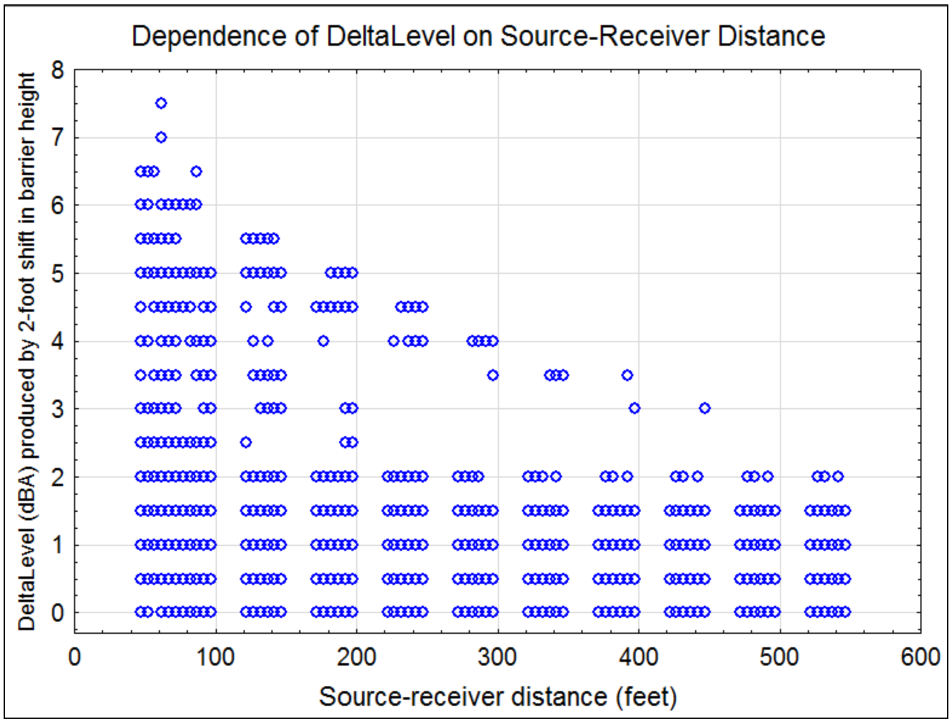

Figure 69 Dependence of DelLev on source-receiver distance

Various other strong patterns were sought, but none were found.

G.6.5 Introduction to Guidance

When a barrier just grazes the source-receiver line of sight, the resulting path length difference for the barrier is nearly zero. For this condition, the barrier attenuation can be highly sensitive to barrier height.

More specifically, when the path length difference (from the upper subsource height) is less than 0.04 feet:

- A 2-foot shift in barrier height can result in 2-to-8 dB shifts in barrier attenuation and therefore in receiver L_{eq}.
- Within this range, the shift is worse for small source-receiver distances:
  - 4-to-6 dB shifts are possible for source-receiver distances less than 300 feet
  - 6-to-8 dB shifts are possible for source-receiver distances less than 100 feet.
- This L_{eq} sensitivity occurs for all vehicle types.
- Over flat ground, such small path length differences occur only for low barrier heights (generally 8 to 10 feet). However, rolling terrain might lower barrier tops of tall barriers, relative to source and receiver elevations thereby producing this high sensitivity even for taller barriers.

G.6.6 Resulting Guidance for TNM input

When any lines-of-site, from upper vehicle subsources to receivers, closely graze a barrier top or berm top, we recommend extra care with TNM barrier input to precisely match (within one foot) barrier heights with physical reality (for existing barriers) and with intended construction heights (for future barriers).

In addition, where uniform-height barriers are planned on undulating terrain, we recommend the same input care for the terrain just under the barrier that is, for the Z-coordinates of the barrier's baseline input points. When recommending barriers to roadway designers, it is best to recommend specific "barrier-top elevations" than to recommend "barrier heights above the ground."

Another matter: These tests have shown very large L_{eq} sensitivity to the exact location of diffracting edges, whenever sound paths just graze across those edges. For those grazing situations, L_{eq} is also very sensitive to the slightest wind in the direction of propagation, which TNM does not consider.

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