TP 14103E

LOCOMOTIVE HORN EVALUATION:
Effectiveness at Operating Speeds

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June 2003

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by

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NOTICES

Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report.

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16. Abstract

This study assessed the placement and sound characteristics of locomotive horns. Its objective was to provide recommendations to ensure adequate warning for safety reasons and to address excessive loudness complaints from crews and from residents near tracks.

The scope of work involved laboratory investigations of desirable warning characteristics, field measurements of the influence of horn position on its effectiveness at operating speeds, and an in-service assessment of alternative horns. Safety effectiveness considerations included pedestrians/trespassers, drivers stopped at grade crossings, and drivers approaching grade crossings.

Recommendations are made to reposition horns in new-build locomotives and to add emergency-only or two-level horns at the front of some models of existing locomotives.

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16. Résumé

L'étude consistait à évaluer le positionnement et les caractéristiques acoustiques des klaxons de locomotives. La recherche visait à présenter des recommandations en vue de s'assurer que ce dispositif produit un signal d'avertissement adéquat aux fins de sécurité. Un deuxième objectif de cette recherche était d'étudier les plaintes de nuisance sonore présentées par les équipages des trains et les riverains des voies ferrées.

Les travaux comprennent des activités de recherche en laboratoire afin de déterminer les caractéristiques d'avertissement souhaitables de ces dispositifs sonores, des mesures sur le terrain de l'influence de la position du klaxon sur son efficacité aux vitesses d'exploitation des trains de même qu'une évaluation en service de systèmes d'avertissement sonore de remplacement. Pour ce qui est de l'efficacité sécuritaire des dispositifs, les chercheurs ont étudié les comportements des piétons et des intrus sur le domaine ferroviaire, des conducteurs de véhicules immobilisés aux passages à niveau et des conducteurs en approche d'un passage à niveau.

Des recommandations sont formulées pour revoir le positionnement des klaxons des locomotives neuves et pour que soient ajoutés des klaxons d'urgence ou des klaxons à deux niveaux, à l'avant de certains modèles de locomotives existantes.

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This study is a part of the Highway-Railway Grade Crossing Research Program, an undertaking sponsored by Transport Canada, major Canadian railways, and several provincial authorities. The program is a component of Direction 2006, a cooperative initiative with the goal of halving grade crossing accidents by 2006.

EXECUTIVE SUMMARY

The objective of this study was to study horn placement on locomotives and emitted sound, and provide recommendations to ensure adequate warning for safety reasons, while also addressing excessive loudness complaints from crews and from residents near tracks.

Test measurements indicate a wide range of performance of existing locomotive horns when measured at operating speeds. The sound output to the front of the locomotive (and particularly the higher frequency components) deteriorates with increasing train speed if the horn is not positioned at the front of the locomotive. Horns mounted behind and close to the engine exhaust hood performed much worse than at other locations. Horns in this position would not provide an effective warning to motor vehicle drivers approaching a grade crossing in many scenarios, and few drivers stopped at grade crossings would be alerted by this horn. Pedestrians would hear the horn, but the nature of the warning from this position is such that less cautious individuals might not consider it to be from a nearby train. Furthermore, they would have a lower perception of urgency than for the same horn mounted at the front of the locomotive.

The warning required for stopped vehicles with long clearance times is beyond the feasible limits of an auditory warning device if the train is travelling at high speeds. Similarly, the demands at passive grade crossings involving high speed on both road and railway approaches are beyond the feasible limits of locomotive auditory warning devices.

A number of desirable characteristics in an auditory warning device were identified and found to be available from the air horn technology currently used on locomotives. The horn's harmonic content is more important than its fundamental frequency. A broader spectrum improves the horn's detection in vehicles and its perceived urgency.

Community impacts can be mitigated without unduly compromising warning effectiveness. One option is to modify the existing fixed-distance warning sequence to a fixed-time warning. A second method is to use front-mounted two-level horns. With these horns, the normal rule-based warning would be sounded at a lower level and perceived emergencies would be responded to with the higher level. Other sound-focusing measures that might be effective in new-build situations were also explored.

In-cab noise considerations are the main constraint to positioning the horn in its most effective warning position. The optimal method of resolving in-cab noise problems requires analytic and experimental investigation, but adequate methods are believed to be available today. Resolving this issue to the mutual satisfaction of railways' management and workers should not prevent action from being completed by the 2006 target of the *Direction 2006* initiative.

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GLOSSARY OF ACRONYMS

ABS	Antilock brake system
ANR	Active noise reduction
DOT	United States Department of Transportation
EA	Enumeration area
FRA	U.S. Federal Railroad Administration
HUD	U.S. Department of Housing and Urban Development
ISO	International Organization for Standardization
LC	Labour Canada
Ldn	The *Day-Night Sound Level* describes the cumulative noise exposure from all events over a full 24-hour period, with events occurring between 10 p.m. and 7 a.m. increased by 10 dB to account for greater nighttime sensitivity to noise.
Leq(p)	The *Equivalent Sound Level* describes the cumulative noise exposure from all events over a defined time period (p). Also denoted as Lex(p).
Lex(8)	The cumulative noise exposure from all events over a defined time period of 8 hours.
LIRR	Long Island Railroad
Lmax	The *Maximum Sound Level* (or loudest part) of a single noise event.
LRC	Light Rapid Comfortable (train designation)
MSW	Minimum sound warning required for the conditions of a given scenario.
MWD	Minimum warning distance required for the conditions of a given scenario.
NDI	The noise depreciation index, which is the percentage reduction of house price per dBA above some base.
NTSB	U.S. National Transportation Safety Board
OSH	Occupational health and safety
RAC	Railway Association of Canada
SEL	The *Sound Exposure Level* describes the cumulative noise exposure from a single noise event for its entire duration. In calculating SEL, the noise exposure is normalized to a time duration of one second so that different noise events can be compared in terms of their sound energy.
S/N	Signal-to-noise ratio
S/M	Signal-to-mask ratio, where the mask is the effective masking influence that background noise has on human hearing.

SPL	Sound pressure level measured in decibels (dB) with respect to a reference level of 20 micropascals.
SPL (dBA)	The *A-weighted Sound Pressure Level* in noise at any moment in time.
SPL (dBC)	The *C-weighted Sound Pressure Level* in noise at any moment in time.
SPL (dBL)	The unweighted or linear *Sound Pressure Level* in noise at any moment in time.
TSB	Transportation Safety Board of Canada
WCE	West Coast Express commuter railway between Mission and Vancouver, British Columbia.

1. INTRODUCTION

1.1 Background

On July 12, 1996, a Via Rail passenger train struck and fatally injured a pedestrian in the Town of Tecumseh, Ontario. The victim's sister was also present, but she managed to avoid the oncoming train. The Transportation Safety Board of Canada (TSB) investigated this occurrence and presented its findings and factors that contributed to this accident [TSB, 1996].

In addition to numerous contributing factors, the TSB concluded that the sound of the locomotive horn of the approaching train did not become audible in time for the pedestrian to localize its source, decide on a course of action and execute the action to avoid the oncoming train. TSB tests showed that the sound intensity of the horn did not exceed that of the background noise (about 55 dB) until five seconds before the train passed. The TSB considered that the following additional factors might also have reduced the effectiveness of the locomotive horn as a warning device:

- *Competing sounds in the environment that can mask the auditory warnings or fail to attract the attention of the listener, or both (e.g. occurrence site is in direct line with one of the flight paths to Windsor Airport).*

- *Day-to-day exposure to the auditory warning of the locomotive horn may have diminished its ability to actively draw the attention of the pedestrians to the approaching train.*

- *The location of the horn on the Via train, midway back on the top of the locomotive, recessed below a barrier and directly behind the exhaust stack, does not optimize the intensity of forward-projected sound (but is within Federal Railroad Administration standards of 96 dB, and alleviates noise within the locomotive cab).*

- *Attenuation of sound from the locomotive horn caused by winds toward the train might have delayed the detection and identification of the locomotive horn by the pedestrians.*

- *Localization of the train may have been compromised by the relative location of the pedestrians and the train. The train was directly behind the pedestrians, creating an auditory environment in which humans are notably poor in localizing sound sources, particularly sounds composed of frequencies below 7,000 Hz.*

The TSB stated, as part of its conclusion:

> *Current federal regulations do not set requirements either for the sound frequencies generated by locomotive horns, or for the amount and pattern of acoustical energy that must be present at specified distances omnidirectional from a stationary or moving locomotive.*

It also raised the following safety concern:

> *It is also noted that the frequency of the horn evolved from the requirement to sound similar to a steam whistle and that the horn placement has been dictated by crew considerations. The Board is concerned that the lack of a comprehensive approach toward the requirements of the locomotive horn has compromised its effectiveness as an adequate warning device. The Board recognizes that there are various constraints that must be taken into consideration before any change can be made to the "traditional" horn design, e.g. familiar (identifiable) sound, cab noise level, urban anti-noise issues. An alternative approach might be the development of an auxiliary auditory warning for use only in emergencies. Such a warning could be of far-reaching intensity, and emit an attention-gathering modulating sound at high frequencies.*[1]

As noted above, Transport Canada's existing locomotive horn regulation states that it should sound like a steam whistle. While the Canadian railways generally follow practices that exceed the Federal Railroad Administration (FRA) regulations for locomotive horns (96 dBA at 30.5 m), the FRA has posted notice of a proposed new rule for locomotive horns [Federal Register, 2000]. The proposed rule is discussed in more detail in Section 5.3. The notice as posted in the *Federal Register* is shown, in part, in Appendix A.

In light of these activities and the ongoing work of the Railway Association of Canada (RAC) to prepare draft regulations for locomotive horns, Transport Canada has asked that the issues of auditory warning effectiveness be reviewed. In cooperation with the Canadian railways and under the aegis of Direction 2006, Transport Canada initiated this review.

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[1] In a report by the Chief Coroner for Ontario concerning the same accident, it was recommended that "VIA Rail Canada Inc. install an audible emergency warning device which differs significantly from the existing level crossing whistle on all its passenger locomotives. This additional device should automatically engage upon application of the emergency brake."

1.2 Focus of, and Exclusions from, this Review

In developing its regulations, the RAC has raised the question of whether higher speed passenger trains should have different specifications. One impetus for the question is the elevated trespasser and grade crossing collision rate associated with passenger trains. The TSB [1996] noted that, for the Canadian trespass accidents reported to it over the period 1992 to 1997, passenger trains had a higher accident rate than freight trains—the VIA Rail average rate (per million train-miles) was 2.71 compared with a freight (and other) rate of 1.2.

Thus, our focus is on high-speed trains, which have a more demanding requirement on horn performance. VIA Rail's particular interests as noted in the request for proposals and reflected in our conduct of the study are:

> *....concern about developing revised locomotive horn specifications that do not address the issues raised by the Tecumseh incident (TSB, 1996). VIA Rail has expressed the need to research further how to provide more effective audible warning, especially in the case of imminent danger. It has suggested that the work include:*
>
> - *The optimum location and sound level of the current horns, considering the forward projection of the warning signal as well as noise levels in the cab.*
> - *The potential benefits of modifying the current horn frequencies.*
> - *The potential benefits of alternative audible warning devices for imminent danger situations, as currently used on emergency vehicles.*
> - *Those factors identified by the TSB, such as noise level above ambient and reaction time at passenger train speeds (TSB, 1996).*

One of the alternatives that has been assessed in the U.S. is the installation of wayside horn systems. While we are not including wayside horns in our review, some observations are made in Appendix B on aspects of the work done to date.

The steering committee also eliminated non-train-sound alternatives from this review. While the application of non-conventional alternatives might lead to long-term safety advancement, there would be definite short-term risks if people do not recognize the alarm as coming from a train. We note that there is considerable room in the existing horns' spectra to consider focusing more on some horn characteristics than others.

Another facet of on-board alerting systems that was included in this project was visual alerting systems. However, the U.S. railroads have been using various forms of auxiliary lighting systems for some years now. We found that the U.S. FRA conducted evaluations of strobe lights and other light systems to raise the conspicuity of a locomotive [Carroll, et al., 1995] and subsequently introduced a regulatory requirement (see Appendix C for additional details). The ditch lights used on most Canadian locomotives already meet the FRA requirement. One issue still being addressed by the FRA is the relative benefit of flashing versus steady burning lights. We do not believe that additional insight would be gained by undertaking further testing in Canada. However, we recommend that Transport Canada monitor the FRA's progress in its assessment of flashing versus steady burning lights. It might also be desirable to assess U.S.

grade crossing accident data in a time series analysis of before/after the switch to strobe light or ditch light usage.

1.3 Objective

Within the stated focus, the objectives of this study are to:

> *Study horn placement on locomotives and emitted sound, and provide recommendations to ensure adequate warning for safety reasons while also addressing excessive loudness complaints from crews and residents near tracks.*

1.4 Report Layout

The remainder of this report is divided into six sections.

In Chapter 2 we present key issues that were identified in our review of the literature and available test data.

In Chapter 3 we develop our criteria for assessing auditory warning device effectiveness and report on detection and urgency experiments.

In Chapter 4 we present our findings with respect to the influence of train speed and horn position on horn effectiveness.

In Chapter 5 we present safety requirements and compare them with horn characteristics.

In Chapter 6 we present our evaluation of alternative horns with respect to safety, community impact and in-cab noise levels.

In Chapter 7 we present our conclusions and recommendations.

2 DEFINITIONS AND CONCEPTUAL ISSUES

2.1 Basic Definitions

In this section we provide the basic definitions of terms used to describe a locomotive horn's characteristics. We offer definitions of other terms as they arise.

Sound measurement is typically made with instruments that measure pressure variation. Sound pressure level (SPL) is usually measured with respect to a reference level (Pref) of 20 micropascals. People's perception of loudness is not linear. An SPL measurement (Pmeas) is usually related on a log (base-10) scale in decibels (dB) where:

SPL (dB) = 10 LOG(Pmeas / Pref).

Because sound is measured on a log scale, each 3 dB rise relates to a doubling of sound level (i.e. 10 LOG(2) ~ 3). However, it takes a sound level increase of approximately 10 dB before someone will subjectively perceive a doubling of loudness.

A sound signal can be characterized by the relative magnitude of its underlying pure-tone frequency components. Locomotive horns can be characterized within the frequency range (or spectrum) of its lowest fundamental frequency (311 Hz for most Canadian locomotive horns) up to the 7th harmonic (or overtone) of its highest fundamental (i.e. 7 X 622 = 4,354 Hz for a 5-flute horn).

The human ear does not perceive all frequencies equally, and sound measurement is often "adjusted" to reflect the way the human ear interprets sound. An A-weighted sound level, abbreviated "dBA", indicates that the sound has been filtered to reduce the strength of very low and very high frequency sounds, much as the human ear perceives sounds of low intensity. Without this A-weighting, noise-monitoring equipment would respond to noise events people cannot hear, such as high-frequency dog whistles and low-frequency seismic disturbances. Where spectral measurements are taken, a linear scale is often used; however, only the frequencies of interest are included in the subsequent analyses.

Sound frequency is also usually related on a log scale. A doubling of frequency represents a change of one octave. To characterize a sound's frequency spectrum, its SPL is aggregated within a specified bandwidth and referred to as the centre point of each band. Sound level meters and much of the literature describe sound measurements on the basis of octave or 1/3-octave bands. We use bandwidths of 1/3 octave for most of the measures in this report.

2.2 Issues

The principal issue in assessing locomotive horn effectiveness is the resolution of the apparent contradiction of findings from different studies. Analytic and sound measurement studies have found a locomotive horn to be an ineffective warning device. On the other hand, some accident studies found that whistle bans lead to increased accident risk.

2.2.1 Auditory Warning Device Limitations

Many sound measurement-based studies have found auditory warning devices in general and locomotive horns in particular to be ineffective. A 1986 study by the National Transportation Safety Board [NTSB, 1986] considered 75 collisions between passenger/ commuter trains and motor vehicles at grade crossings. It found that in 27 cases the train's audible warning system was ineffective because of either high ambient interior noise levels of the vehicle or noise levels caused by vehicle engines. The fact that the occupants of the vehicles could not hear the audible warning system of the train indicated to the NTSB that the existing audible warning system was inadequate as a primary warning system. The NTSB concluded that locomotive horns should be improved to better address the audibility concern.

The role of the locomotive horn was also included in a more recent NTSB [1998] safety study of passive crossings. It reviewed 60 accident investigations that occurred at passive crossings. The locomotive horn was known to have been blown in 55 of the cases. Interviews with surviving drivers were possible in 18 cases. Of these, the horn was sounded in 14. Yet only two drivers reported hearing the horn from inside their vehicle (two other drivers were already outside of their vehicle when they heard the horn).

The NTSB also undertook field measurements of a locomotive horn, which was set at the FRA regulatory requirement of 96 dBA at 100 ft. Under stationary test conditions at 100 ft., it found the following:

> *Safety Board measurements determined that in one test vehicle (a 1997 Thomas/Ford school bus) the sound level of the train horn was not audible above the noise level of the idling engine. In seven test vehicles, the sound level was not audible above the idling engine and fan noise. In no test vehicle that had both the engine idling and the fan operating did the train horn provide the 10 dB above ambient noise level necessary to "alert" a motorist to the train.*

The NTSB concluded that:

> *for drivers of some highway vehicles on the road today, the sound of a train horn 100 feet away is not sufficient to penetrate the vehicle shell and to alert them to the presence of a train.*

At the NTSB's public forum, an audiologist testified that:

> *more emphasis than is presently being given, [should] be given to the fact—not the idea, but the fact— that horns are not and cannot be audible under many circumstances.*

Aurelius and Korobow [1971] conducted early investigations of a range of locomotive horns in use at the time (including a Hancock whistle, a 156 Hz single-flute air horn, a number of different two- and three-flute air horns, and a 5-flute air horn). The tests of auditory alerting requirements and required warning distances are discussed in more detail later in subsection 5.2.3. On the basis of meeting the required alerting sound levels for all of the individuals tested, and using the average output sound level of all horns tested, they found that the available sound level fell short for all speed combinations. The shortfall ranged from -2 dB at 30 mph for trains and motor vehicles to -22 dB at 70 mph for trains and motor vehicles. The study concluded that:

> *Railroad horns [as designed now] cannot reliably warn motorists when either the train or motor vehicle is going [faster than] 50 mph.*

Researchers have made similar findings for emergency vehicle sirens. Caelli, et al. [1980] through in-vehicle tests demonstrated the difficulty drivers have in localizing sirens. The most common error was overestimation of distance, which occurred for all directions and extended up to a factor of two times the actual distance. Another frequent error was direction reversal when the siren was behind or in front. To be effective, a siren signal (like a locomotive horn) must compete with the masking noise generated by the road, car radios and ventilation fans, and must overcome modern sound insulation techniques. A U.S. Department of Transportation (DOT) report (Skeiber, et al., 1977] assessed the average signal attenuation of a siren's effective frequency range through closed-windowed automobile bodies and including typical masking noise. Their analyses found that the maximum effective distance at urban intersections was only 8 to 12 m (26 to 39 ft.). Only modest improvement in the situation occurred at suburban intersections and straight-ahead highway conditions. The DOT report concluded that sirens would never become effective warning devices.

2.2.2 Accident Prevention Studies

In spite of the limitations of auditory warning devices, studies of accident data have found that completely eliminating the use of locomotive horns at some grade crossings adversely affects safety. The FRA [U.S. DOT, 1990] published the results of a time-sequence study that examined the accident experience at Florida East Coast Railway Company and CSX grade crossings affected by Florida's bans on the use of locomotive horns. The FRA [U.S. DOT, 1995] subsequently published the results of a cross-regional study examining the same issue on a nation-wide basis. This study indicates that at crossings where horn bans were instituted (more than 2,000 crossings), the occurrence of accidents increased.

The FRA found that accidents were reduced when horn use was resumed at crossings with previously imposed whistle bans. Specific results varied—Florida decreased by 69 percent, and 12 other case studies covering 8 states other than Florida saw the accident rate decline by an average of 38 percent. The results applied equally to nighttime-only whistle bans and 24-hour whistle bans.

In a recent update [U.S. DOT, 2000] to its nation-wide study, the FRA pointed out problems with the underlying data in the Chicago area (see Table 1). As can be seen in the table, a 100 percent normalized average increase in accidents is attributed to whistle bans (nation-wide, with the exclusion of the Chicago area). Other parts of the report indicate that when only fully automated crossings (i.e. with gates) are considered—since whistle bans only involve automated crossings—and more recent data are used, the average increase is 66 percent.

Table 1 U.S. comparison of crossing accidents with and without whistle bans

APF Group	Without Whistle Bans			5-Year Whistle Ban			% Increase with Ban	Normalized Increase %
	Number of crossings	5-Year Accidents	Accident Rate	Number of Crossings	5-Year Accidents	Accident Rate		
A	29,132	683	0.0234	90	5	0.0556	137.0	113
B	35,173	1,287	0.0366	104	7	0.0673	83.9	80
C	20,022	1,390	0.0694	141	18	0.1277	83.9	108
D	20,477	1,945	0.0950	142	26	0.1831	92.8	120
E	11,429	1,661	0.1453	118	38	0.3220	121.6	131
F	6,580	1,207	0.1834	111	47	0.4234	130.8	133
G	5,780	1,422	0.2460	124	40	0.3226	31.1	35
H	3,477	1,048	0.3014	103	53	0.5146	70.7	66
I	3,039	1,101	0.3623	100	73	0.7300	101.5	93
J	1,572	734	0.4669	63	91	1.4444	209.4	129
Total	136,681			1,096	10 Group Average >		104.23	99.79

U.S. nation-wide data excluding Chicago, 1989 to 1993, all types of active crossings, excluding collisions with sides of trains, collisions with vehicles without drivers and pedestrians struck.
Source: [U.S. DOT, 2000]

Transport Canada [1995] also published the results of a study of the safety effect of whistle bans at about 400 crossings in Canada. The study had problems deriving statistically significant estimates for the small number of crossing accidents involved. It found that elimination of whistling at active crossings without gates, and with no counterbalancing safety measures, increased the vehicle collision rate by between 24 percent and 82 percent, and increased the pedestrian-at-crossings collision rate by 50 percent. These findings were for the time period before 1989, at which time Transport Canada changed its guidelines to ensure other risk criteria were met before whistle bans were granted. The analysis of data for the after period (1989 to 1995) could not reach statistically significant impacts on crossing risk—accidents rates were found to be altered within a range of -70 percent to + 47 percent. The results for active crossings with gates differed from the U.S. findings in that the Canadian data showed no change in accident risk associated with whistle bans where gates were used.

It is difficult to rationalize the significant impact of whistle bans against the findings of ineffective alerting sound levels identified in studies of locomotive horns and emergency vehicle sirens. With respect to the NTSB's horn tests conducted at the regulatory 96 dBA output at 30.5 m (100 ft.), we note that most railways operate with higher output levels than the 96 dBA regulatory minimum. Nonetheless, there is general agreement that auditory warning devices have limitations and cannot be depended on in all circumstances. While pursuit of why a horn is effective might seem to be an academic exercise, it is important to determine when and why horns are effective in order to devise the best characteristics for a locomotive horn for those situations where it is effective. Understanding its limitations is also necessary to identify possible modifications to the environment and/or education themes for the public in situations where it cannot be effective.

2.2.3 Issues and Data Gaps Addressed in this Report

From our review of the literature we believe that the empirically demonstrated effectiveness of existing locomotive horns must be due to the fact that drivers either:

a) are alerted at lower signal-to-noise (S/N) ratios than many have assumed or
b) require less warning time/distance than many have previously assumed.

In addition to the basic question of the effectiveness of an auditory warning device, our initial literature review identified limitations in the basic characterization of locomotive horns. We noted that Labour Canada (LC) sound measurement tests [Seshagiri & Stewart, 1991] found that the SPL measurements for the locomotive when approaching at 40 mph were all lower than the SPL measurements made over the same distance range for a stationary locomotive. The finding raises the question of whether train speed affects a horn's output level. Also related to speed influence, the TSB's review of the Tecumseh fatality [TSB, 1996] raised the question of whether the warning quality of the horn was influenced by its position on the locomotive when travelling at high speed. In assessing cause, the TSB noted:

> *The ineffectiveness of the locomotive horn as a warning device was a result of some combination of factors related to the attention-demanding qualities of the horn, as well as its forward-projecting intensity in the existing circumstances.*

The issues of signal detection and urgency were addressed with laboratory experiments conducted at the auditory labs of the Psychology Department of Queen's University and are discussed in Chapter 3. The horn characterization task and interaction of horn position and train speed as they influence the horn's performance are addressed via pass-by sound measurements of revenue service trains and are discussed in Chapter 4. The question of warning time/distances is addressed as part of our safety performance assessment in Chapter 5.

3 SIGNAL DETECTION AND ASSOCIATED URGENCY

3.1 Insights from the Literature

Where standards have been developed for auditory warning devices they have been quite demanding. The American National Standards Institute (ANSI) [1978] recommendations for immediate evacuation signals state that:

- *The signal level should be 10 dB above the maximum overall typical ambient noise and at least 75 dB everywhere evacuation is considered essential.*
- *The fundamental should be below 1,000 Hz and the modulation rate should be less than 5 Hz.*
- *If levels greater than 115 dB are required, consideration should be given to the use of visual alerting signals.*

Other standards do not specify a sound level but do call for relatively high S/N ratios. Byrne and Driscoll [1998] summarize the International Standard (ISO 7731, 1986) that defines criteria applicable to the recognition of auditory danger signals, especially for high ambient noise areas. Guidelines are given in this standard for sufficient audibility based on overall A-weighted sound level readings, octave band analysis, or 1/3-octave band measurements. Using the A-weighting scale, the signal should exceed the level of ambient noise by 15 dB or more. When using octave band analysis, the alarm signal must be at least 10 dB greater than the employee's masked threshold in one or more octave bands between 300 and 3,000 Hz. If 1/3-octave band levels are used, the alarm signal must exceed the masked threshold by a minimum of 13 dB in one or more 1/3-octave bands in the frequency range 300 to 3,000 Hz. The alarm signal should be based on the 300 to 3,000 Hz frequency range, with sufficient energy below 1,500 Hz to meet the needs of individuals with hearing loss. Temporal characteristics of the alarm signal are also discussed in the ISO Standard. Pulsating signals are preferred over signals that are constant in time. A repetition frequency range of 0.2 to 5 Hz is specified.

Abrams and Lipscomb [1996] note that the human ear can detect signals in the 2.5 to 3 kHz region at an SPL of 6.5 dB, while recognition of a broad spectrum signal requires 3 to 8 dB above the detection threshold. Drawing on the findings of Skeiber, et al. [1977] and Fidell [1978], they note that full alerting to a response requires 9 to 10 dB above detection.

Skeiber, et al. [1977 and 1978] tested 24 licensed drivers in a vehicle simulator in a realistic driving scenario. Siren signals were introduced at increasing loudness until the test subjects applied the brakes. The action-response S/N ratios were noted in each case. The average response level S/N ratio for the most readily detected siren source was 12.4 dB. The authors note that the response level (indicates recognition of the signal and alerting to action) was on average 9 dB above the simple detection level. The response S/N levels for the four subjects over 60 were only 1.1 dB higher than for the other 20 subjects under 29. In comparing the various siren signals, the high-low sound was found to be least effective. The authors believe that this was due to the masking of lower frequency by in-auto background noise and concluded that frequencies below 1,000 Hz were largely wasted.

Fidell and Teffeteller [1981] assess the effect of the level of concentration in other tasks on signal detection. Detection levels of intruding sounds in the presence of background noise had an average S/N (for the highest difference 1/3-octave band) of 14.2 dB. Previous experiments not involving a foreground task led to average detection ratios of 3.6 dB.

3.1.1 Detection at Negative S/N Ratios

Rapoza, et al. [1999] offer an explanation of the conflicting views of horn effectiveness with a signal detection theory model of whistle effectiveness at grade crossings. They draw from the unpublished thesis of Wilson [1983] in developing a detection model for locomotive horns. Wilson found that the required S/N ratio must be present in at least two octave bands for horn signal recognition. Rapoza, et al. conducted their analyses on the basis of the required S/N ratio being exceeded in at least five 1/3-octave bands. The S/N thresholds required to explain the findings of previous accident-based horn effectiveness studies led to a 50 percent probability of detection at +5.2 dB for passive crossings and -5.2 dB for active crossings.[2] On this basis, they found that warning distances that satisfy highway design standards for brake reaction time (2.5 s) and braking rates (approximately 0.35 g) would be achieved by at least some horn types. As noted, their explanation depends on being alerted with negative S/N ratios.

We did find research supporting the viability of negative S/N ratios. Corliss and Jones [1976] identify a number of earlier experimental investigations that show that the ear is an effective filter that can select an organized signal from a chaotic background even though it exceeds the power of the desired signal by an order of magnitude. They developed a communications theory model of the behaviour of the ear in detecting signals under conditions of background masking noise. Just as the ear is better at sensing sounds in the 1 to 6 kHz range, it is better able to filter out noise in this range. They demonstrate that their model provides a good fit to previous experimental data of S/N detection ratios over the human ear's frequency range (the data provide S/N ratios of -15 to -30 dB over the frequency range 100 Hz to 10 kHz).

Figure 1 compares the human ear's audibility threshold in the absence of noise with its audibility threshold (as derived from Corliss's model) for organized signals in the presence of a broad spectrum masking noise.[3]

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[2] We note that the background noise for both crossing types was associated with a 50 km/h vehicle speed. For those active crossing collisions associated with drivers deciding to go through after stopping their vehicle, the background sound level would be lower and the S/N ratio thereby elevated.

[3] In applying Corliss and Jones's model, we have taken noise and signal measures referenced to 20 micropascals rather than to the audibility threshold that they adopted. We interpret their statement that the auditory threshold should be added to the S/N to mean that it must be considered an additional constraint rather than the literal interpretation that it be added directly to the result.

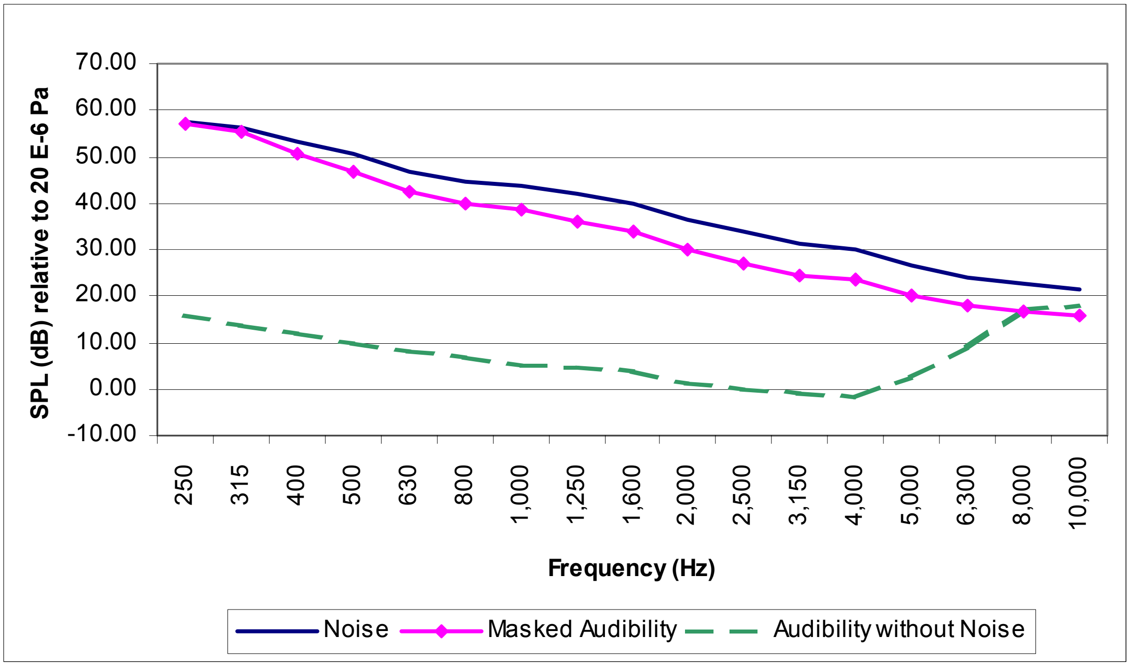

Figure 1 **Effect of background noise on audibility (Corliss's model)**

It is important to note that Corliss's model defines audibility, which is clearly frequency dependent. An S/N ratio of 0 dB at the 1/3-octave band centre frequency of 250 Hz would be at the audibility threshold predicted by their model, while an S/N ratio of -6 dB would be at the audibility threshold for frequencies above 1.6 kHz. The results are similar to those reported by Zwicker and Fastl [1990] for detecting tones in critical bandwidth noise (Zwicker's results were -2 dB, -3 dB and -5 dB or 250 Hz, 1,000 Hz and 4,000 Hz, respectively). Neither model considers a nonlinear noise characteristic such as the interior of an automobile, where the ''upward spread of masking''[4] influence could be relevant. This effect is explored in more detail in subsection 3.2.2.

3.1.2 Loudness Threshold Levels

While Corliss's model predicts detection at negative S/N ratios for most of the frequency range, they assume that actual identification and understanding of a multi-frequency signal would require a minimum signal intensity equivalent to normal conversation at 1 m (65 dB in a quiet ambient). Thus, even though a 1 kHz signal would be at the threshold of audibility with a negative S/N ratio in the presence of the assumed background noise, they predict that +12 dB would be required for recognition and alerting to the signal.

We note that if their second assumption were true, locomotive horns would seldom, if ever, alert drivers of highway vehicles. We do agree that the specification of both a minimum S/N ratio and

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[4] The upward spread of masking is a hearing phenomenon that has been known for many decades. It describes the fact that lower frequency noise can have a stronger masking influence on a pure tone than higher frequency noise. The effect is counterintuitive since the auditory threshold of lower frequencies is higher than for high frequencies.

a minimum loudness SPL are required to assess/predict a horn's effectiveness. In low noise conditions the threshold SPL becomes the governing criterion. For example, the masking noise levels in an automobile drop below 40 dB for frequencies beyond 1 kHz. If one assumes that the equivalent of 65 dB in a quiet ambient is required for alerting, then low S/N detection levels in automobiles would have no relevance. The question is whether 65 dB or higher is required for alerting.

There is research support for lower alerting thresholds. Experiments with fire alarm systems have found sound levels of 55 dB and lower to be effective. Nober, et al. [1983] conducted three sets of experiments with household fire/smoke alarms. In the first experiment 30 sleeping subjects were subjected to audible alarms—10 each to 55 dB, 70 dB and 85 dB. On average, those exposed to 55 dB awoke in 14 seconds, while those exposed to 70 dB awoke in 10 seconds and those to 85 dB in 7 seconds. In a second experiment, 55 dB and 70 dB signals were used in the presence of background air-conditioning sounds of 51 dB. The 55 dB group awoke in 43 seconds, while the 70 dB group awoke in 19 seconds. While the results indicate the advantages of a louder signal, the lowest signal tested (55 dB) is still effective. Also, experimental work of Haas and Edworthy [1996] found 40 dBL to be the alerting threshold for alarm signals. We explore this work in more detail in Section 3.3.

The experimental data of Aurelius and Korobow [1971] tends to support an alerting S/N level over a fairly broad range. Seventeen subjects participated in actual driving sessions with sound recordings of different locomotive horns played from an exterior speaker. Output was introduced for 2.5 seconds and replayed at random intervals and loudness (5 dB steps). Data were analyzed over a range of speeds and three vehicle types. The prime measure was the sound level (measured outside the vehicle) at which the driver was first able to detect a signal. The measured mean signal-alerting level outside the car was about 87 dB. If insertion loss ratios of 30 dB existed,[5] then sound levels of 57 dB were adequate for half the test subjects and many were alerted at lower values (the standard deviation was 6 dB). Figure 2 presents an interpretation of Aurelius and Korobow's data for three speed ranges on the assumption that the underlying data followed a *Normal* distribution.

While the data distribution was not reported, the reported range and their use of the data indicate a *Normal* distribution. We note that the response distribution derived by auditory researchers in tests of alerting response also follow *Normal* distributions [Green & Swets, 1966].

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[5] Insertion loss was not measured, but 30 dB is typical for the measurements made by Rapoza, et al. [1999] in the horn frequency spectrum.

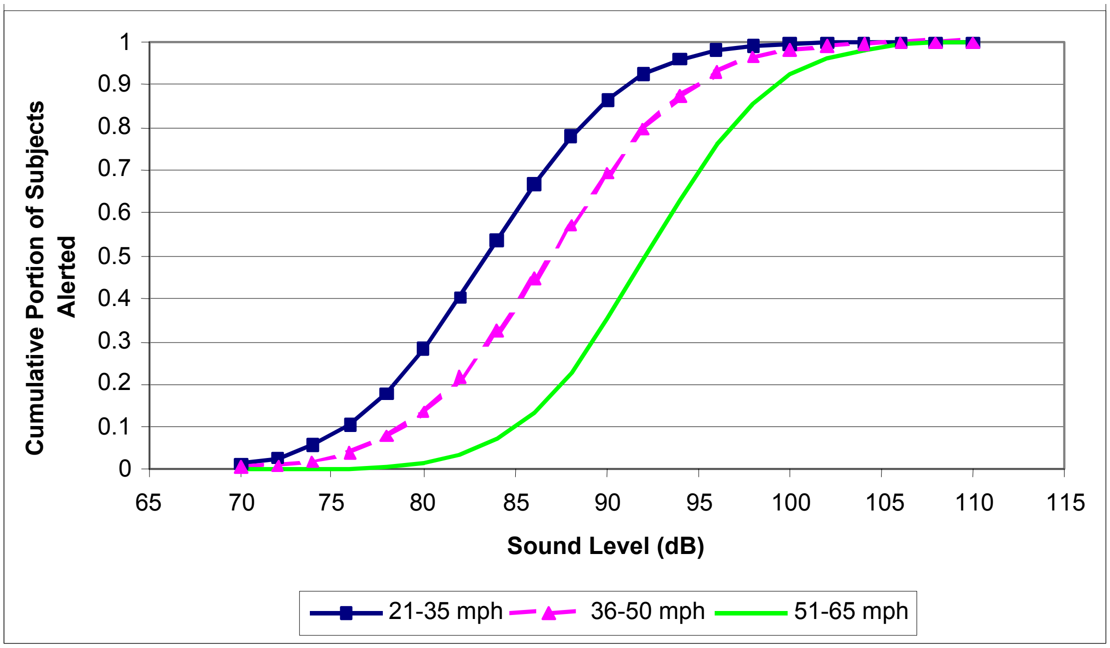

Figure 2 **Aurelius's alerting sound levels required outside vehicles**

Some of Aurelius's other findings of interest were:

- radio music added about 4 dB to detection levels, conversation added 0.5 dB.
- the newest and quietest vehicle had the lowest detection levels.

The fact that the quietest vehicle had the lowest detection level is important since it was a 1970 vehicle and today's vehicles are quieter than it would have been. The insertion loss for a horn sound is dictated by the glass windows, which have not significantly changed. The engine noise, tire noise and aerodynamic noise have all been reduced through better lower-body noise insulation and aerodynamic body design. Thus, newer, quieter vehicles would likely realize even lower detection levels than those observed in 1970 vehicles.

While windows were closed for all tests, a key variable not denoted is the fan speed—although the newest vehicle was reported to have air conditioning (whether it was used was not reported). All non-control conditions were described as normal driving, so we presume that the fan was operating in all cases.

3.2 Signal Detection Experiments

While the auditory model of Corliss and Jones has direct relevance to in-vehicle signal detection, it is based on uniform (flat) noise data. The phenomenon of 'upward spread of masking', whereby low-frequency noise can mask higher frequency signals, is widely accepted. The International Organization for Standardization (ISO) recommends an upward spreading mask influence of -7.5 dB per octave [ISO, 1986]. As can be seen in Figure 3, the -7.5 dB/octave rate closely follows the car noise characteristic measured by the Volpe Center [Rapoza, et al. 1999]. However, assessments of signal detection in downward sloping noise characteristics have raised the question of whether the 7.5 dB rate is too conservative [Robinson & Casali, 1999]. Therefore, we undertook laboratory experiments to assess signal detection levels in a downward sloping vehicle noise characteristic, and also tested several models of human hearing.

3.2.1 Experimental Results

The objective of the signal detection experiment was to assess S/N detection levels of pure tones in a noise environment consistent with in-vehicle background noise. The in-vehicle noise level adopted in the experiments was the average of 14 vehicles tested by Rapoza, et al. [1999]. The noise SPL versus frequency characteristic is downward sloping, as illustrated in Figure 3.

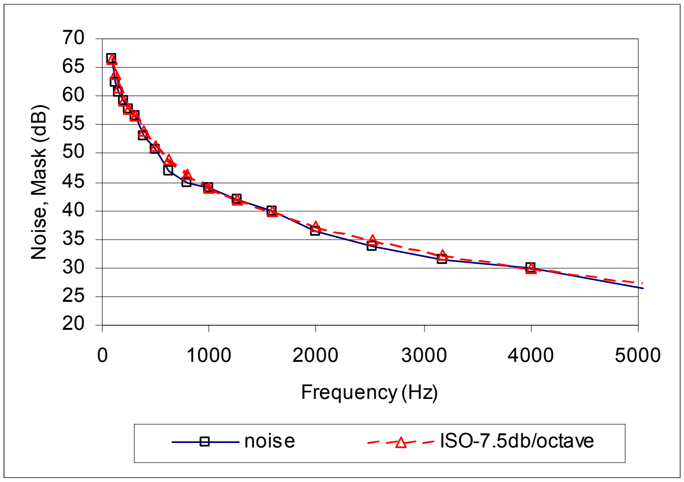

Figure 3 Noise and ISO masking curves

The signal detection experimental procedure and results are presented in Appendix D. The S/N detection levels that resulted in our experiment were lower than expected (-6 to -12 dB was achieved, while 0 to -6 dB was expected). The laboratory results were further explored with limited in-vehicle tests. The in-vehicle tests were conducted with an idling vehicle and an external, single-tone signal. The in-vehicle results showed an S/N relationship of similar shape but not as low as the laboratory experiments.

Larger temporal variation of the laboratory noise might have contributed to the lower signal detection thresholds achieved there. Noise involves some level of random variation over time. The background noise used in the experiment was calibrated in magnitude to an average of automobiles at 50 km/h. The signal tones were of a constant magnitude, while the noise involved short-duration random variation of intensity. In comparing the software-generated noise signal with an actual recording of in-vehicle noise, we found that the 1/3-octave SPL variation over 50 ms of the simulated signal was much higher than the recording (about +/-6 dB compared with +/-3 dB for the actual). The ear is able to detect signals of 20 ms duration and thus the temporal variation of the laboratory noise might explain the low S/N levels that were observed in our experiment.

The proposed explanation of why detection levels were lower in the lab than in-vehicle tests highlights the importance of another sound characteristic. It is important to have constant tones in an auditory warning device to achieve detection in a time-varying noise environment. We also note that music and conversation have higher short-term variations than the base noise components of a moving vehicle.

Another finding of the in-vehicle tests was the sensitivity to head position and orientation. Standing waves were evident for the 562 Hz tone such that a short lateral shift of head position would dramatically change the S/N detection level. Measurements with a sound level meter confirmed that the signal changed by 20 dB over the lateral shift of 15 cm. Signal detection of frequencies higher than 2,500 Hz was significantly affected by head orientation, a result that was also evident in the laboratory tests. The test experience led to two conclusions:

1. Individual observations within the same vehicle can produce significantly different results, making it difficult to draw general conclusions.
2. A signal composed of many frequencies has a better chance of being detected than a signal with a few frequencies.

Figure 4 illustrates the combined results of in-vehicle and laboratory testing.

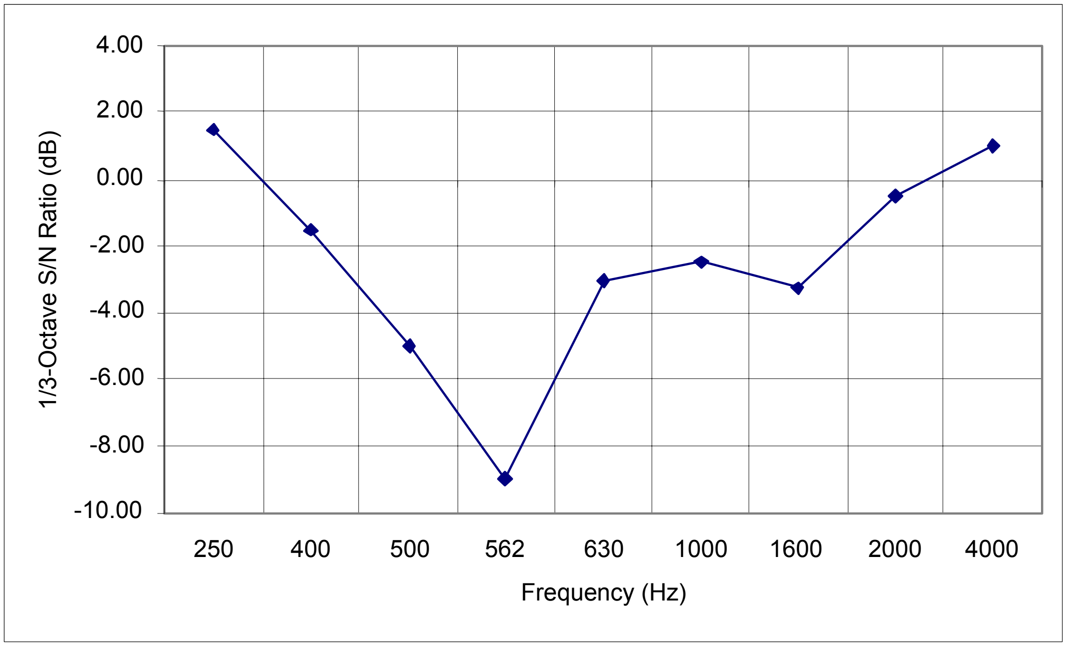

Figure 4 Average of laboratory and in-vehicle detection

In comparison with Corliss's model and Zwicker's data (discussed in subsection 3.1.1), two observations stand out:

1. The S/N detection levels are better than predicted at lower frequencies and worse than predicted at the high frequencies.
2. There is an apparent "sweet spot" at 562 Hz.

There are possible explanations for the findings. The higher frequencies could be affected by an upward spread of masking from the lower frequencies. The better than predicted S/N detection at lower frequencies could be a combination several factors. Equal loudness contours were shown by Robinson and Dadson [1956] to drop by 5 dB at 500 Hz in the 40 to 70 dB range relative to the shape at auditory threshold. The inter-aural phase differences of binaural hearing favour lower frequencies (Zwicker & Fastl, 1990). We note that the experimental setup consisted of a lateral signal with an enveloping noise. The particular inter-aural phase differences associated with tones in the laboratory (and vehicle) tests represent only one of many possible head orientations. The head positions and related inter-aural phase differences for actual horn signal warning situations would vary greatly, and thus we put less emphasis on the lower frequency S/N results.

3.2.2 Auditory Signal Detection Model Selected

The experimental results confirmed that detection exists at negative S/N ratios within the vehicle noise characteristic. However, the relationship with frequency is different than predicted by Corliss's model. We evaluated a number of other auditory models. We found that Lyon's model [Slaney, 1988] predicted excessive masking by low frequencies. The *Detectsound* model [Laroche, et al., 1991] derives a mask from equivalent loudness summation and was too complex to implement in our scope of work. Patterson's first model [Patterson & Nimmo-Smith, 1980] gave a similar result to those predicted by Corliss's model, while his later simplified model [Patterson, et al., 1982] predicted excessive masking by lower frequencies. We chose to use Patterson's first model but selected coefficients to better fit our data. The end result is a filter shape that falls between Patterson's first and later models, as illustrated in Figure 5 at 4 kHz. Our model took the form

$$P = k\int H(g)^2$$

where

$$H(g)^2 = \left[1 + \lambda g + a_2(\lambda g)^2 + a_3(\lambda g)^3\right]e^{-\lambda g}$$

$g = (f_l - f_o)/f_o$ (a normalized frequency factor for frequency *f*)

We derived the frequency-sensitive attenuation factor *k* from a curve fit of Moore's [1990] data such that $k = 0.32834 + 252.34 / f_o$

We modified the value of the exponent coefficient λ for the lower frequency range from 20.7 to 14.5 and set all other coefficients the same as Patterson's original model. The detection threshold predicted by the model for the case of interior automobile noise is illustrated in Figure 6.

We note that there might be situations where binaural hearing could accentuate the lower frequency detection as found in our laboratory-based experiments. However, our assumed binaural masking characteristic for 90-degree signals is shown for illustrative purposes. We used the adapted Patterson masking characteristic in the safety effectiveness section of this report (Chapter 5).

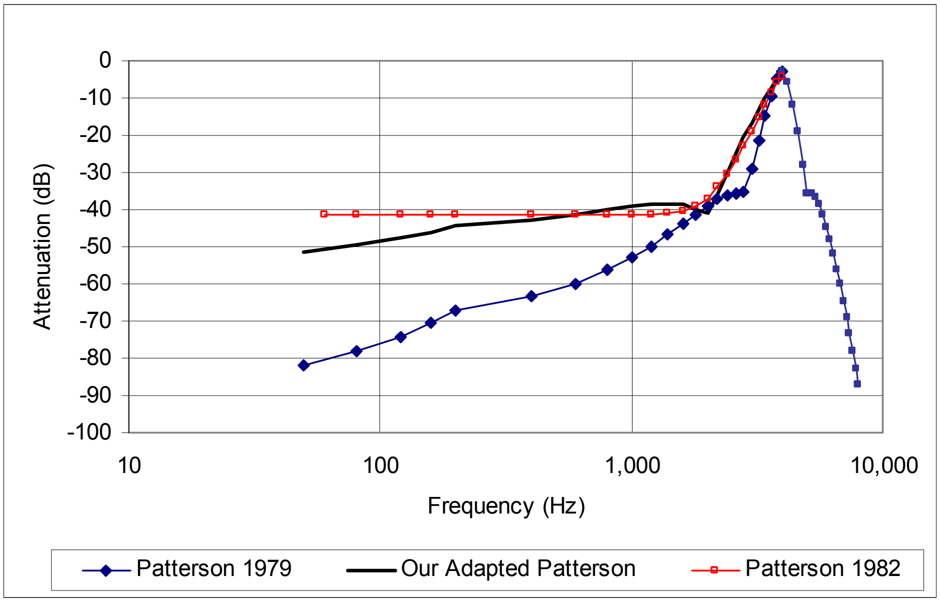

Figure 5 **Comparison of auditory filters at 4 kHz**

3.2.3 Model Correlation with Other Data

As noted earlier, Robinson and Casali [1999] conducted signal detection experiments that indicated that the ISO masking recommendation [ISO 7731, 1986] might be too conservative. We assessed their published data and compared the masking threshold levels predicted by our model with the ISO procedure. Robinson's tests involved detection of a backup signal in the presence of a high ambient noise by someone wearing a muff-style hearing protection device. The tests are particularly relevant since the test noise environment under the insertion loss of hearing protection devices is steeper than our automobile noise characteristic and has about the same magnitude at the detection level. Robinson's experimental analysis was confined to full spectrum SPL and resulted in S/N detection levels of >90 percent at -16 dB and 65 percent at -24 dB. However, there is enough information in the report to derive the 1/3-octave band SPLs. We used the data to compare our masking model with the ISO masking recommendation.

The second column shows the flat exterior noise signal and the third column the noise inside the hearing protector. The fourth column shows the masking level of the interior noise predicted by the ISO standard. The next pair of columns are the 1/3-octave band components (outside and inside the hearing protector, respectively) of the backup signal associated with the reference 0 dBA S/N ratio for the full spectrum SPL. The final pair of columns compare the signal-to-mask (S/M) threshold ratios for the ISO and adjusted-Patterson masking models.

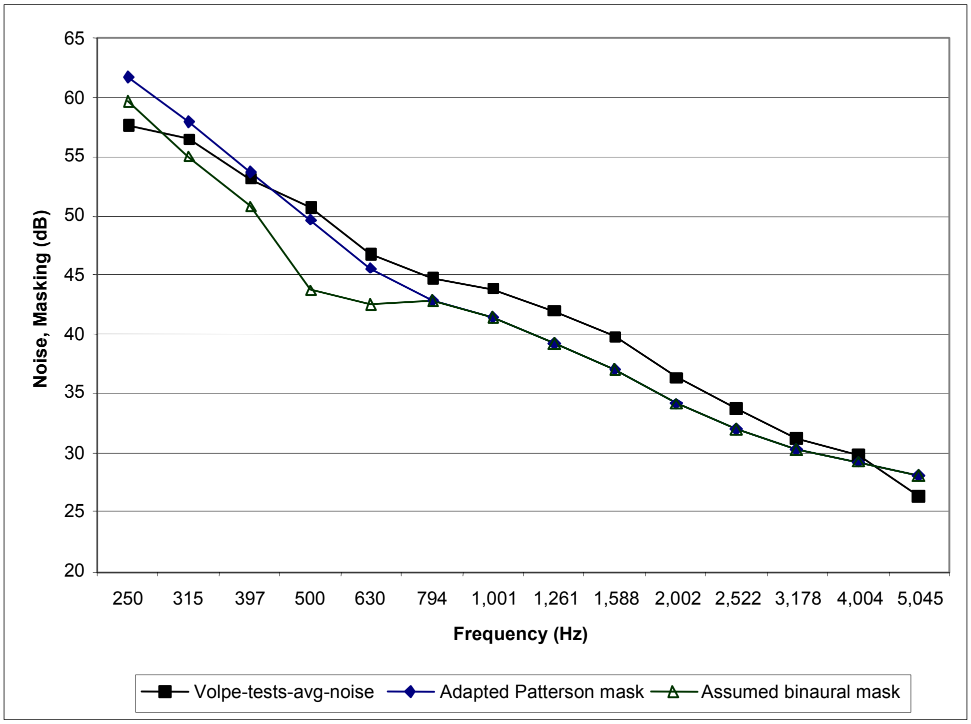

Figure 6 **Derived masking characteristics for in-vehicle noise**

Table 2 **Comparison of ISO and adjusted-Patterson masking levels**

1/3 Octave (Hz)	Exterior Noise	Interior Noise	ISO-based Mask	0.0 dBA S/N		-16.0 dBA S/N	
				Exterior Signal	Interior Signal	S/M (ISO)	S/M (Adj.-Patterson)
250	80.1	59.3	63.1				
315	80.1	57.1	60.6				
400	80.1	52.7	58.1				
500	80.1	48.1	55.6				
630	80.1	43.7	53.1				
800	80.1	38.8	50.6				
1,000	80.1	36	48.1	92	47.9	-16.2	-5.2
1,250	80.1	37.3	45.6	96	53.2	-8.4	0.5
1,600	80.1	37.8	43.1	72	29.7	-29.4	-23.2
2,000	80.1	39.1	40.6	84	43	-13.6	-11.0
2,500	80.1	41.3	41.3	86	47.2	-10.1	-4.0
3,150	80.1	36.9	38.8	73	29.8	-25	-18.6
4,000	80.1	31.6	36.3	77	28.5	-23.8	-19.9
5,000	80.1	33.6	33.8	77	30.5	-19.3	-19.3

Since the masking level is an indication of the threshold of hearing for a signal masked by the noise, one would expect a positive S/M ratio to exist for at least one of the signal's frequency components. One can see that the dominant component of Robinson's backup signal occurs at 1,250 Hz. For that frequency, the ISO mask indicates that the 90 percent signal detection that was observed for the -16 dBA signal was achieved with a -8.4 dB S/M ratio, while our modified Patterson mask indicates that the 90 percent detection result was associated with a +0.5 dB S/M ratio. While not shown in Table 2, the 65 percent detection rate (achieved at a -24 dBA S/N) is associated with a -16.4 dB S/M (ISO) and a -7.5 S/M (Adj.-Patterson). We conclude that our masking model is a better predictor of the upward spread of masking than the ISO method.

3.3 Urgency Assessment

3.3.1 Insights from the Literature

Much of the research literature on auditory warning devices deals with emergency vehicle sirens. Nonetheless, the issues and findings are relevant to locomotive horns. Edworthy, et al. [1991] conducted an investigation of the effects of signal characteristics on perceived urgency. The influence of fundamental frequency, harmonic series, amplitude envelope shape, and delayed harmonics, as well as rhythm and melodic characteristics were assessed. All factors were found to have an influence on perceived urgency. Fundamental frequencies from 150 to 530 Hz were tested, each with harmonic content up to 4 kHz. In signal comparisons, those with higher fundamentals were perceived to have a higher urgency, although the magnitude of the shift was not as important as the direction (e.g. there was a larger urgency difference between 350 and 200 Hz than between 530 and 150 Hz). The effect of the amplitude envelope was clear—fast onset and offset ramps (20 ms) were judged more urgent than slow onset or offset ramps. The signal with regular harmonics (all of equal magnitude) was considered less urgent than signals with irregular amplitudes. Random amplitude variation was more urgent than standard pattern irregularities (e.g. all even harmonics 10 percent lower in amplitude). As far as melodic structure was concerned, atonal sounds (no apparent melodic structure) were perceived most urgent.

In relation to Edworthy's findings of perceived urgency associated with a rapid rise time, we note that as a train approaches, its sound volume increases (from reduced losses as the distance is reduced), thereby introducing a form of onset ramp to the listener. Thus, it becomes more important to ensure that the actuating mechanism produces as fast a rise time as possible. In addition to alerting effectiveness, rise time directly affects the warning distance available. For example, if a locomotive horn does not attain the effective output level for two seconds, a 160 km/h high-speed passenger train will have travelled close to 90 m (300 ft.) before the warning level is attained. There are implications for the control valve location and the type of valve. A horn manufacturer indicates that two seconds is typical of manual actuating valves that are not located close to the horn, but that output is almost instantaneous with an automatic valve located at the horn base. We recommend that the actuating valve be positioned as close to the horn as possible in new and retrofit installations of horns.

In a recent continuation of this work, Haas and Edworthy [1996] experimented with auditory warnings by varying pitch, speed and loudness. They found that the most urgent signals were those that have pulses with a fairly high fundamental frequency (800 Hz), SPL above 40 dBL, and a short inter-pulse interval. They also found that perceived urgency increases as fundamental frequency increases and inter-pulse interval decreases.

Another factor is the selection of fundamental frequency. A lower fundamental frequency produces a much broader set of harmonics in a given bandwidth (a 250 Hz fundamental has 15 harmonics up to 4 kHz, while a 622 Hz fundamental has only five harmonics). One could predict that a lower fundamental would have a higher probability of detection, given its many harmonics. However, Edworthy's findings indicate that a higher fundamental (with fewer harmonics) is a better alerting mechanism. We note that the overall intensity of each signal was held constant in Edworthy's study. Thus, the higher fundamental with fewer harmonics requires a higher intensity per harmonic to attain the same overall intensity. The impact of irregular harmonic amplitudes also leads to some harmonics with a higher intensity and some with a lower intensity than the fixed intensity of the regular signal. The findings may indicate that peak intensity of harmonics within the signal spectrum is the underlying influence rather than the number of harmonics present.

In either case the findings are relevant to a horn design. If one is designing to a fixed sound level threshold, the findings indicate that a horn system with a higher fundamental and fewer high-intensity harmonics is better than a low fundamental with many lower-intensity harmonics. However, our detection experiments indicate that frequencies above 2.5 kHz are very sensitive to head orientation. Since the sound level inside a vehicle can never be significantly above the 'detection' level, one runs the risk of not detecting a signal based on few harmonics. Also as will be shown in subsection 3.3.3, a lower fundamental frequency horn can be designed to produce harmonics more easily than a high frequency horn. These factors, combined with the disadvantage of deviating too far from the existing known sound of a railway horn, lead us to recommend lower fundamental frequencies for locomotive horns.

3.3.2 Pure Tone Experiments

Tests were conducted at low signal intensity levels to relate to the lower sound levels received inside a vehicle. The experimental procedure and results are presented in part 2 of Appendix D. The assessed urgency of pure tones in the absence of noise is illustrated in Figure 7. In the absence of noise and at these low sound intensities, there is little impact on assessed urgency of increasing sound levels, but there is increased urgency with increasing frequency of the signal. The conclusion drawn is that even at low signal intensities, the urgency relationship to frequency follows the findings of others.

Another experiment was conducted with pure tones in the presence of vehicle noise. The results are summarized in Figure 8. The tone signal intensities in this experiment ranged from the beginning of the detection threshold (derived from earlier test results) and extended to +6 dB. Since all signals were detected at negative signal-to-noise (S/N) levels, a zero signal-to-mask (S/M) threshold value corresponds to a negative S/N ratio.

Since the vehicle noise characteristic decreases with increasing frequency, the 0 dB S/M ratio data points are at a lower signal intensity at 4,000 Hz than at 500 Hz. The numbers identified on the plot are the signal intensities associated with the 0 dB S/M curve at each frequency. Thus, a 0 dB S/M curve involves a 39 dB signal at 500 Hz and a 21 dB signal at 4,000 Hz. As a consequence of either the presence of noise or the fact that the noise characteristic involves decreasing sound level with increasing frequency, the assessed urgency is not as sensitive to increasing frequency as it was in the absence of noise. Nonetheless, it can be seen that a lower signal intensity at 4,000 Hz has about a 50 percent incremental urgency over a higher intensity signal at 500 Hz (e.g. 41 percent assessed urgency for a 27 dB signal at 4,000 Hz, compared with 27 percent urgency for a 45 dB signal at 500 Hz).

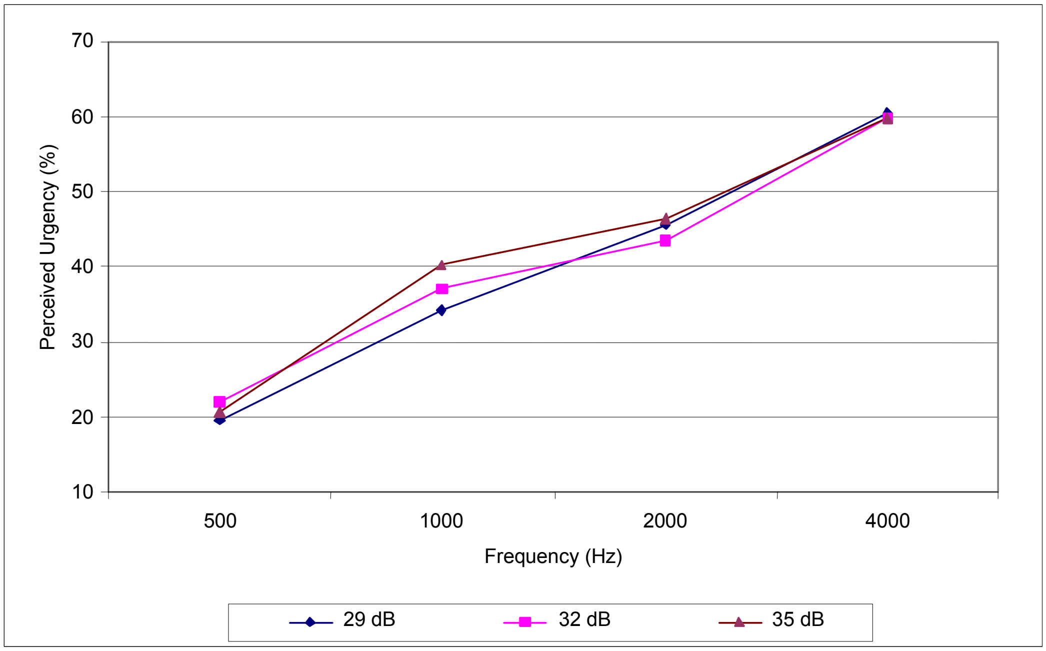

Figure 7 **Perceived urgency of pure tones with no noise**

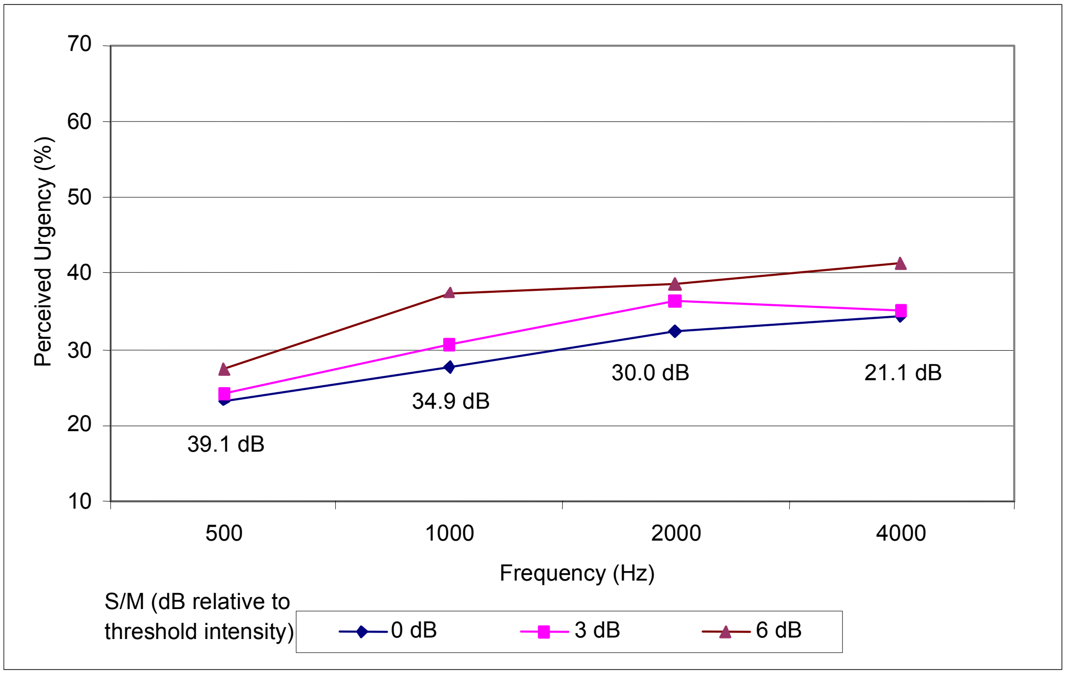

Figure 8 **Perceived urgency of masked tones**

3.3.3 Horn Sound Experiments

Locomotive horns were characterized with the participation of a horn supplier Airchime Manufacturing Ltd. [1985]. Sound level measurements were taken at a distance of 180 m in an unoccupied railway yard in Mission, BC. The individual horn spectral characteristics (1/3-octave band values) are summarized in Table 3. It should be noted that the fundamental frequencies shown are the nominal labels attached to the horns. There was some variation in the actual frequencies obtained. Most were within 12 Hz of nominal but a few were far enough off that it affects the interpretation of the results. Nominal-415 was actually 431 Hz, nominal-494 was actually 512 Hz, and nominal-512 was actually 550 Hz.

Table 3 Frequency spectrum of individual horn flutes (dB, normalized to 100')

1/3-Octave Band (Hz)	Nominal Fundamental Frequency of Horn									
	261 Hz	311 Hz	370 Hz	415 Hz#	440 Hz	470 Hz	494 Hz#	512 Hz#	622 Hz	660 Hz
250	91	58	57	55	55	58	59	59	59	60
315	56	94	59	53	53	57	54	58	60	58
400	50	56	88	95	86	62	56	54	62	57
500	86	54	53	83	91	94	94	91	59	58
630	56	91	75	53	53	57	57	83	97	96
800	88	64	97	95	91	63	57	55	60	62
1,000	90	91	82	82	95	95	94	93	62	65
1,260	86	86	89	86	86	76	59	85	96	95
1,600	87	80	85	82	80	84	92	91	63	65
2,000	92	91	83	89	88	93	86	92	88	90
2,500	93	92	92	89	92	88	85	90	83	87
3,200	88	89	87	89	86	89	85	85	80	87
4,000	90	86	86	82	85	86	90	90	80	86
5,000	85	86	83	81	83	80	90	86	78	81

\# The actual frequencies for these horns were off by more than 12 Hz from the nominal (see text).

The values in Table 3 are normalized to 100 ft for each horn and those 1/3-octave bands higher than 90 dB are highlighted. One can see that the lower fundamental frequency flutes (261 Hz and 311 Hz) generated more signal energy above 1,600 Hz than did the high fundamental frequency flutes (622 Hz and 660 Hz).[6] The 622 Hz and 660 Hz flutes have most of their energy in the fundamental and second harmonic, while the 261 Hz and 311 Hz flutes have more energy content in the 4,000 Hz and 5,000 Hz bands than do the 622 Hz and 660 Hz flutes. It is noteworthy that the 494 Hz and 512 Hz flutes have the highest content in the 4,000 Hz and 5,000 Hz bands.

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[6] We note that the newly manufactured horns and the ground effects at the measurement distance might both accentuate the higher frequency bands in comparison with locomotive horn measurements made at 30.5 m. However, the main purpose of the tests was to obtain a comparison between horns at a warning distance relevant to higher speed trains.

Twenty-three different horn sounds were electronically mixed from seven of the single-flute railroad horns recorded in the Mission tests. The sounds were assessed for urgency in a laboratory experiment (see part 3 of Appendix D for details). Each combination horn sound was played at 70 dB, and participants were asked to assess the urgency associated with the sound. The sounds involved 3-flute, 4-flute and 5-flute horn combinations of varying middle frequencies. The lowest fundamental and the highest fundamental frequencies were constant at 311 Hz and 622 Hz, respectively, for all horn combinations.

The best fit of the data, consistent with theoretical expectations, indicated increasing perceived urgency with:

- increasing centroid (the amplitude weighted mean of the frequency spectrum),
- increasing musical dissonance, and
- increasing number of flutes.

The experiment results are summarized in Figure 9. Centroid was the most significant factor, explaining 35 percent of the variance. Dissonance and the number of flutes each explained about 14 percent of the variance. However, there was a high cross-correlation between dissonance and the number of flutes, making it difficult to isolate these two factors with statistical significance. We note that much of the variance could be explained by the presence (or absence) of the 494 Hz flute in the horn. However, this parameter had a high correlation with the centroid and there is no theoretical basis for its explanatory role. Therefore, it was not included in the predictive equation.

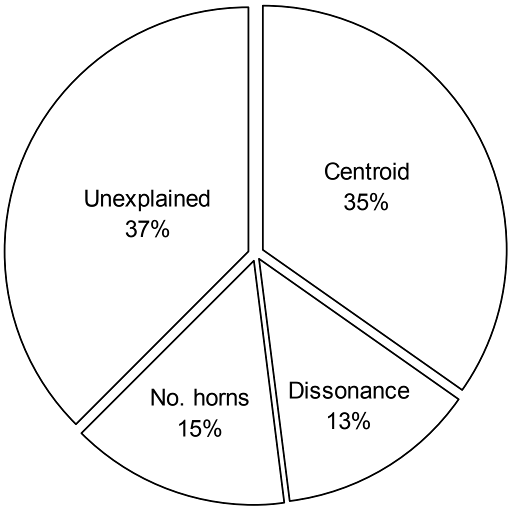

Figure 9 Explained urgency of horn sounds

3.3.4 Discussion of Findings

One could argue that the harmonic chord of present day locomotive horns is more a product of nostalgia than safety. However, it is the recognized sound of a train in North America and any change to its characteristic sound would have to be tested to be sure it is still recognized as a locomotive horn. Our findings indicate that the existing range of flutes available for locomotive horns is sufficient to provide the desirable attributes of an auditory warning device.

The 5-flute horn performed best in all of our safety-alerting evaluations. This does not necessarily mean that a 5-flute horn is required; a combination of three flutes that produce more output in the 2,000 to 4,000 Hz range might also be effective. Our yard measurements of new 3-flute horns showed a spectrum width close to that of the 5-flute horns. However, the 3-flute horns as characterized in the literature and in some of our revenue train measurements did not fill the spectrum as well. Our findings for in-vehicle signal detection indicate that a broader spectrum has an effective advantage of 5 dB over a narrow spectrum signal of the same magnitude. The high volume of air required by a 5-flute device also makes it more susceptible to air pressure variations.[7] The warning output both from freight trains after extended brake applications and from cab cars that draw air from the brake line would be more adversely affected by additional flutes. We do not see a significant enough advantage in five flutes over three to recommend them as a standard for all locomotives. However, we believe that locomotives operating over 70 mph should have a 5-flute horn available to the crew in emergency situations. We also stress the importance of selecting frequency combinations and specifying the harmonic content at the time of purchase and refurbishing so that 3-flute horns provide a broad-spectrum warning signal.

Our findings indicated some increase in perceived urgency with increased dissonance. The effect was not as great as the frequency effect and its influence could not be statistically separated from an increase in the number of flutes. We recommend that those railways that implement a two-level or emergency-only horn select the combination of frequencies such that some dissonance exists. We do not see this as a regulatory requirement nor do we see it as desirable for a normal horn used frequently in a rule-based warning mode.

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[7] Another advantage of a reduced number of flutes is that it is easier to focus/shield. It would be much more difficult to recess a horn system with output spread across the 750 mm width of a 5-flute horn than the 200 mm diameter of as single flute horn. A consideration for new build locomotives with two-level horns is to have the normal 3-flute horn recessed in the hood to reduce in-cab and community noise concerns and the incremental pair of emergency flutes mounted on the roof.

4. INFLUENCE OF HORN POSITION AND TRAIN SPEED

4.1 Insights from the Literature

4.1.1 Position Influence from Static Tests

To assess the warning effectiveness of different horn types and locations one needs to have a good representation of its frequency spectrum. Some 1/3-octave band data exist in the literature or are available from operating railways. We have drawn upon three sources in selecting representative horn characteristics: measurements made for the FRA by the Volpe Center [Keller & Rickley, 1993], measurements made by VIA Rail and measurements made by Seshagiri and Stewart [1991, 1992]. We compared these data with our own yard test of free-standing newly manufactured horns.

There was reasonable agreement between VIA Rail's and Keller's data for the magnitude of a 3-flute mid-locomotive horn, and the horn's spectral shape was in agreement with our measurements (made at operating speeds) for both 3-flute and 5-flute horns located behind and close to the exhaust stack. There was not good agreement on the shape and magnitude of the front-mounted 3-flute horn. Our yard and revenue train measurements indicate that there is less of a penalty (both in breadth of spectrum and sound intensity) in going from five flutes to three flutes than Keller's characteristic shows. Thus, we have adopted Keller's data as representative of the 5-flute front-mounted horn and a behind-exhaust, mid-locomotive horn, and use our own measurements of a 3-flute front-mounted horn.

The representative horns' spectra (emitted to the front of the locomotive) that we use in this report are illustrated in Figure 10. The legend entry 3F-110dB is a 3-flute front-mounted horn that produces 110 dB at 30.5 m (100 ft.). Similarly, 5F-112dB is a 5-flute front-mounted horn that produces 112 dB at 30.5 m (100 ft.) and ML-101dB is representative of either a 5-flute or 3-flute horn when mounted mid-locomotive. Our focus is on the spectral shape of 5-flute and 3-flute horns' SPL when mounted up front and mid-body. There was reasonable agreement on the spectral shape of a 5-flute front-mounted horn, but a variation in magnitudes.

The horn manufacturer's data indicates that a single flute horn (as well as two, three and four flutes) can attain the same output loudness as a 5-flute horn if sufficient airflow is provided. Our revenue service tests indicated a range of 108 to 115 dB for both 3-flute and 5-flute horns when measured at the best line-of-sight angle. For our purpose, the magnitudes are not as relevant as the shape.

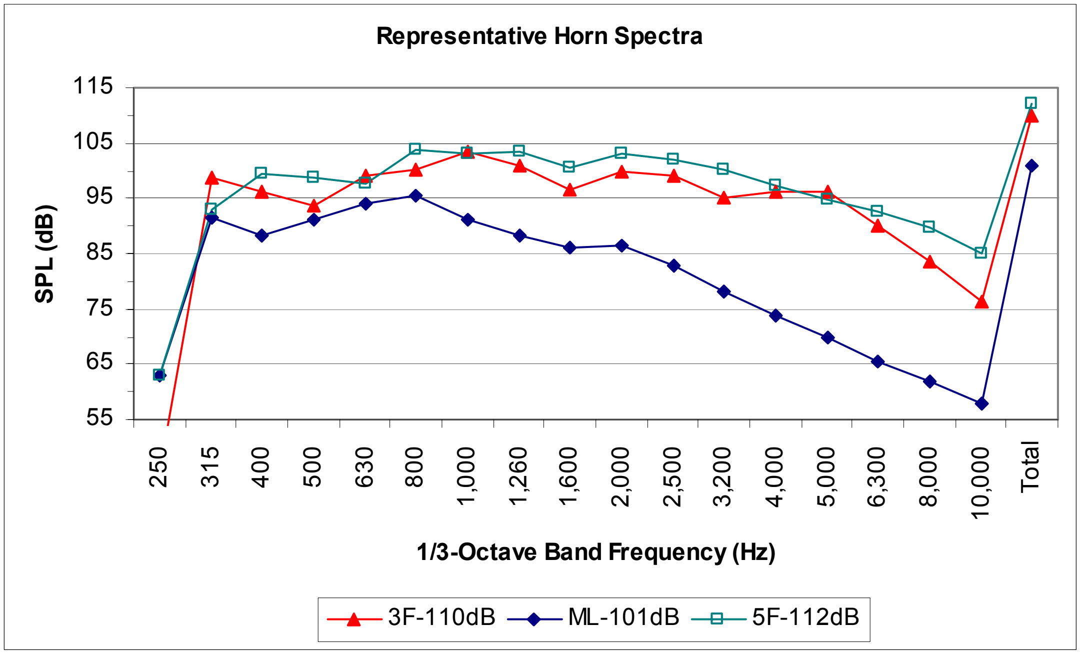


Figure 10 **Representative horns' spectral characteristics**

4.1.2 Speed Influence Demonstrated in Others' Data

In reviewing the literature on previous horn studies we noted that Labour Canada [Seshagiri, & Stewart, 1991] found that the SPLs for the locomotive when approaching at 40 mph (67 km/h) were all lower than the SPLs made over the same distance range for a stationary locomotive. Figure 11 illustrates the curve fit to the test measurements involving multiple tests at each location.

The locomotive horn exhibited a 3 dB reduction at 800 m when the locomotive was going 40 mph. This was the location where the horn was first applied. The output reduction grew to 12 dB at 50 m when whistling stopped. While the authors did not raise the possibility of a speed influence, the findings led us to review other published data to see whether a hypothesis that horn output deteriorates at speed could be refuted.

Aurelius and Korobow [1971] measured SPLs for stationary Metroliners and for pass-by tests of Metroliners at approximately 110 mph. The result of a curve fit to their test measures is illustrated in Figure 12. The data did not include an overlap of distances, but extrapolation on the basis of a 6 dB drop per doubling of distance indicates that the moving train had a lower output averaging about 4.5 dB.

The horn position for the Labour Canada test was mid-locomotive and off to one side (the opposite side from which the measurements were taken). The position for the horn in Aurelius's data was on the cab roof, a metre or so back from the front edge.

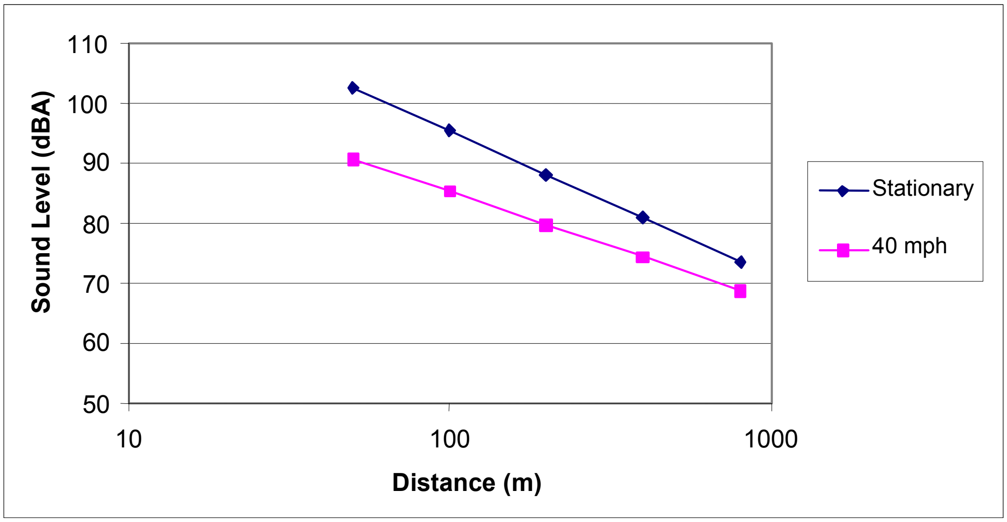


Figure 11 **Labour Canada's stationary and moving horn measurements**

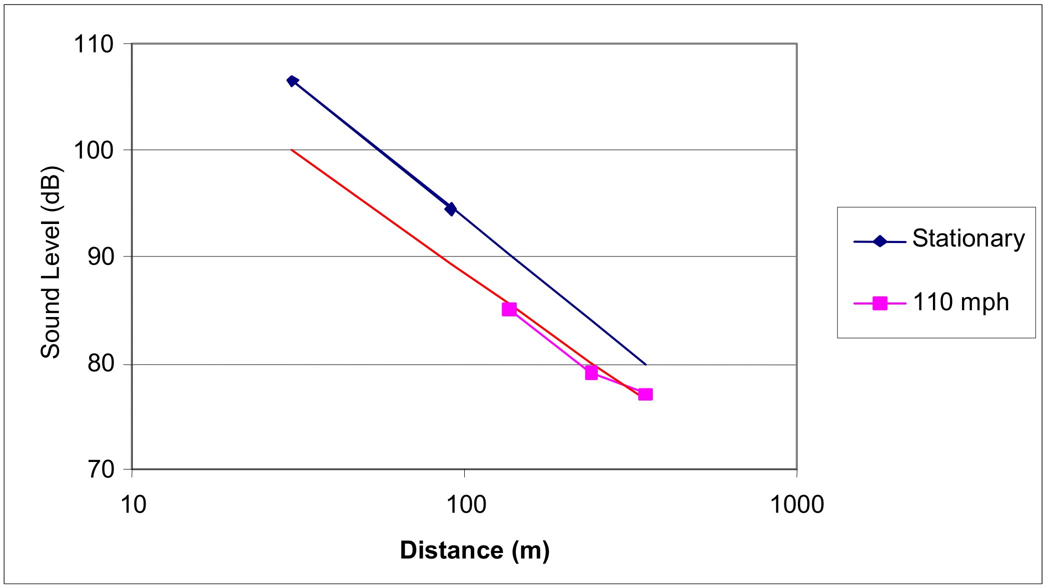


Figure 12 **Aurelius's stationary and moving Metroliner horn tests**

We reviewed VIA Rail test data involving repeat runs of a test locomotive at varying speeds and with different horn locations. Spectral data were only available at calm wind conditions for two tests (62 mph and 86 mph). In both runs the horn was mounted to the right side of its normal position on the locomotive to avoid the exhaust duct. We extracted data from each run as close to 200 ft. (61 m) as the 1/2-second sample interval allowed. The full output was 106.2 dBA (at 62 mph and 199 ft.) and 103.2 dBA (at 86 mph and 215 ft.). The difference in distance could account for about 0.67 of the 3 dB difference.

The frequency spectra for the two speeds are shown in Figure 13. The lateral shift in frequency for the higher speed data series is due to the Doppler effect, which also explains the shift of all fundamental and harmonic frequencies in both data series to higher levels than one would obtain from stationary tests. One can see that the lowest fundamental (311 Hz) and its harmonics have a lower output, while the two higher-frequency / shorter flute fundamentals are quite similar. The longest flute produces the lowest fundamental, which is located between the other two shorter flutes. It is possible that the long flute is more susceptible to back-pressure built up by moving through the air at 28 and 39 m/s, while at the same time shielding the other two flutes from the air stream.

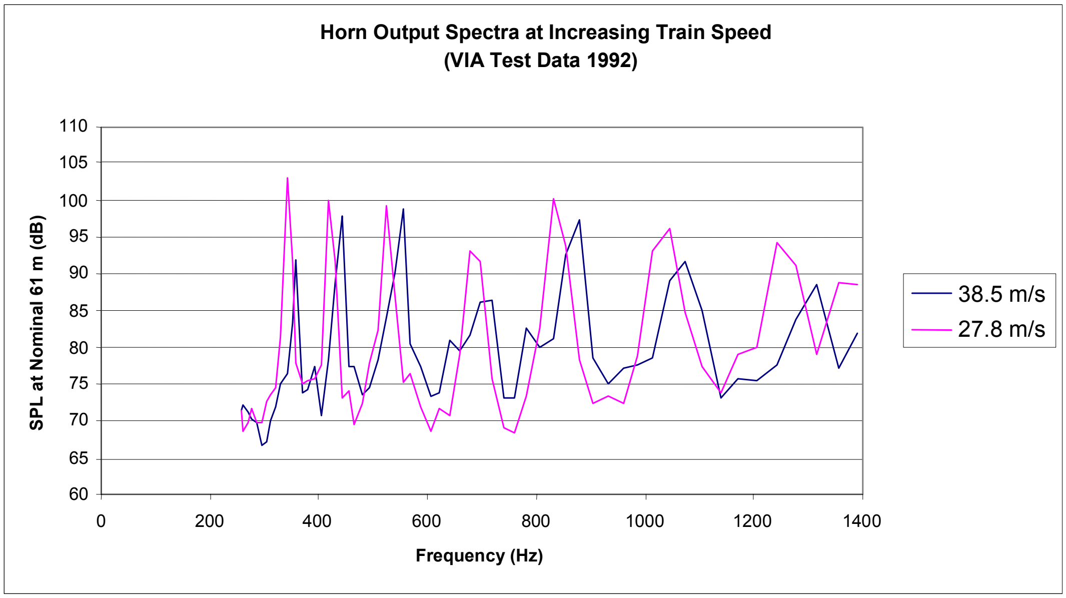


Figure 13 VIA Rail tests: horn spectra measured at two speeds

There is a possible interactive effect of position and speed on a horn's output. In the mid-1980s the Canadian railways moved the horn from the front of the locomotive to the middle in order to reduce the in-cab sound level. On passenger locomotives, the horn was positioned behind the exhaust stack. VIA Rail noticed that the clarity of its horn was not as good at high speeds and one hypothesis offered was that the rising hot exhaust gases dissipated the sound. VIA Rail conducted a series of tests in the early 1990s to evaluate its horn's performance. It conducted stationary tests with the engine fully loaded to assess full exhaust conditions. It found that the sound output at 30.5 m in front of the locomotive was no different at full load than at no load. The hot and vertically moving stream of air in front of the horn did not appear to be the source of the problem. Since the horn performed above the FRA's regulatory limit under its test conditions and since exhaust gas did not seem to affect its output, no changes were made.

4.2 Test Sites/Procedures

A major focus of this project was to characterize the output of a broader range of horn types and positions as well as to determine the influence of train speed on their output. To accomplish both goals with a minimum of disruption, we undertook pass-by sound level measurements of revenue trains. The advantage of revenue service testing is that the actual field conditions are captured exactly as they would be experienced in the intended application. The principal objective in our selection of revenue service tests (other than the reduced cost and disruption effects) was to characterize the influence of train speed on output performance. We have made comparisons of the warning effectiveness of approaching trains for a wide range of horn types/positions and train speeds. These comparisons represent a direct measure of the actual field experience, many occurring within minutes of each other under the same environmental conditions.

The analysis of "as-received" signals represents the most realistic and accurate representation of a locomotive horn's alerting performance, since it measures what would be heard at the crossing location. Nonetheless, it is not a measurement on which a standard can be based. Most characterizations of locomotive horns are based on the present industry recommended standard, which is based on a stationary measurement made at 30.5 m (100 ft.) from the front of the locomotive. Thus, we have further analyzed the signals to estimate the characteristics of the source signal as it would be measured at the standard's reference distance of 30.5 m.

The remainder of this chapter is presented in three sections. The first section presents an overview of the test sites where measurements were made. The second section presents the comparison of "as-received" signals, and the third section presents the derived source characteristics.

Several grade crossing locations were used to measure the output of horns under revenue service conditions. One of the best sites for a wide range of locomotive horn positions and train speeds was South Blair crossing in Whitby, Ontario. It is an open area with grass and one or two small trees on the north side of the tracks. Pictures taken in each track direction are presented in Figure 14. The geometry of the grade crossing is illustrated in schematic form in Figure 15.

The train activity at the South Blair site includes:

- GO Transit commuter trains going 55 km/h with 5-flute horns mounted mid-locomotive behind the exhaust stack (F59PH locomotives of late 1980s vintage).
- GO Transit commuter trains going 100 km/h with 5-flute horns mounted up front over the cab of a cab car.
- VIA Rail passenger trains going 145 km/h with 3-flute horns mounted mid-locomotive behind the exhaust stack (F40 locomotives of mid-1980s vintage).
- VIA Rail passenger trains going 145 km/h with 3-flute horns mounted over the cab of the locomotive (LRC locomotives of late 1970s vintage).
- A range of freight locomotive types.

The conditions allow the influence of speed on horn output to be assessed over a range of angles from the front of the train. The approach geometry is such that the initial sounding of the horn occurs at shallow horn angles (about 15 to 20 degrees), while the last blow occurs at 65 degrees for westbound trains and 150 degrees for eastbound trains.

Measurements were made using a number of different Bruel and Kjaer (B&K) Type 1 sound level meters (B&K 2239, B&K 2231 or B&K 2209), with calibration checks using B&K 4230 or Quest 12-M calibrators (94 dB, 1 kHz). Outdoor measurements used B&K UA-0237 windscreens on the microphones. The signals were recorded on either a B&K 7006 reel fm tape recorder, or a TEAC R61D fm cassette recorder. Digitization and spectral analyses were done at sample frequencies ranging from 12 to 48 kHz using 16 bit digital signal processing hardware (either Siglab 20-42, Keithley-DAS-1600 or CS-4297A). Train speed was measured with a Kustom HRS hand-held radar gun, and wind/temperature/humidity conditions with a Kestrel 3000 weather meter.

westbound, cab car leading

along approach roadway, looking south

eastbound, locomotive leading

Figure 14 South Blair grade crossing photographs

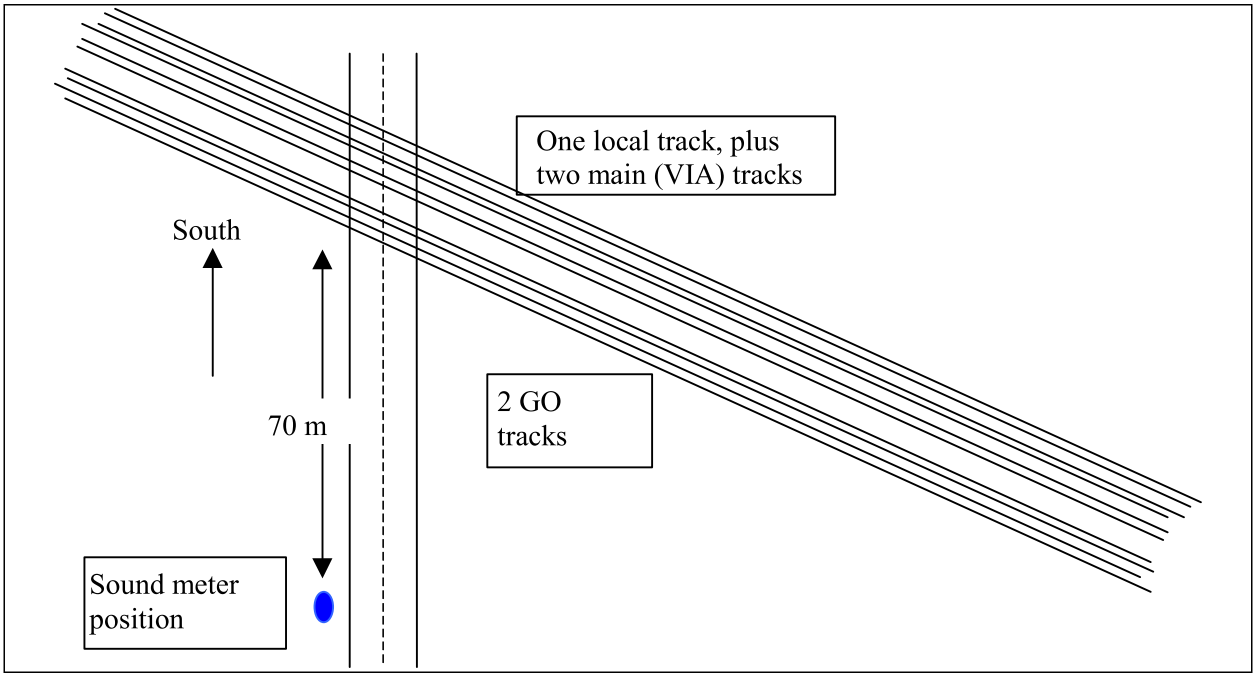


Figure 15 **Schematic of South Blair grade crossing geometry**

4.3 As-Received Signal Comparison

4.3.1 Total-Energy Sound Level Comparison

In this subsection, the full spectrum SPL as recorded at the measurement location is compared for several different horn locations and train speeds. Representative measurements are presented in this subsection. See Appendix E for a more complete set of measurements. Figure 16 shows the horn sounding sequence (two long blasts, one short and one more long) of GO Transit 5-flute horns mounted in two different positions on trains approaching the South Blair crossing.

The sound level, as measured at a point 70 m north of the grade crossing, is shown on the vertical axis, while the horizontal axis shows the distance between the train front and the sound level meter at the corresponding sound level measurement. A measurement was taken every 0.5 seconds. The top black line is a reference line showing the theoretical fall off of 6 dB per distance doubling, referenced at 110 dB at 30.5 m (100 ft.) The dashed line plots the sound output of westbound front-mounted horn going 90 km/h (56 mph). The horn sequence was initiated late (inside the normal 1/4 mile/400 m whistle post). The horn is seen to produce an output within close proximity to the reference line over its full pattern (representing output at a 20 degree horn angle at first and increasing to 60 degrees at the end).

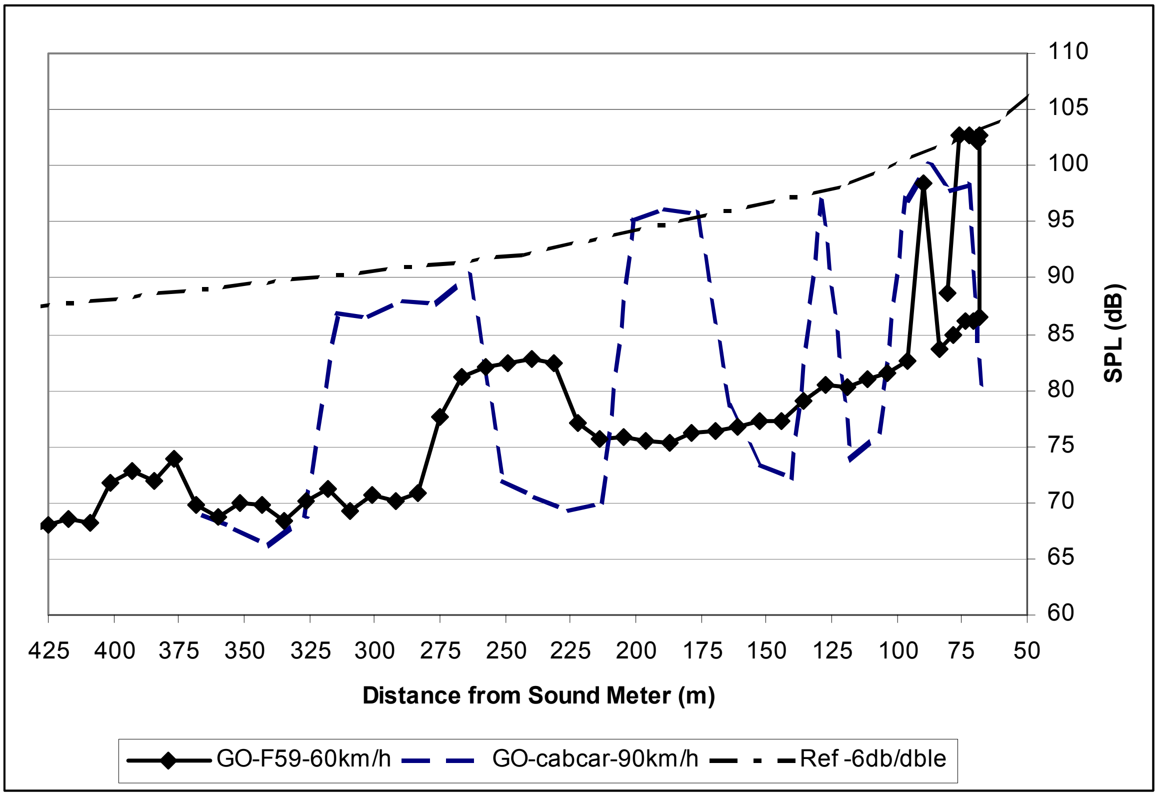


Figure 16 **Comparison of 5-flute horn sound pressure level**

The solid black line is the SPL measurement of an eastbound train going 60 km/h (36 mph) with a mid-locomotive horn mounted behind the exhaust of an F59 locomotive. Because of the geometry at the crossing, eastbound trains pass a point perpendicular to the sound level meter before reaching the crossing. The last horn blast of the eastbound train occurs close to the perpendicular point (shortest distance to the sound level meter). There are several measurements plotted over a track distance that involves very little change in distance to the sound level meter. The train then gets farther away from the sound level meter as it continues to blow. The horn output is considerably below the 110 dB reference line at the initial shallow angles of output (about 15 degrees) and attains the reference line before and after the perpendicular point is reached. Thus, the solid line turns back on itself while the dashed line does not.

Figure 17 presents the measured SPL of two different eastbound VIA Rail locomotive horns approaching the South Blair crossing at about 145 km/h (90 mph). The dashed line plots the sound output of a front-mounted horn of a Light, Rapid Comfortable (LRC) locomotive going 147 km/h. The horn is seen to produce an output within close proximity to the reference line over its full pattern (representing output at a 15 degree horn angle at first and increasing to 150 degrees at the end). The solid line is the SPL of an F40 locomotive with a behind-exhaust mid-locomotive horn. The horn sequence for this locomotive was stopped well short of the grade crossing. Therefore, the last horn blast of the train occurred close to the perpendicular point (shortest distance to the sound meter) and does not get farther away as is indicated for the LRC train. The horn output is seen to be considerably below the 110 dB reference line (and indistinguishable from the background noise level) at the initial shallow angles of output (about

15 degrees), begins to climb at the 125 m distance, and attains it by the time it reaches the perpendicular point.

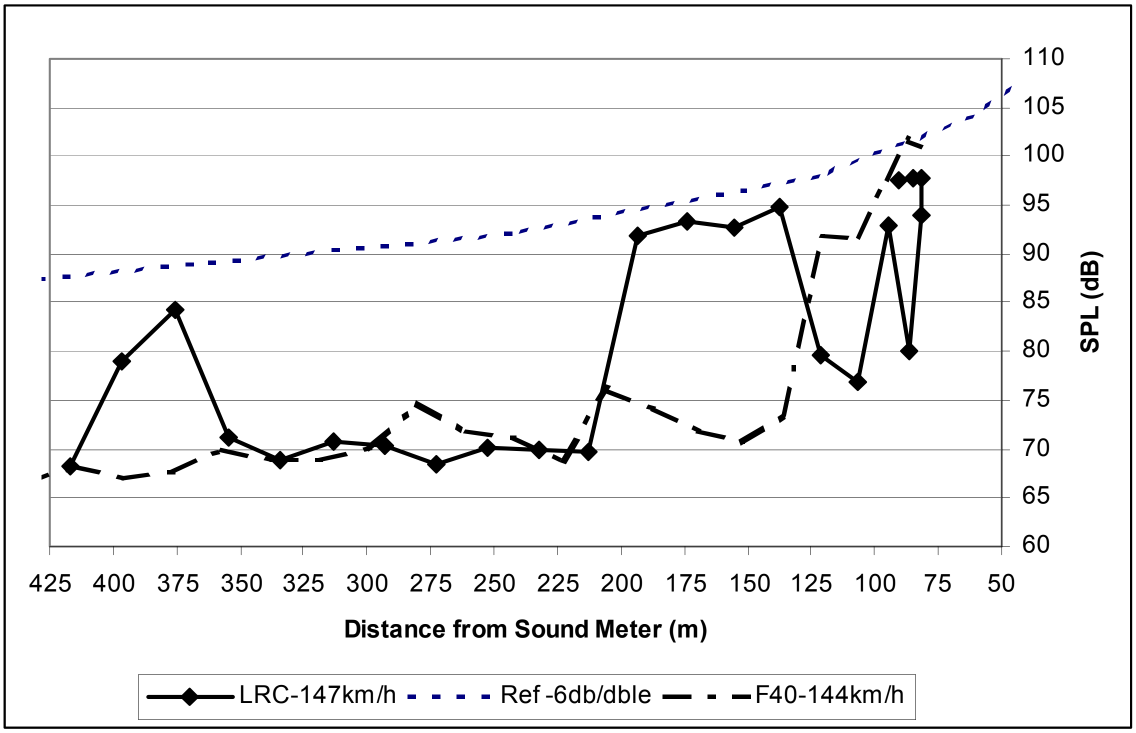
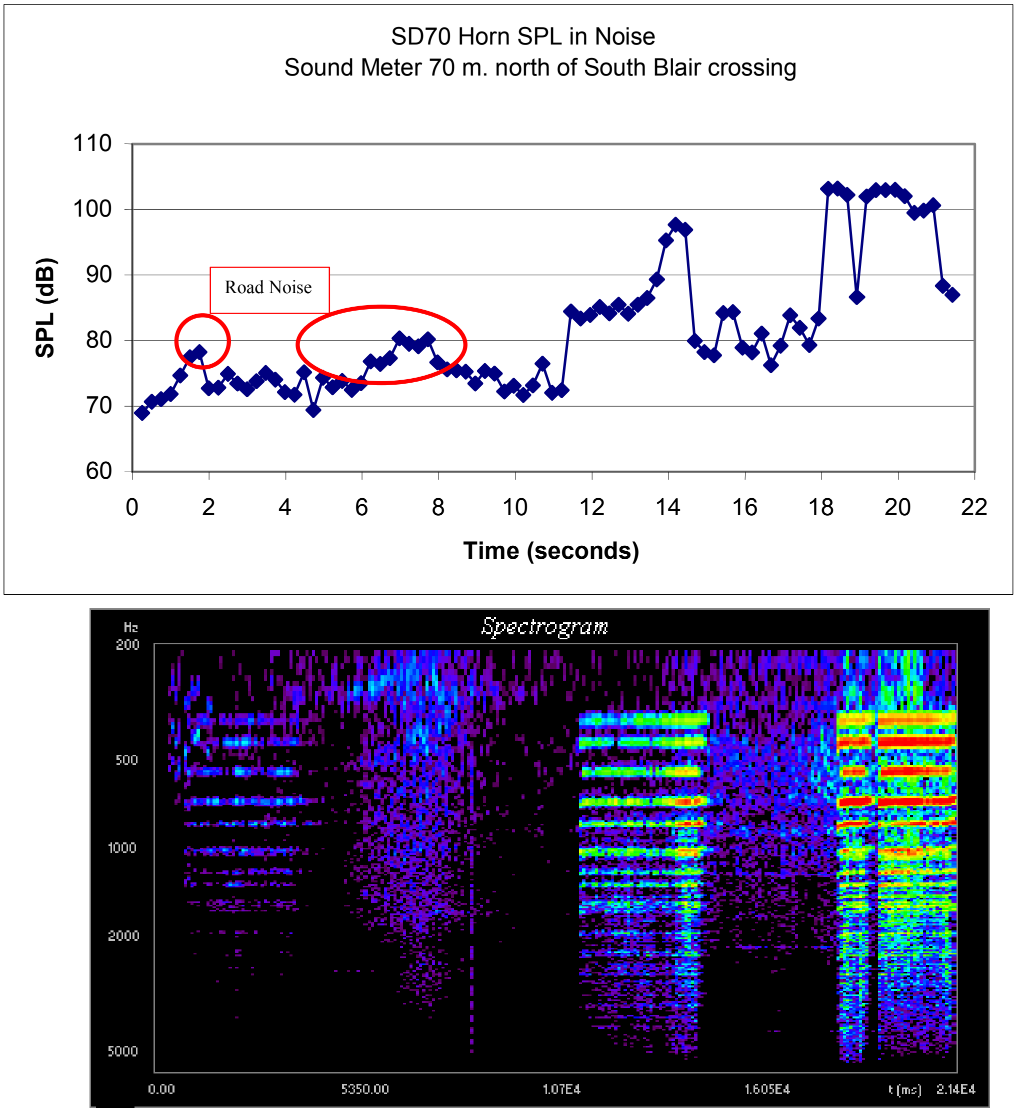


Figure 17 **Comparison of 3-flute horn sound pressure level at South Blair**

4.3.2 Spectrogram Illustration at Low S/N Ratio

We note that the fact that the horn's SPL is indistinguishable from the background noise level does not mean that it would not be heard by a pedestrian. The drawback of the total energy comparison is that the frequency content is not shown. If the horn sound occurs at a different frequency than the background noise, it could still be detected, even though it does not show up on the total energy comparison plot. This limitation is illustrated in Figure 18, which shows the SPL in the upper plot and the corresponding spectrogram below it for an SD70 freight locomotive approaching the South Blair crossing at 40 mph. The SPL plot is misleading in that the sound recorded at one second and seven seconds could be expected to be the horn signal. In fact, these sounds are from passing highway trucks. The horn signal's total SPL is actually below that of the highway vehicle. The difference between highway vehicle noise and the horn is clearly seen in the spectrogram below the SPL plot.



Spectogram illustration of the horn/noise sound spectrum

Figure 18 Signal/noise comparison of sound pressure level and spectrogram

The spectrogram shows the spectral content of the horn signal for the same approach pattern, measured at the same location. The vertical axis is the frequency component of the signal going from 200 Hz at the top to 5,000 Hz at the bottom in steps of 11 Hz. The horizontal axis is the time scale, adjusted to cover the sounding pattern of the horn in its approach to a grade crossing. A spectral slice is measured every 85 ms. The third dimension of the plot is the sound level of the received signal as indicated by colour variation. The colour scale starts with purple at 47 dB and proceeds with increasing sound level through blue, green, yellow and orange to red at 95 dB. A more detailed discussion is presented in subsection 5.1.2. The elimination of sound below 47 dB combined with the absence of signal content below 200 Hz eliminates much of the train-source background noise from the chart.

One can see that background noise also contributes to the overall SPL between 18 and 21 s. Both the single value SPL plot and the spectrogram capture the rise in sound pressure at about 14 s in the plot. The abrupt 13 dB change in the SPL profile is a good indication of the shielding influence of the roofline in front of the horn. The shielding effect is best illustrated in polar plots of the horn output, which are derived in section 4.4.

The spectrogram clearly differentiates the tonal output of the horn from the random noise of the passing vehicle. One can see that the horn would be distinguishable even though its cumulative SPL is lower than that of the passing vehicle. However, we note that while the spectrogram gives a good visual illustration of the relative effectiveness of the warning signal, it offers limited value in producing a quantitative comparison. Thus, in section 4.4 we use 1/3-octave values in the horn spectrum range to isolate the horn and predict its source SPL. We use spectrograms in more detail in chapter 5, where the urgency characteristics of the sound are discussed.

4.4 Derived Source-Signal Polar Plots

We have taken the same measured data used above and conducted further analyses to estimate the performance of the horn at the regulatory equivalent distance. The use of revenue service trains in this way introduces a number of undesirable factors that increase the uncertainty of the derived source characteristics. While the primary influencing factors have been measured and incorporated into the analyses and data reduction activity to minimize the uncertainty, the findings will contain a larger uncertainty band than would be realized with controlled stationary tests. Table 4 summarizes the items of uncertainty and mitigating measures taken.

As indicated in Table 4, we used 1/3-octave data to isolate the horn spectrum from the train's background noise, which was predominantly below 300 Hz. In general, we tried to avoid situations such as the passing of highway trucks where background noise was high in the horn spectrum (as illustrated in Figure 18). We eliminated most measurements where coincident spectral noise was a significant factor. However, there were a few situations where either there were no other data measurements of a specific locomotive/speed combination or the horn signal was always very low. In those cases, where the 1/3-octave band S/N was less than 5 dB, the horn signal was derived by subtracting the measured background noise as follows:

$$S = 10 \times LOG\left[10^{(M/10)} - 10^{(B/10)}\right]$$

where

S = horn signal SPL (dB)
M = measured SPL (dB)
B = average measured background noise in the absence of a horn signal (dB)

Table 4 Source signal derivation procedures

Influencing Factor	Mitigating Steps Taken
Train speed variation	Speed measured with radar, acceleration performance included in position calculations where relevant.
Varying whistle patterns	The position where the horn stopped blowing was noted (relative to the crossing exit) and in combination with speed measurements provided distance versus time data.
Grade crossing geometry	Most grade crossings were selected for straight track approaches; a one-degree curve was present at two sites and was accommodated in the distance and angle calculations.
Low S/N levels	Background noise was always highest at frequencies below the horn's spectrum. One-third octave data were used to isolate the horn and the data were compensated for background noise levels where necessary.
Frequency-dependent absorption	Atmospheric absorption effects were included with ANSI-1.26-1978 calculations. The range of environmental conditions involved in the tests led to changes of less than 1 dB in the full spectrum SPL, but had significant influence in the 3 to 5 kHz range.
Frequency-dependent ground effects	Ground effects can be very complex. Since the main interest is the received signal rather than deriving the originating signal, ground effects were ignored from both the derivation of source characteristic and the attenuation in later applications to needs/effectiveness comparisons.

The measured 1/3-octave band horn signal was then converted to a standard 30.5 m (100 ft.) reference SPL by adjusting for signal dissipation at 20 times the LOG of the distance ratio (or 6 dB per distance doubling) and applying ANSI 1.26-1978 calculations of atmospheric absorption. The atmospheric absorption calculations are most sensitive to temperature and humidity and have a significant impact on the higher frequency range of the horn spectrum. However, since the horn SPL is dominated by the frequency components in the 600 to 1,200 Hz range, the influence on the cumulative SPL of the horn was in general less than 2 dB.

Each data point derived in this way occurred at a specific time in the approach sequence. The distance between the horn and the sound level meter, and the corresponding angle of output for the horn relative to its direction of travel were calculated on the basis of the grade crossing geometry and measured train speed. The end result is an estimate of the polar output of the horn at a reference distance of 30.48 m (100 ft.).

4.4.1 Longitudinal Position Influence

We had the opportunity to measure a wide range of horn positions. Our focus was on passenger locomotives; however, a limited number of freight locomotives were measured to see whether the same sensitivities held. Each of the locomotives and horn positions is illustrated in pictures presented in Appendix E. The GO Transit cab cars and one GO Transit locomotive had the horn at the front top corner of the crew cab's windscreen. The VIA Rail LRC locomotive (which was only operational for a few months early in the study) had the horn on the cab roof roughly a metre back from the front edge of the roof. Its roofline was flat and the front edge of the roofline was rounded. The GO Transit-F59 locomotives, VIA Rail-F40 locomotives and GP9 freight locomotives all had the horn mounted behind and close to the engine exhaust hood. Many of these had air-conditioning equipment mounted on the cab roof in front of the exhaust. The newer VIA Rail Genesis locomotives had the horn on the right side of centre and recessed in a well that partially shielded some of the horn flutes. The roofline was otherwise smooth in front of the well. The SD40 freight locomotives had the horn on the left side of the locomotive (one at 8.7 m and the other at 12.2 m back from the front of the locomotive). West Coast Express (WCE) had newer F59 locomotives with the horn fully recessed in a well and behind the engine exhaust. The

Dash 9 freight locomotives had the horn in a well, mid-locomotive but ahead of the engine exhaust. The SD70 locomotives had the horn in a well and behind the exhaust but much farther back from the well face than the other locomotives.

4.4.1.1 Three-Flute Horn Comparison

The polar output for a range of speed and horn positions is presented in this subsection. We note that the polar plots illustrated in this subsection are valid for the speed at which they were measured. Train speed influences the horn's effective forward output in a non-linear relationship as is discussed in subsection 4.4.2.

Figure 19 illustrates the loss of output in the forward direction for two types of passenger locomotives at high speed (nominal 90 mph). As discussed in section 4.2, the F40 locomotives have the horn mounted behind the exhaust hood while the LRC's horn is mounted on the cab roof. The plots present the 30.5 m (100 ft.) equivalent output of the horn for increasing angles from the forward direction. Two different F40 locomotives at two different test locations are illustrated in the plot. The nominal speed is 90 mph (actual speeds were 89 mph at South Blair grade crossing and 92 mph at Oliver grade crossing). The measurements were made on one side only and symmetry is assumed for the centre-mounted horn. The characteristic is such that the forward output is well below the minimum recommended standard, and full output of the horn is not realized until +/-40 degree angles from forward. The LRC's characteristic was measured at South Blair grade crossing at 91 mph (and decelerating). VIA Rail replaced the LRC locomotive with newer Genesis locomotives early into our study and thus, we did not have a wide range of LRC measurements.

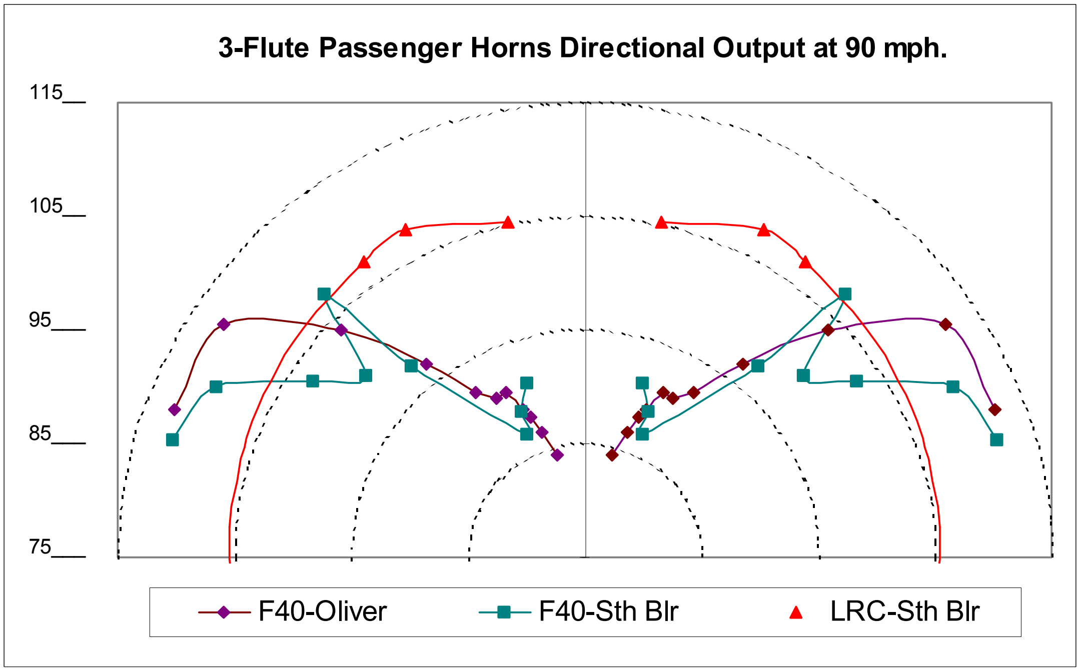


Figure 19 **Passenger locomotive 3-flute horn polar plots**

Figure 20 presents the polar plots of a number of different freight locomotives that use 3-flute horns. One can see that the GP9 locomotive, which has a similar horn placement to the F40 and F59PH locomotives, produces a similar result. The other freight locomotives have a steeper rise in output with increasing angle. The SD40, which has the horn mounted on the left side of the locomotive is seen to have a reduced effectiveness at shallow angles on that side of the locomotive, even though there is a direct line of sight from horn to sound meter. This is consistent with our findings for 5-flute passenger locomotives as discussed in subsection 4.4.1.2.

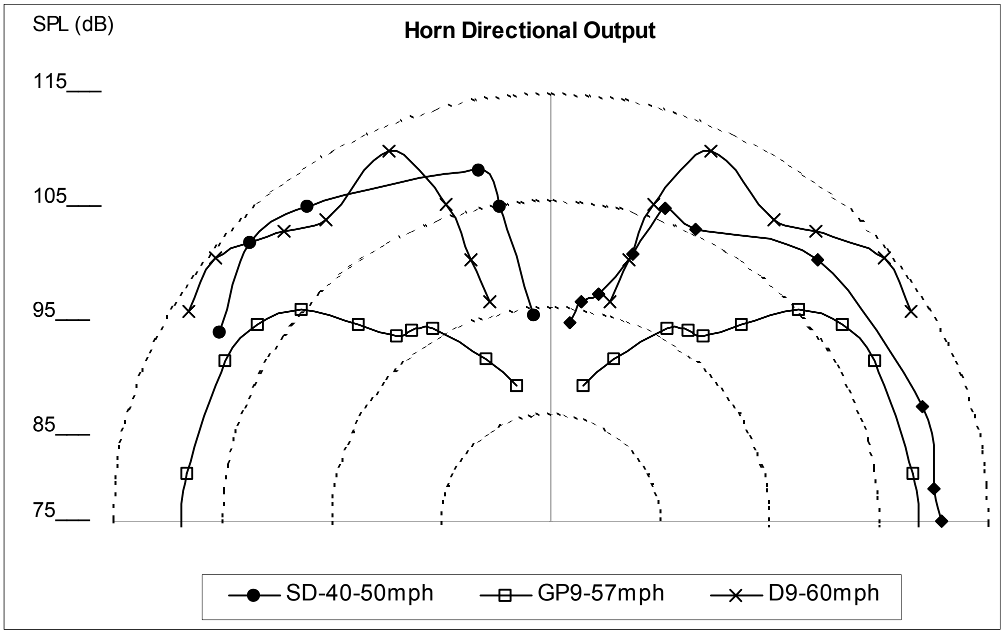


Figure 20 Freight locomotive 3-flute horn polar plots

4.4.1.2 Five-Flute Horn Comparison

GO Transit's F59 locomotives have a 5-flute horn mounted in a position similar to VIA Rail's F40 locomotive horn (Figure 21). GO also had one locomotive on lease that had the horn mounted at the top, front edge of the cab roof.

The directional output of the two horn locations when travelling at medium speed (35 to 50 mph) is compared in Figure 22. The attenuation of output to the front of the mid-body horn position is evident.

The directional output of VIA Rail's Genesis locomotive horn at 75 mph is illustrated in Figure 23. Of interest is the fact that the output to the front of the mid-body horn position is attenuated more on the horn-mounted (right) side than on the opposite side.

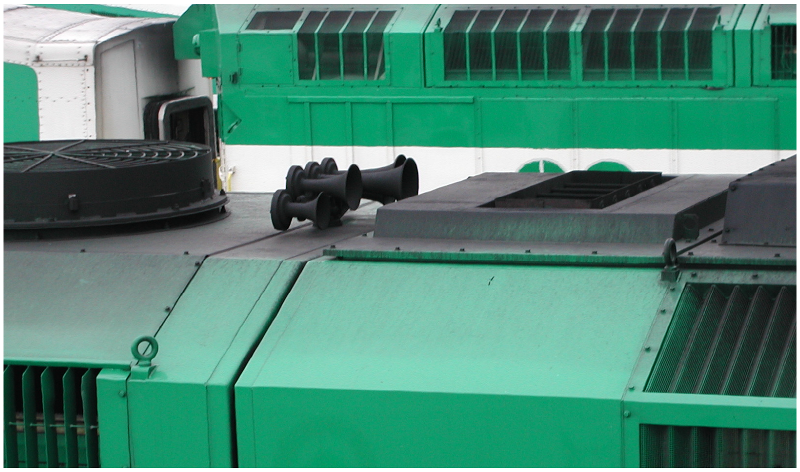


Figure 21 Photograph of mid-body horn position

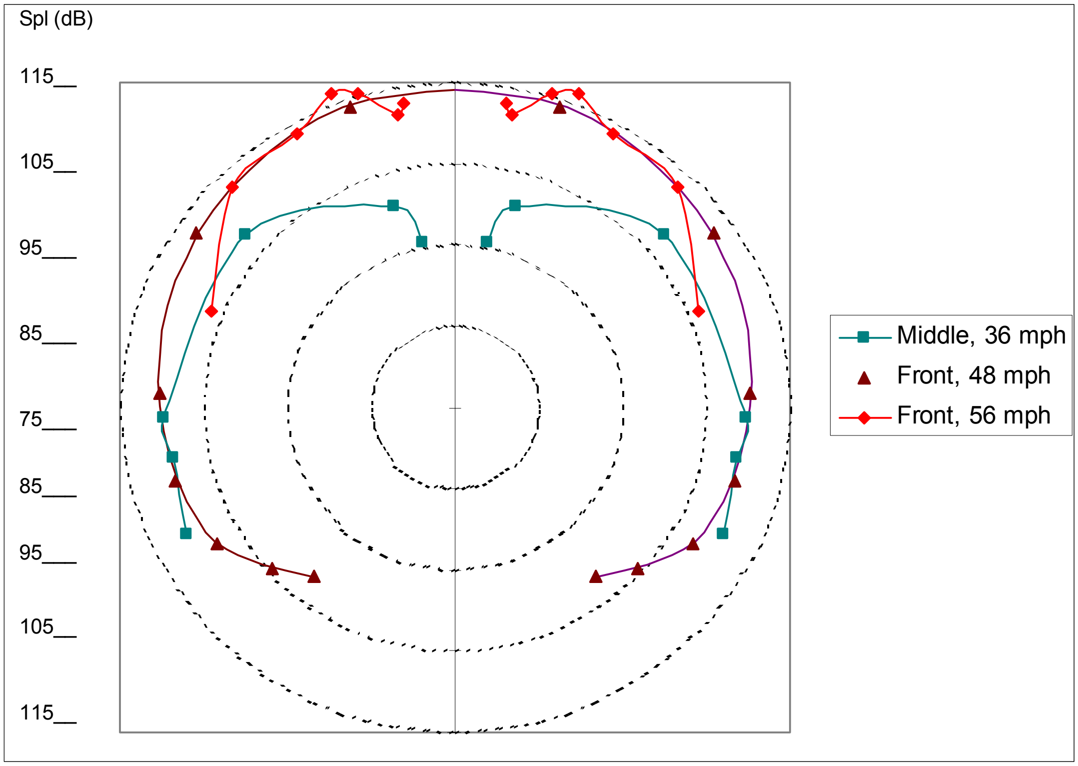


Figure 22 Five-flute horn directional output at medium speed

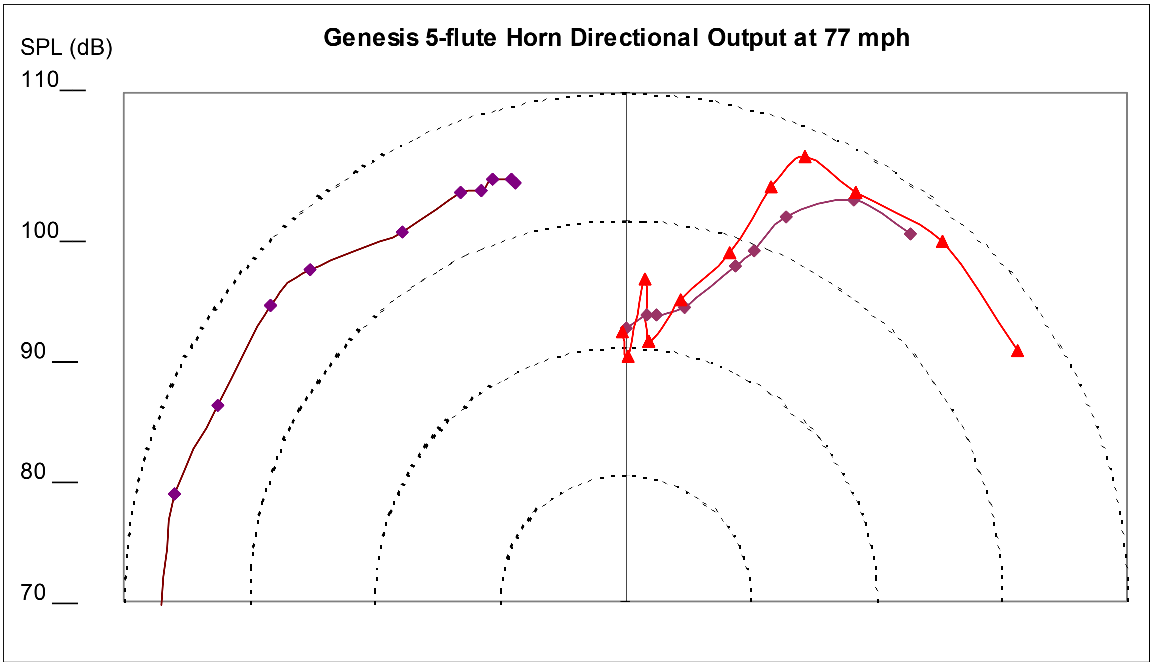


Figure 23 **Genesis locomotive 5-flute horn directional output**

4.4.2 Speed Influence

There was enough range in speeds for most horn positions to infer an influence of train speed on the horn's sound output. Output was not significantly changed for horns mounted at the front of the locomotive (or other lead vehicle). However, the sound output to the front of the locomotive deteriorated with increasing speed for all horns tested in locations back from the front of the locomotive. Because we were dependent on revenue train testing, we did not get all of the data points we would liked to have had for all horn combinations. The most complete set was for the passenger trains, which were the only trains to exceed 60 mph in our tests. Nonetheless, all mid-locomotive horn positions showed decreases to the front that were larger than reported in the literature for static testing, and are consistent with the fuller data set we have for the passenger locomotives.

The sound loss characteristic as a function of speed is illustrated in Figure 24 for GO Transit's F59 locomotive (5-flute horn, behind exhaust). The loss characteristic is such that a leveling off is achieved for speeds between 45 and 100 km/h and then continues to decrease with increasing speed beyond 100 km/h. We note that the loss characteristic is derived from revenue train testing at different locations and different times and does not reflect the accuracy of experimental design and controlled conditions. Nonetheless, it is representative of the losses seen in multiple locomotives across several locations. It also fits with the controlled test measurements reported by Labour Canada (LC) for the side-mounted horn used in its tests—the LC test range data in Figure 24 is the range shown in Figure 11 for the measurement distance range 50 m to 400 m.

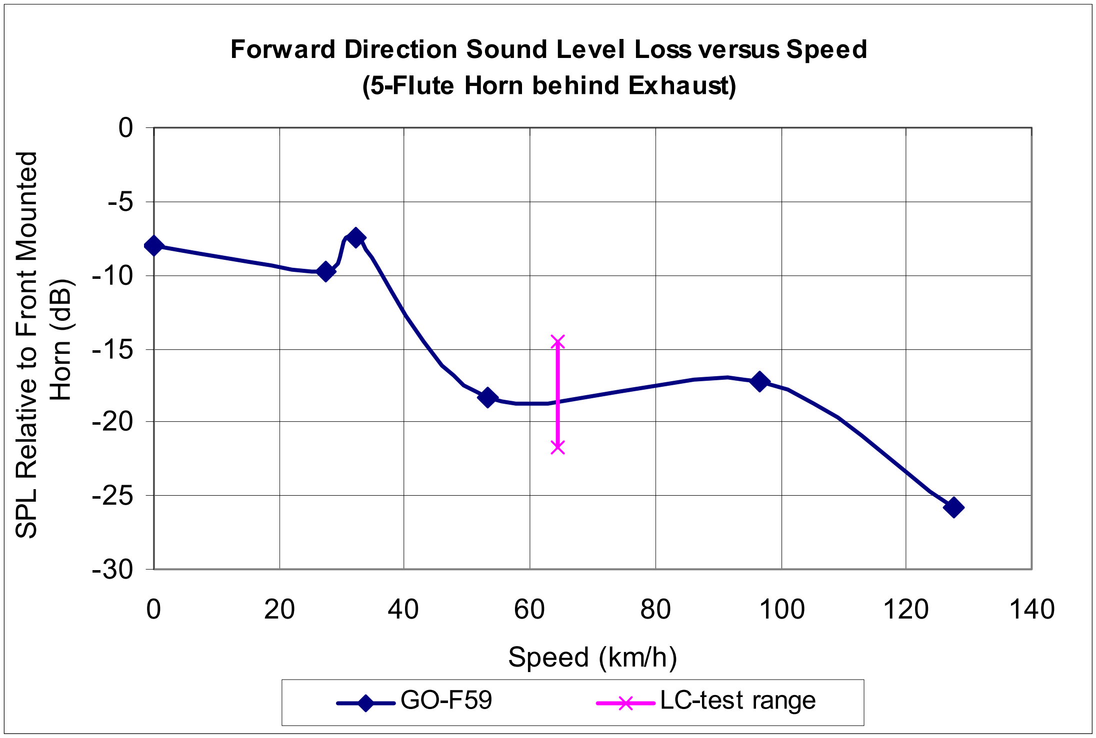


Figure 24 **Speed influence on forward output sound attenuation**

We believe that Figure 24 is a reasonable characterization of the influence of speed on horns that are located behind and close to the exhaust stack. The loss of output is accentuated when the horn is located behind the engine exhaust, but also seems to be related to the air turbulence produced by roof-mounted equipment or abrupt changes in the roofline. Attenuation due to normal wind turbulence has been documented [Daigle, 1979]. We reiterate that the loss is only in the forward direction. Output to the side is unaffected (and possibly amplified at some lateral angles) by the mid-locomotive positioning.

The loss to the front that was illustrated in the polar plots of the SD40 and Genesis locomotives (Figure 20 and Figure 23) indicate there is an impact even when there is a clear line of sight between source and receiver. Both horns suffer a loss of output at shallow angles from the side of the locomotive on which they are mounted. We presume that, in addition to turbulence, there might be a diffraction impact from the effective wind gradient set up by the locomotive body moving through air. Headwind gradients are known to bend sound upward in a mechanism known as refraction [Lamancousa, 2000]. The effective air-speed gradient seen by the propagating sound along the locomotive body will increase in speed the farther it gets away from the body (see Figure 25). The horn sound could be bent away from the body through this sound refraction mechanism.

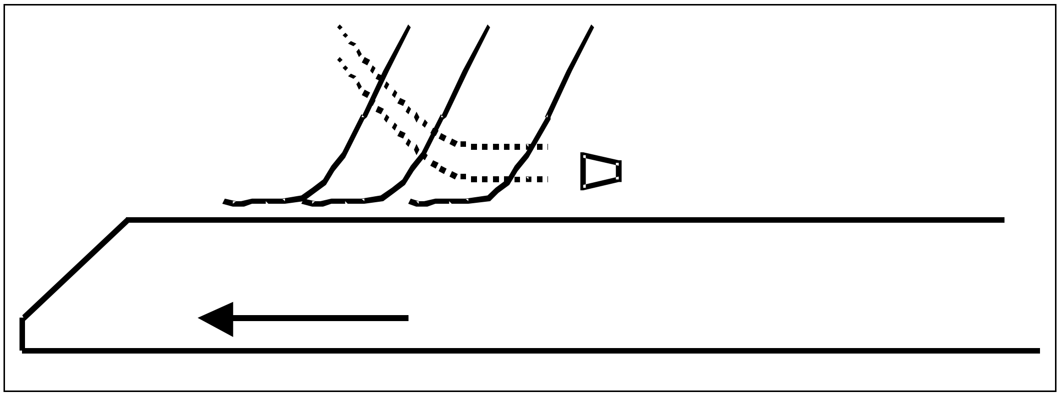


Figure 25 **Illustration of horn sound refraction**

We would expect that both turbulence and refraction would be mitigated with smoother roof surfaces and increasing mounting height of the horn. However, there is an impact even when the horn is mounted such that there is a clear line of sight path from horn to receiver. VIA Rail raised one of its Genesis horns such that there was a clear line of sight to the front of the locomotive for all five flutes—the normal horn has four flutes partially shielded and one flute fully shielded by the well in which it is recessed. However, there still was a loss of output in the forward direction with the raised horn, even on the side of the locomotive on which the horn is mounted.

Figure 26 summarizes the influence of train speed and horn height on its warning characteristics at about 4 s warning for the Genesis locomotive horns in comparison with a front-mounted horn. We note that the selection of a 4 s reference point has no particular meaning, but was dictated by the data—all of the different trains were blowing their horns at this time interval from the grade crossing.

As can be seen from the total SPL bars at the right side of Figure 26, the full spectrum SPL is only improved by 6 dB with raising the horn and is still 8 dB below the front-mounted horn at the same speed. On the other hand, the higher frequency content is significantly affected. Looking at the green and red bars in the 4,000 Hz 1/3-octave band, one can see that the raised horn at 92 mph has a 25 dB higher sound level than the unraised horn at 87 mph. This would improve its alerting characteristics. We explore this observation in more detail in our evaluation of warning needs of horns (subsection 5.1.3).

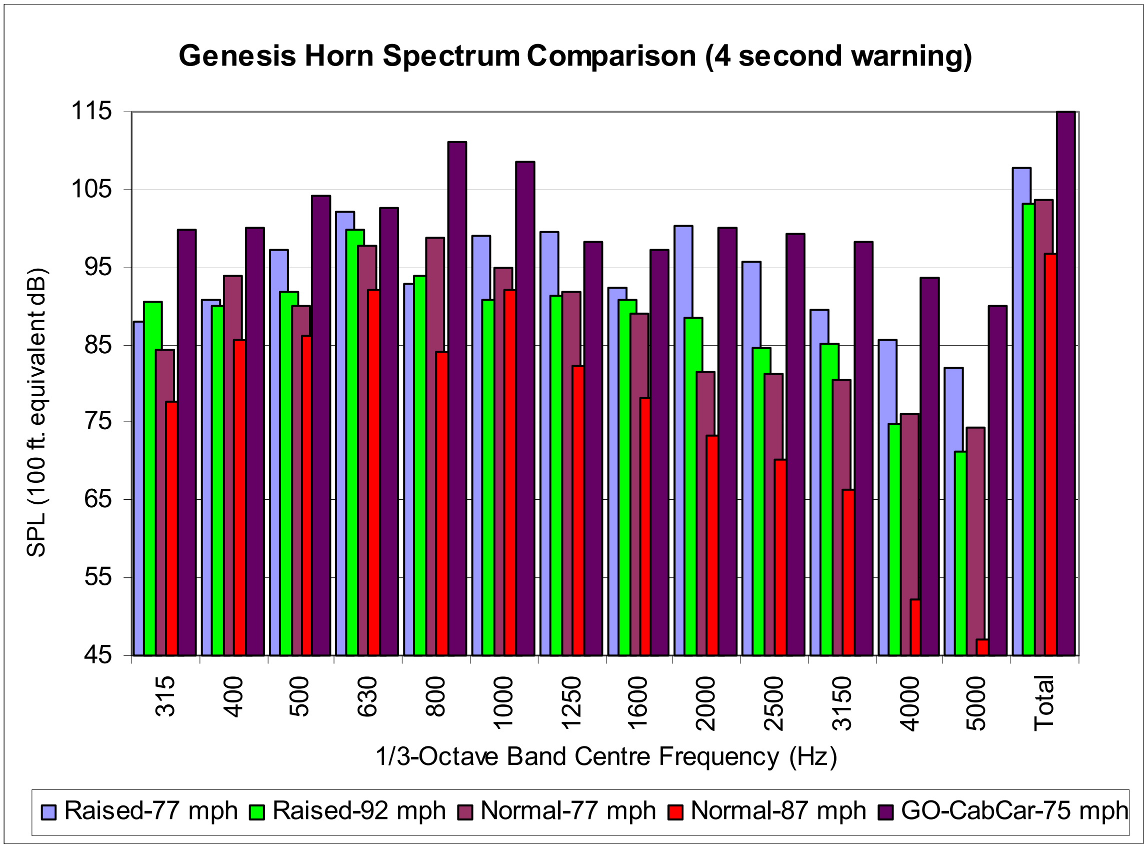


Figure 26 Genesis locomotive horn height/speed influence

4.5 Weather/Geometry Influences

The revenue tests were conducted to purposely avoid conditions of high wind. By testing in low wind conditions, we were getting an indication of the average signal. It is known that wind and temperature gradients will bend sound paths much as a glass refracts light rays. Thus, the polar plots we have generated from low wind conditions would display a wider variation in different wind (and possibly temperature) conditions. Horns that are positioned behind protrusions (or other shielding influences) are more significantly influenced by wind conditions. The Genesis horn, which was the mid-locomotive horn with the least amount of shielding, can be expected to be most sensitive to wind and temperature effects, but all shielded horn positions will exhibit sensitivity to wind.

Figure 27 illustrates the influence of tests done within 15 minutes of each other under wind conditions that averaged 13 km/h (at ground level) with gusts to 19 km/h. The test conditions were outside our test criteria. Nonetheless, the measurements offer insight to the effects of wind and wind gradient. The wind was blowing along the track, such that an eastbound train had a tail wind condition while a westbound train had a head wind condition. The impact of the wind is significant, producing a 20 dB difference between train directions at the shallowest measurement angle. In the same way, lateral winds can be expected to either reduce or exacerbate the angle at which full output is attained in polar plots. Consequently, one can expect to have situations where the mid-locomotive horns perform either better or worse than our low-wind measurements indicate. Nonetheless, it should be emphasized that these influences are not as significant for front-mounted horns, where there is a direct path for the sound. It is those locations that require an indirect path for the sound that will exhibit the most sensitivity to wind conditions.

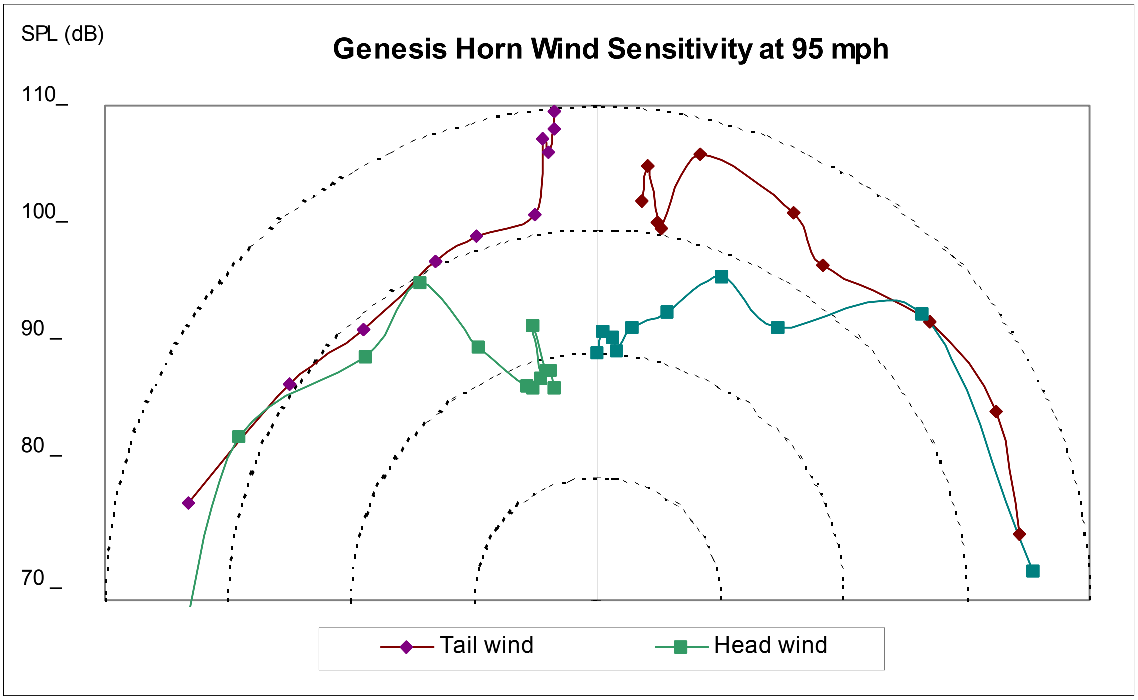


Figure 27 Genesis locomotive horn's sensitivity to wind conditions at 95 mph

Similarly, the geometry of approach roads will have an influence beyond that of the ground effects discussed in section 4.6. An elevated approach road could avoid the shielding effect of roof wells on mid-body locomotive horn positions, while an elevated track would exacerbate the shielding effect. The former has been demonstrated in stationary tests with a sound level meter mounted on 16 ft. high pole [Fann, 2001]. Just as with wind conditions, there will be geometric conditions under which a mid-locomotive horn will be more effective than our site measurements indicate. However, such scenarios will be in the minority and will have an equal number of scenarios that are worse than the average conditions we are presenting.

We note that the tail wind condition depicted in Figure 27 might offer additional insight into the refraction mechanics affecting the sound of the horn. When the locomotive gets closer, the angle of refraction is not enough to bend the sound down to the sound level meter. The farther away the locomotive, the higher the SPL (100 ft. equivalent) reaching the sound level meter, to the extent that on its first blow (at about 400 m) the horn is operating at 110 dB. The actual *wind gradient* was not known; however, it is possible that the gradient associated with the 13 km/h ground wind speed required 400 m to bend the sound path down enough to counteract the 145 km/h aerodynamic wind gradient acting over the 10 m of locomotive body length that the sound initially travels.

The front-mounted horn avoids locomotive-body induced screening, air turbulence and refraction influences. Avoiding these influences with mid-locomotive horn positions requires elevation of the horn. We note that the increased line clearances generated on many mainline railways to accommodate double stack containers and tri-level auto-rack cars might allow elevation of mid-locomotive horns to a height where they can realize a warning effectiveness comparable to front-mounted horns. We assessed the effectiveness of raising the horns of a VIA Rail Genesis locomotive above the well in which it normally sits and attained some improvement. We were not able to conduct tests to determine the necessary height to fully achieve the performance of a front-mounted horn.

4.6 Height of Front-Mounted Horn

The height of a front-mounted horn introduces two possible influences: shielding and ground effects. The lower the horn is positioned, the higher the probability of shielding due to parked rail cars, or adjacent rock cuts or earth berms. This influence would favour locating the horn as high as possible. Similarly, freight locomotives that might travel in the reverse direction at times would provide a better signal to the rear with a rooftop-mounted horn.

Ground effects arise from the fact that the acoustic pressure wave received by a listener is a combination of those pressure waves transmitted in a straight line of sight from the source and those that are reflected off the ground. The reflected wave takes a longer path and will lose some of its intensity due to dissipation at the ground surface (see Figure 28).

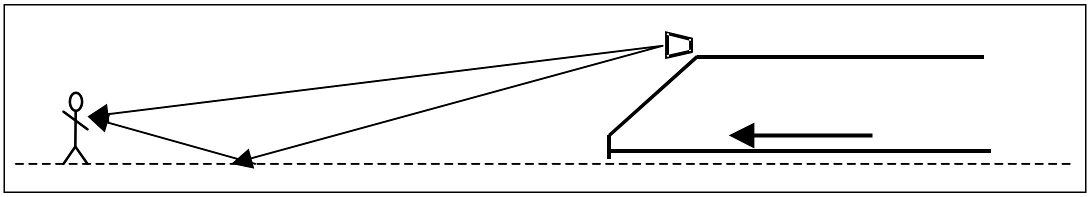


Figure 28 Illustration of ground effect on sound reception

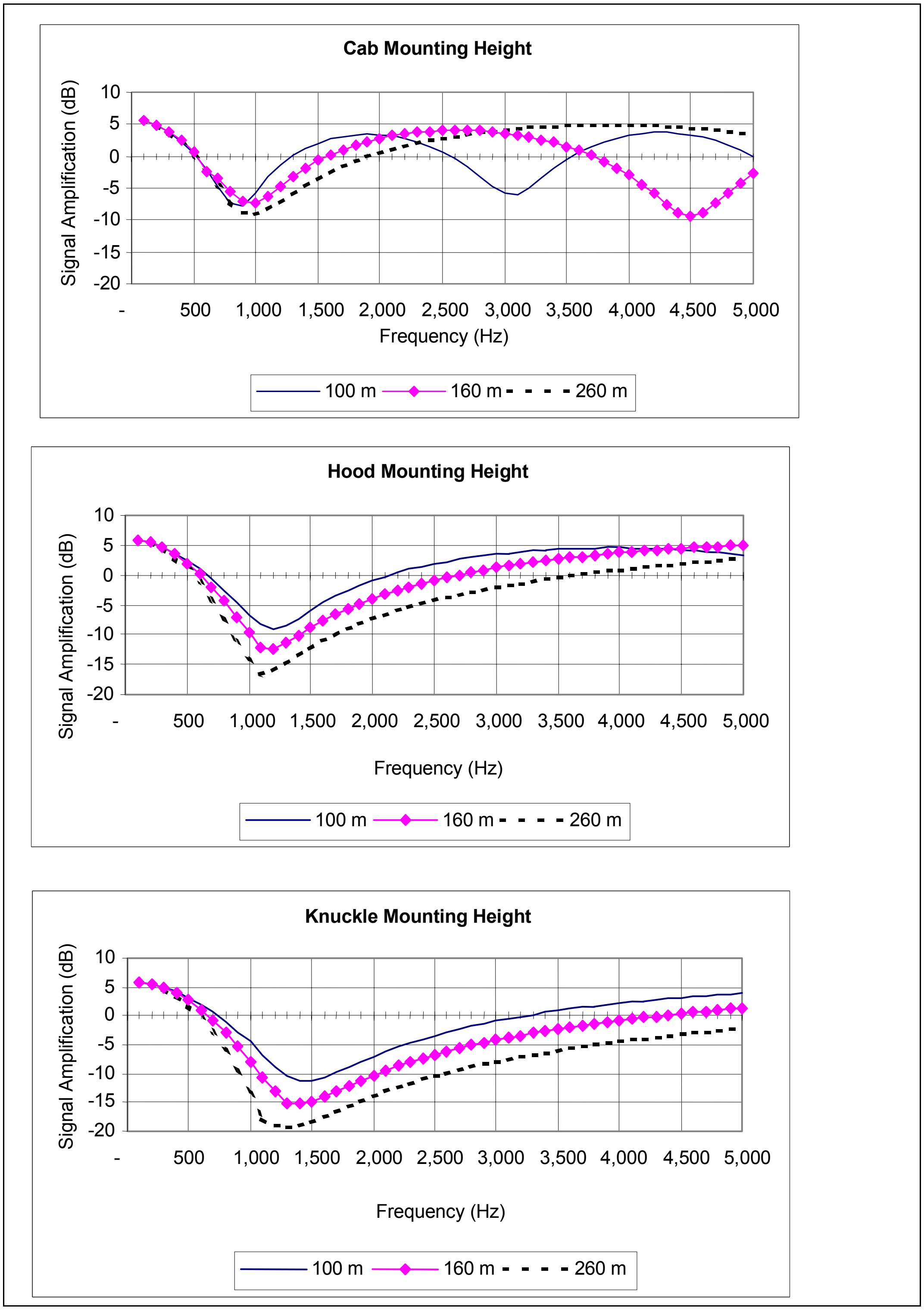
The longer path taken by the reflected wave results in a frequency-dependent aggregate signal. Some frequencies can be attenuated and others amplified and the analytic process is quite complex [Rudnick, 1947]. Since ground effects are sensitive to the ground type, slope and relative height between source and receiver, generalization of the consequences is not possible. However, a pedestrian or trespasser on the track presents a more uniform condition. We assessed the ground effects of different mounting heights on the warning signal received by a pedestrian/trespasser on the track in front of a locomotive using the implementation of Rudnick's algorithm in the Community Noise Model of the University of Central Florida [2002]. Table 5 summarizes our analytic assumptions.

Table 5 Parameters assumed in ground effects calulations

Parameter	Assumed Value
Cab-mount height	4.4 m
Hood-mount height	1.7 m
Knuckle-mount height	0.9 m
Receiver height	1.5 m
Track ground effect impedance	2,000 CGS Rayls
Track gradient	0.0 percent

The predicted ground effect over the horn's frequency range and for each of the three mounting heights is illustrated in Figure 29. It is evident in Figure 29 that the lower mounting heights have a broader range of attenuation than the higher mounts. As the locomotive gets closer to the receiver, the characteristic of the highest mounting position becomes more complex. Table 6 compares the integrated full spectrum, A-weighted SPL of the auditory signals received by a subject of 1.5 m height at the three distances illustrated in Figure 29 (100 m, 160 m and 260 m). The calculation applies the ground effect characteristics of Figure 29 to the frequency spectrum of K3L and K5L horns.

One can see that the top-of-cab position has an advantage over the other two positions for all but one combination (K5 at 100 m). The advantage of the cab mount over the knuckle position at 260 m is the most significant at 8 dBA. We note that the analytic results display a similar sensitivity to (but are larger in magnitude than) field measurements made by the Volpe Center [Rapoza & Fleming, 2001]. Their hood and knuckle positions produced increased attenuation-per-distance-doubling of 1.3 dBA and 2.4 dBA, respectively. Their results were based on measurements over a range of 30.5 to 122 m, which is at the lower and least sensitive end of our analytic range.


Cab Mounting Height

Hood Mounting Height

Knuckle Mounting Height

Figure 29 Horn height influence on ground effects

Table 6 Height influence on ground effect, full spectrum SPL (dBA)

Horn type	K5L			K3L		
Distance	100 m	160 m	260 m	100 m	160 m	260 m
Knuckle mount	-1.2	-3.6	-6.4	-3.1	-5.4	-7.9
Front-hood mount	1.4	-0.1	-2.9	0.1	-1.3	-3.9
Cab mount	0.5	1.5	1.8	0.3	0.3	0.4
Avg. Cab advantage						
Cab - Hood	-0.9	1.6	4.7	0.3	1.6	4.2
Cab - Knuckle	1.7	5.1	8.2	3.5	5.7	8.3

We also note that pedestrians at grade crossings, wayside employees and possibly passengers at stations would be exposed to higher sound levels if the horn were mounted at a lower level. The U.K. horn regulations [U.K. Railway Group, 1995] include a maximum limit of 135 dB at trackside on a 10 km/h pass-by test (at 1.5 m above the top of rail and both 1.2 and 2.0 m horizontal from the nearest rail). This would not pose a problem for a horn mounted at roof level but might if the horn were mounted at a 1.5 m height.

All the above factors favour a rooftop location. On the other hand, a lower position might reduce the in-cab sound level as well as the community impact. Test measurements made by the Volpe Center [Rapoza & Fleming, 2001] indicated that there was reduction in the in-cab sound level for horns positioned at coupler height of 4 dB. Their hood-mount location was on top of the hood. It is possible that a front-of-hood location would have a lower in-cab SPL. Also, for trains with a high community noise impact, the hood location offers potential to recess the horn and achieve shielding to the side, thereby lowering community noise impacts. Locomotives might achieve significant reductions in community noise impact with modest reductions in safety warning performance and we recommend that hood mounts be considered for service areas where community noise is a concern. For existing locomotives, retrofit costs might dictate another position where performance thresholds can be met at a lower cost.

5 LOCOMOTIVE HORN EFFECTIVENESS

5.1 Spectrogram Comparison

5.1.1 Pedestrian/Trespasser Warning Needs

Auditory warning devices can be the only warning device for some situations involving pedestrians (e.g. walking away from the train or crossing with view obstructed by another train). In many cases the auditory warning has limitations. Trespassers must be seen before an auditory warning device can be sounded. Low visibility and poor sight lines around curves can prevent a crew from seeing a pedestrian in time to provide adequate warning. Even when sightings are made in time, wind conditions and noise can prevent even the loudest auditory warning device from being heard in time. Nonetheless, an auditory warning device is often the only warning available. We note that trespassers who have headphones on or who are on snowmobiles are better characterized by the analysis of vehicles stopped at crossings (subsection 5.2.2). In this subsection, we only consider open-air conditions.

We had hoped that video surveillance cameras that were installed in locomotives during the study would have given a basis to define warning/reaction times. Unfortunately, there were very few incidents captured on video. Nonetheless, there was sufficient evidence that there is quite a spread in reaction times. We have adopted a 3.1 s reaction time for an auditory warning device, composed of a 0.6 s alerting time and an additional 2.5 s for visual confirmation. We assume an additional 2.5 s required to move out of harm's way—a total required warning time of 5.6 s. In the absence of relevant data, we assume that 5.6 s is a conservative warning time. If a loud signal is received and has some perceived urgency, we would expect a shorter reaction time could suffice.

The above time must be increased by the lag time associated with the speed of sound in air. The train will travel some distance during the interval between horn application and receipt of sound by the pedestrian. The effect is proportional to train speed and results in a warning time equation of

$$T_{awd} = {T_{res}} \Big/ {\left(1 - \frac{V_t}{V_s}\right)}$$

where

Tawd = minimum warning time from the auditory warning device,
Tres = minimum response time required by the subject (3 to 5.6 s),
V_t = speed of the train, and
V_s = speed of sound in air (331.9 m/s).

One can see that for a train speed of 161 km/h (100 mph), the warning time increases from 5.6 to 6.47 s. For the distance associated with each train speed, we calculate the sound dissipation to determine the required output from the horn at the regulatory 30.5 m (100 ft.).

5.1.2 Spectrogram Criteria

As noted in section 4.3, a total energy SPL number has analytic advantages for some comparisons but does not provide a good illustration of the complex warning mechanism involved. We use spectrograms to visually illustrate and compare warning signals in some cases. Figure 30 illustrates the colour criteria used in the spectrograms to be presented. The sound measurement shown in Figure 30 is a front-mounted 5-flute horn on a train going 58 mph. The vertical axis is the frequency component of the signal going from 200 Hz at the top to 5,000 Hz at the bottom. This frequency range encompasses the lowest fundamental frequency of the horns (311 Hz) and the eighth harmonic of the highest fundamental frequency (8 X 622 = 4,976 Hz). The horizontal axis is the time scale, adjusted to cover the sounding pattern of the horn in its approach to a grade crossing. The third dimension of the plot is the sound level of the received signal as indicated by colour variation. Each colour pixel shown represents the SPL that is 11 Hz high and 85 ms long. The bar at the top of the chart shows the colour scale. Sound levels below 47 dB are not present. This, combined with the absence of signal content below 200 Hz, eliminates much of the background noise from the chart.

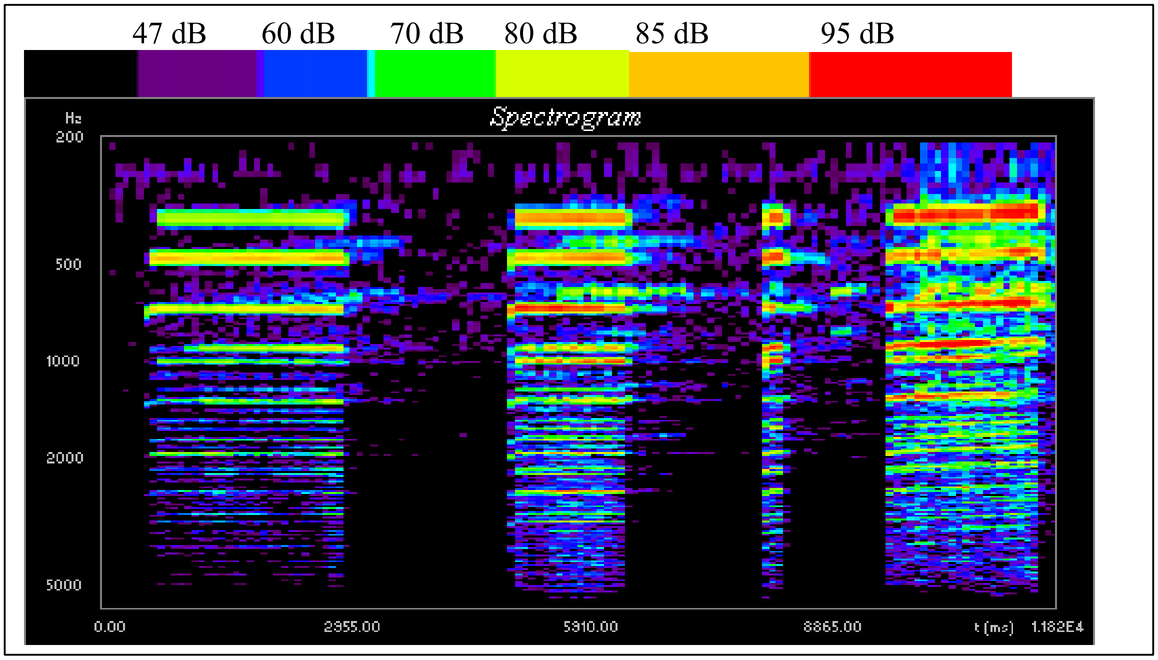


Figure 30 Spectrogram colour coding illustration (5-flute front-mounted horn)

The use of a constant colour scale for the full spectrum is a reasonable interpretation of in-vehicle signal detection (as discussed in subsection 5.2.1 and illustrated in Figure 36); however, it is not an ideal format for signal detection by pedestrians. Nonetheless, the spectrograms offer some insight into the detectability and urgency of the various horn signals. One can roughly interpret the colours as follows:

- purple represents the onset of audibility to a pedestrian in an outdoor low-noise environment,

- yellow represents the onset of alerting inside an automobile with low internal noise levels,
- orange has a good chance of being detected inside a noisy automobile and being alerting inside a quiet vehicle,
- red would be alerting for many in-vehicle situations.

5.1.3 Spectrogram Comparison for Pedestrians/Trespassers

The effectiveness of an auditory warning device is influenced by its frequency spectrum. Sound propagation in the atmosphere and the effectiveness of the human ear are both frequency dependent. The frequency response of the human ear at low sound intensities is often characterized by an A-weighting. The 96 dBA sound level requirement in the present horn standard is derived from a log summation of all frequencies after weighting each frequency band according to its A-filter factor. The combined effects of A-filtering and absorption at 20ºC at two different relative humidity levels are illustrated in Figure 31. One can see that a sound transmission from source to brain on a summer day attains peak efficiency in the 1,000 to 2,000 Hz frequency range. The ear increasingly attenuates frequencies below 1,000 Hz, and the atmosphere increasingly absorbs frequencies above 2,000 Hz. Our urgency experiments further accentuate the desirability of signal components in the higher frequency range (2,000 to 4,000 Hz).

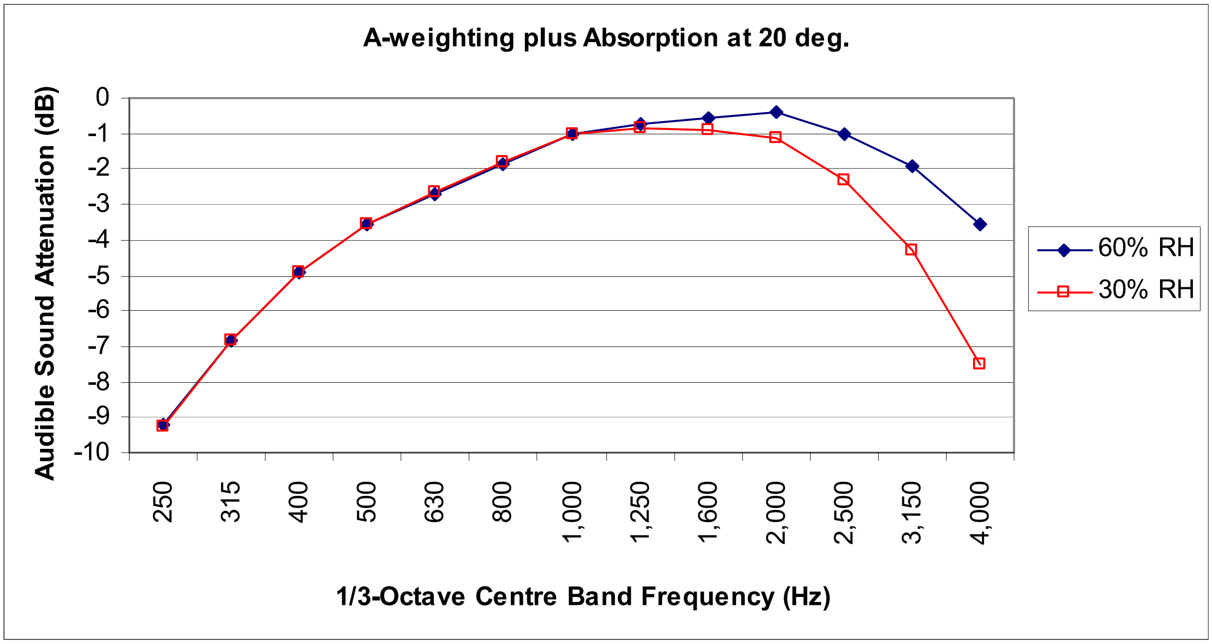


Figure 31 **Effect of the ear and atmosphere in attenuating the horn spectrum**

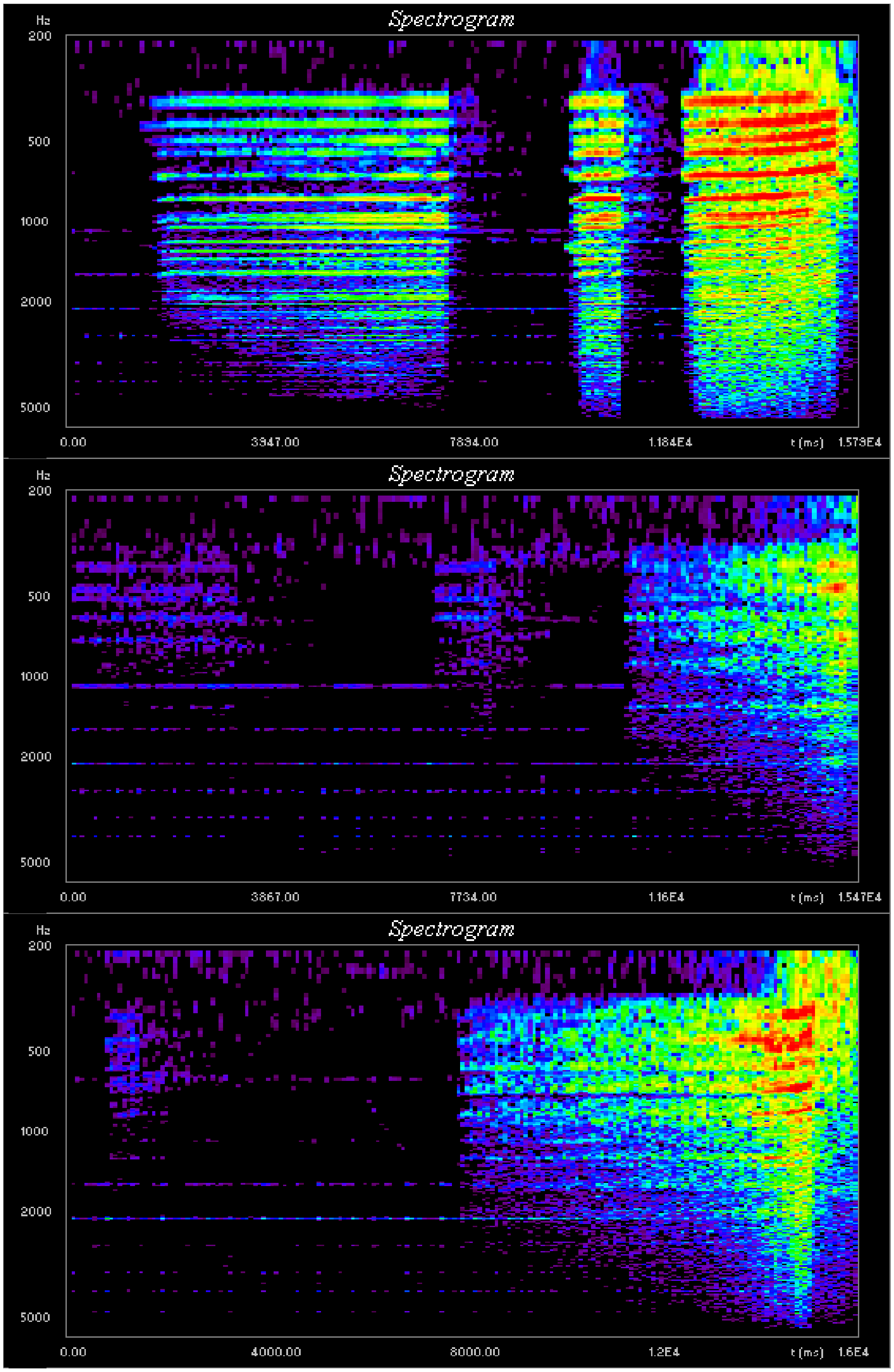
Figure 32 compares spectrograms of two different trains approaching the Beechgrove grade crossing in Scarborough, Ontario. Each plot is 15 s duration. The sound level meter is located close (18 m) to the grade crossing and thus the horn's angle of emitted sound is shallow for much of the approach, depicting what a pedestrian near the track would hear. The crossing bell sound is evident in each plot as the broken lines occurring between 1,000 and 5,000 Hz. The upper plot in Figure 32 is of a 5-flute horn mounted at the front of a cab car, while the middle and lower plots are of a 5-flute horn mounted mid-locomotive behind the exhaust. The cab car was going 75 mph while the locomotive was going 79 mph (middle plot) and 60 mph (lower plot). The cab car approaches the grade crossing from a direction that has curved track back at the initial horn sound location. The locomotives come from the opposite direction and have a straight stretch of track for the full measurement interval.

The 5-flute horn mounted up front on a cab car going 75 mph provides a strong full spectrum signal from beyond 10 s of warning. A pedestrian would hear the horn's spectrum with clarity up to 4,000 Hz from the first blow of the horn. The horn would also be heard inside a vehicle at the crossing with 10 s warning and would reach an alerting level with more than 6 s warning.

The two mid-locomotive horns shown in Figure 32 can be seen to be audible to a pedestrian, but the intensity is well below that of the up-front cab car horn of Figure 30.

The presence of background noise or earphones would make their sounds inaudible for much of the approach. The horn would not be heard inside a closed vehicle at the crossing until the locomotive passed ahead of it. The sound quality also lacks the clarity and spectral content of higher frequencies that were evident in the cab car horn's spectrum of Figure 30.

Our laboratory experiment conducted on perceived urgency was intended to assess different horn compositions rather than to assess the urgency of field recordings. We note that the original experiment included the 5-flute horn used on both the trains recorded at Beechgrove. However, the experiment on urgency was conducted in a laboratory with recordings of new stationary horns. The revenue test sounds involved trains at high speed. Nonetheless, applying the urgency equation derived in that experiment offers some insight into the relative urgency of the two warning signals.



Front,
75 mph

Mid-Loco,
79 mph

Mid-Loco,
60 mph

Figure 32 Spectrograms of 5-flute horns front and mid-locomotive

Table 7 shows the calculated urgency associated with the horn sound characteristics at specific warning times. The front-mounted horn going 75 mph presents a sound characteristic that falls in the data range of the experiments (assessed urgency ranged from 37 to 72). The calculated negative value for the 5 s warning from the locomotive horn located behind the exhaust at 60 mph is an indication that the sound spectrum is outside the data range of the laboratory experiments. Nonetheless, the calculation gives an idea of the urgency relationship between the two horn sounds. We emphasize that the recordings compared in Table 7 are of the same type of horn, the only difference is the location. The difference in sound is also only relevant for the forward direction; sound characteristics at angles beyond 40 degrees are the same. As far as the urgency variables are concerned, only the centroid is different—the number of flutes and musical dissonance are the same.

Table 7 Extrapolated urgency calculation for different horn locations

Horn Location	Train Speed	Warning Time	Extrapolated Urgency
Front	75 mph	5 s	56.5
Behind Exhaust	79 mph	1 s	17.5
Behind Exhaust	60 mph	5 s	< 0

Another factor not captured in the urgency calculation, but which is evident in the spectrograms, is the relative clarity of the sounds. The intermittent, muffled characteristic of the horn sound when located behind the exhaust is subjectively assessed to give an impression of being from a distant origin. The clarity and high harmonic content of the up-front horn is assessed to have a close proximity as well as a higher urgency.

We conclude that, even though both horns can be heard in time for a cautious person to react, the nature of the sound of the horn located behind the exhaust stack is such that a less cautious individual might not consider it to be from a nearby train and would have a lower perception of urgency than for the same horn mounted up front.

5.1.4 Spectrogram Comparison 70 m from Grade Crossing

The reader is referred back to the spectrogram in Figure 30 for the colour coding and explanation of spectrogram content that is shown in this subsection. The spectrogram in Figure 30 is the warning pattern of the same GO Transit cab car with front-mounted horn and illustrates several desirable characteristics of the horn's sound:

- The signal attains a high level of harmonic content in its first blow (shown previously to occur at about 300 m from the sound meter). The eighth harmonic of the highest fundamental is audible and would provide a high centroid measure that is important to the perceived urgency associated with the signal.
- Several of the tones (from 500 to 2,000 Hz) attain a yellow sound level that could be detected inside a car. The second blow, with 6 s warning time contains some red and many orange level tones.
- The clarity of the signal is evident in the long narrow lines that would be associated with constant pure tones.

Figure 33 presents the spectrograms of four different horn positions / train speeds as the trains approach the South Blair grade crossing. The blue/purple broken lines occurring between 1,600 and 5,000 Hz of the lower left and upper right spectrograms are from the sound of the crossing bell, which is heard in these measurements.

The two spectrograms on the left compare two different 3-flute horns approaching from the west. As discussed in section 4.2, the grade crossing orientation is such that the initial blow of the horns occurs at a shallow horn angle about 400 m from the sound level meter and the final blow occurs at a horn angle of 120 degrees and 70 m distance (see Figure 15). The upper left spectrogram is of a 3-flute horn mounted over the cab of an LRC locomotive, while the lower left spectrogram is of a 3-flute horn mounted mid-locomotive behind the exhaust of an F40 locomotive. This F40 horn characteristic suffers on several fronts in comparison with the LRC spectrogram. Both trains are travelling at about 90 mph. As seen by the Doppler shift of frequency, the LRC slows down as it gets closer to the crossing, while the F40 stays at speed and has a very rapid Doppler shift.

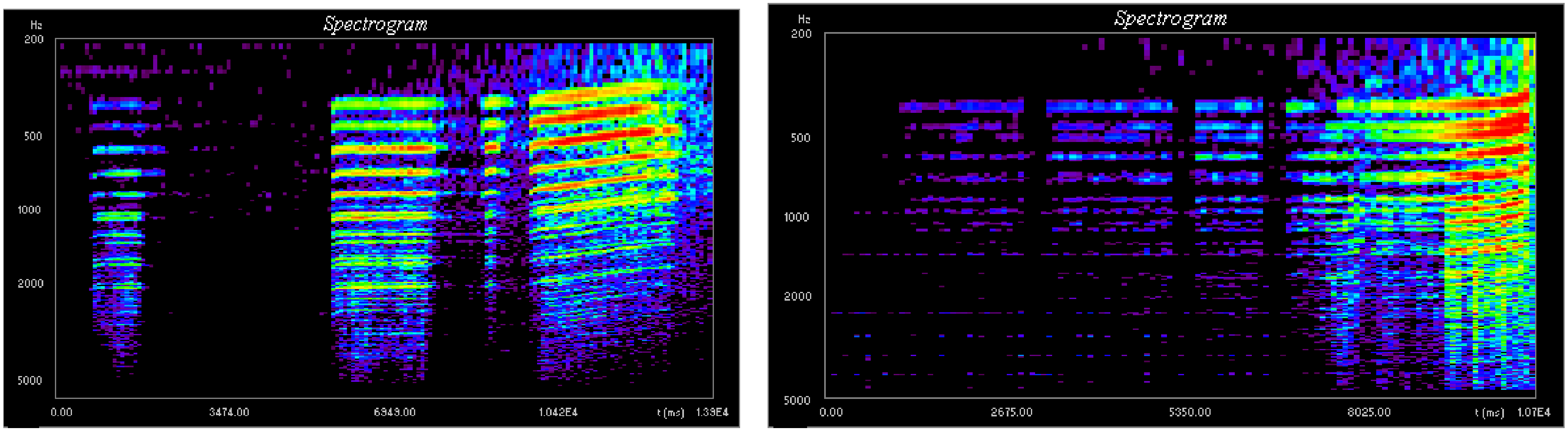
Looking at the F40's spectrogram (lower left in Figure 33) one can see that:

- the first blow is barely audible,
- the long second blow is only audible to pedestrians in an intermittent muffled presentation, (even though the locomotive engineer blows it continuously from 2.5 to 6 s),
- the signal would not become detectable inside a quiet automobile (yellow colour) before the train is about 1 s from the crossing.

The Genesis locomotive at 90 mph (upper right spectrogram) can be seen to have a better characteristic than the F40 but not as good as the LRC at the same speed and not as good as the freight locomotive at 63 mph (lower right).

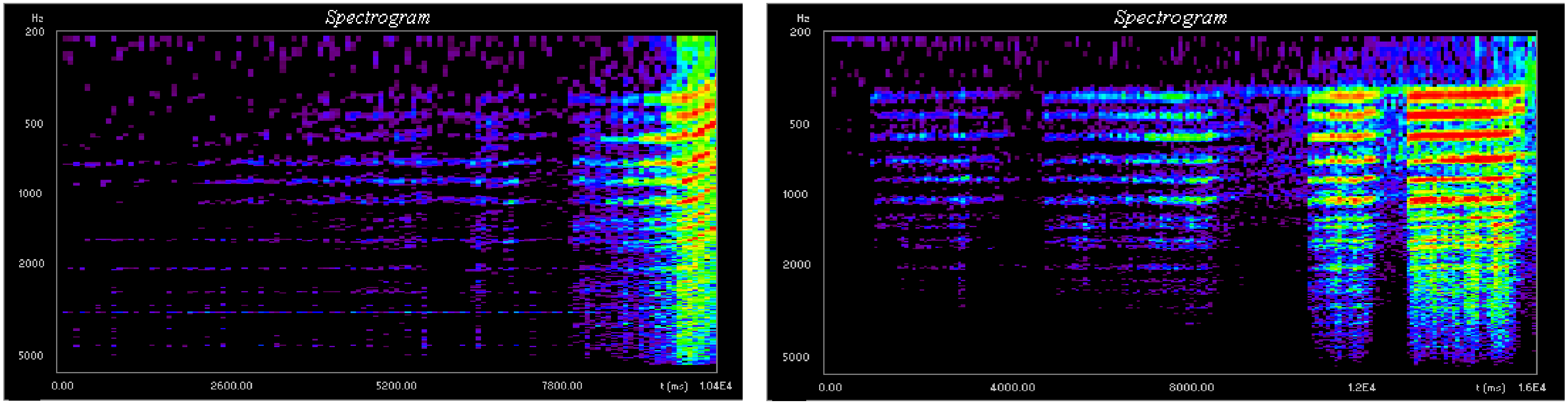
The lower right plot is of a freight locomotive at 63 mph. It is better than the Genesis at 90 mph but not as good as the LRC's cab-mounted horn at 90 mph. The freight spectrogram has an increase in output about halfway through the second blow of the horn and is close to normal output by the third blow. It is similar to the previously shown spectrogram (Figure 18) of an SD70 locomotive at 40 mph

Spectrograms provide a good visualization of the sound spectrum and general insights into the sound's warning effectiveness. However, the S/N criteria are a better means of assessing the requirements and effectiveness of an auditory warning device for in-vehicle situations. Thus, the vehicle approaching grade crossing scenarios are assessed in more detail with S/N criteria in subsection 5.2.



LRC, 3-flute, top-of-cab, 90 mph

Genesis, 5-flute, partial well, 90 mph



3-flute, behind exhaust, 92 mph

Freight, mid-locomotive, 63 mph

Figure 33 Spectrograms taken 70 m from the grade crossing

5.2 Grade Crossing Vehicle Warning Needs

We consider two in-vehicle conditions at grade crossings:

1. stopped at a crossing and assessing whether to proceed, and
2. approaching a passive crossing.

We do not separate active crossings. Onboard auditory warning devices play a secondary role at active crossings. Active warning systems are usually associated with higher traffic volumes, and the highest traffic volumes will have gates as well as flashing lights and bells. With higher traffic volumes there is a higher probability that vehicles are already stopped at the crossing before the train reaches the critical warning distance.

The demands on the horn are more rigorous at passive crossings. The locomotive horn and certain auxiliary locomotive lights are currently the only alerting signals given to a driver at a passive grade crossing to warn that a train is present. From the viewpoint of auditory output, a horn signal that is effective at passive crossings would be effective at active crossings.

The remainder of this section of the report is presented in three subsections. In subsection 5.2.1 we discuss the range of noise conditions and driver attitudes that might exist and select a criterion for a minimum sound warning from a locomotive horn. We then assess the warning effectiveness of different horns, first for vehicles stopped at a crossing in subsection 5.2.2, and then for vehicles approaching a crossing in subsection 5.2.3.

5.2.1 In-vehicle Warning Needs

Our minimum sound warning criteria follow from the discussion of chapter 3. The levels recommended in existing auditory warning device standards are infeasible for locomotive horns. We noted that Haas, et al. [1996] found SPLs of 40 dBL to be alerting. Our experiments indicated that perceptions of urgency of tones at 30 dB conform to the literature with respect to frequency sensitivity. We impose an alerting threshold of 30 dB for an in-vehicle environment but note that the S/N criteria demand signal levels greater than 40 dB in most scenarios. We note that it might be desirable to educate the public to understand that horn sound levels inside a vehicle can never have the level of urgency associated with warning sounds heard in the open air. The 30+ dB insertion loss translates into a perception of loudness that is about 12 percent of the loudness perceived for the sound outside the vehicle. Our open air warning criteria (for trespassers/ pedestrians) assumes a 47 dB threshold must be reached. This is in recognition of the fact that most people are accustomed to hearing locomotive horns at a louder level in the open air.

5.2.1.1 In-vehicle Noise Conditions

The Volpe Center [Rapoza, et al., 1999] derived insertion losses and internal noise levels for a range of personal road vehicles travelling at 50 km/h (30 mph). As noted in chapter 3, we used their average for the seven 1991 vintage vehicles in our signal detection experiments. This average reflects only one speed and is based on a quiet interior—no fan or radio.

To provide some insight into the sensitivity to other factors, we conducted a series of tests with one vehicle type (a 1998 Ford Windstar van). The results for road type, fan position and music presence at a speed of 60 km/h are illustrated in Figure 34, while Figure 35 illustrates the importance of fan speed on noise by comparing a stationary vehicle with its fan running to moving vehicle cases.

One can see from Figure 34 and Figure 35 that fan noise has the most influence across the horn spectrum. The legend shows the speed, fan position and radio position in each case (e.g. V60-F3-noR is 60 km/h with fan on 3 and no radio). A stationary vehicle with its fan set on high has about the same noise level in the horn frequency range as a moving vehicle. Above 2 kHz the noise is louder for the stationary-vehicle/fan-4 case than for the 80 km/h/fan-3 case. The gravel road surface is seen to influence the lower frequency range but has little impact above 1 kHz. Increasing vehicle speed from 60 km/h to 80 km/h affects the frequency range below 1 kHz more than the range above 1 kHz. Music raises all 1/3-octave bands by about 2 dB and a few (in this case 630 Hz, 2,500 Hz and 5,000 Hz) by 5 dB. The frequencies most affected are obviously dependent on the type of music being played, but all music has a larger temporal variation than do the other sources of vehicle noise. The loudest noise scenario is with air conditioning on maximum (and two fans running). The average SPL of the moving vehicle conditions is about 10 dB higher than the Volpe characteristic, while the stationary vehicle with no fan or radio is quieter.

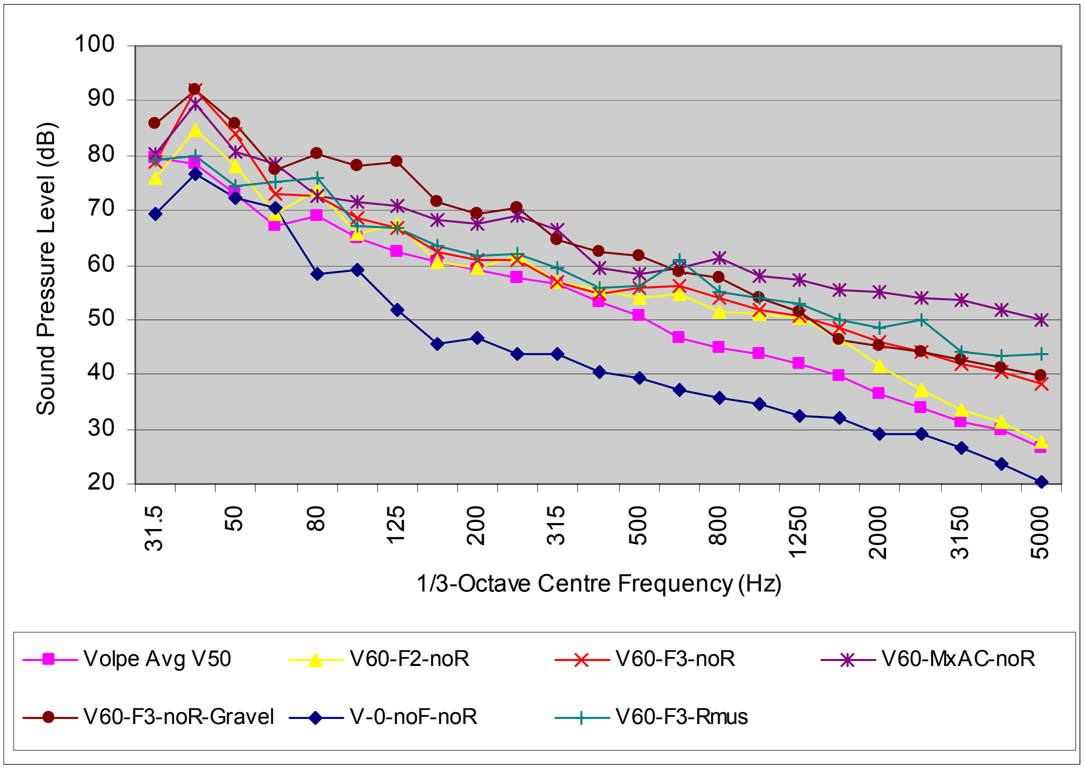


Figure 34 **Vehicle interior noise sensitivity at 60 km/h**

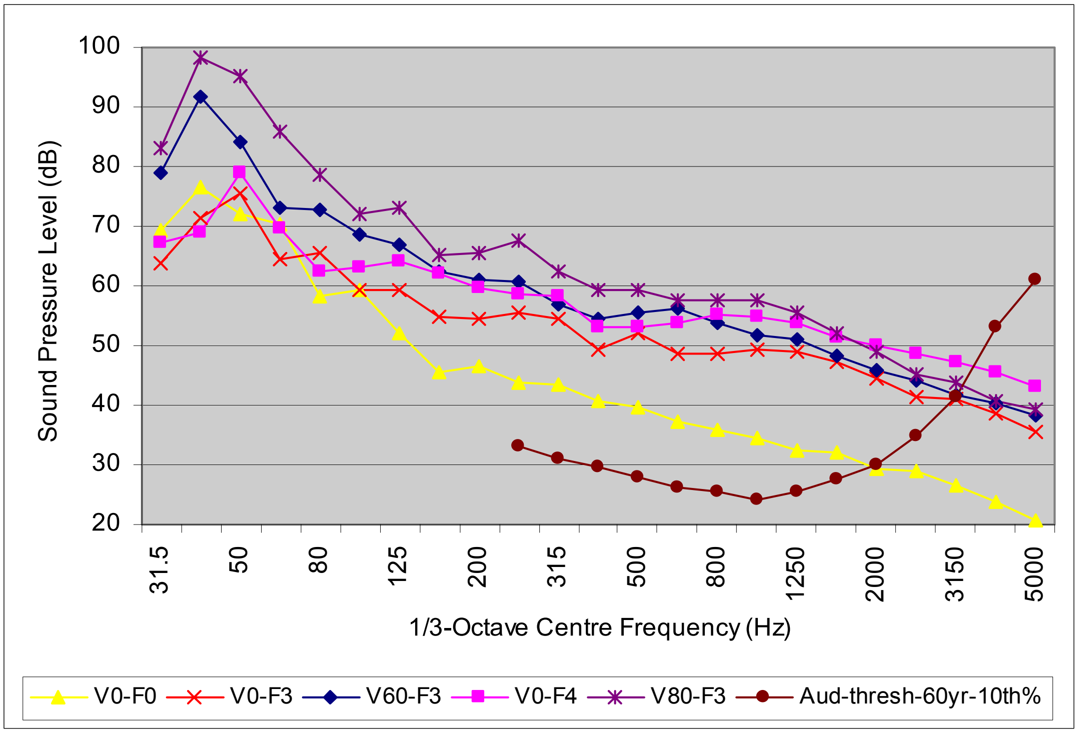


Figure 35 Vehicle interior noise sensitivity to fan noise

We also assessed the impact of age-related hearing loss on signal detection inside a vehicle. The hearing threshold of a 10th percentile 60-year-old male [ISO 7029, 1984] is also shown in relation to the masking thresholds inside a vehicle in Figure 35. One can see that, given other requirements, age-related hearing loss is not an issue for the horn spectra and does not significantly reduce the importance of higher frequency content. The 42 dB hearing threshold at 3,150 Hz is below the noise level associated with fan position 3. Our threshold of 47 dB for pedestrian-alerting situations also exceeds the audibility threshold for all frequencies up to 3,150 Hz. We note that the thresholds of hearing of 25th percentile 70-year-old males and of 10th percentile 70-year-old females are close to that of the 10th percentile 60-year-old males in this frequency range. People who have age-related hearing loss beyond these limits would not benefit as much from an increase in higher frequency content.

5.2.1.2 In-vehicle Alerting Criteria

There is a wide range of masking levels possible—the range in Figure 34 is more than 20 dB for much of the spectrum. We selected the case of 60 km/h vehicle speed with a fan setting at position 2 (of a maximum 4) as an average condition. Given a noise scenario, there is a range of individual response levels. We selected the three scenarios summarized in Table 8 for evaluation.

Table 8 Assumptions for stopped-vehicle alerting scenarios

Description of Driver Type	Cautious	Listening	Distracted
Background Noise Condition	Fan/radio off	Fan set to 75%	Fan set to 75%
Required Alerting S/M	+ 9 dB	+ 9 dB	+ 18 dB

It should also be noted that these scenarios are illustrative, in that other scenarios exist with both less and more demanding conditions associated with lower and higher speeds and/or noise levels. In addition, there are different interpretations of the alerting levels required. The signal-to-mask ratio of 9 dB is at the threshold where experimental data show people begin to be alerted, while 18 dB is far enough above the alerting threshold that most, but not all, would be alerted. Our criterion considers the total energy in all 1/3-octave bands in the horn frequency range. As discussed in Section 3.1, some researchers assume that detection is all that is required, others have indicated that +9 dB is required in one of the 1/3-octave bands. The latter assumption would add approximately 7 dB to our criterion. On the other hand, the threshold of signal detection is below our base threshold for alerting a listening driver.

We note that the first two levels put the onus on the driver to listen for a warning; the first level might further require that the driver take steps to reduce noise (if the fan and radio are not already off). The third level assumes the driver requires alerting from some distraction.

Our findings indicate that for horns located behind shielding protrusions, the sound output to the front of the locomotive (and particularly the higher frequency components) deteriorates with increasing train speed. However, the lateral output is not mitigated. Thus, the effectiveness of the horn is sensitive to the angle at which the recipient of the warning is located. We accommodate this fact by depicting the output requirements of an auditory warning device on polar plots of SPL output required and the associated horn angles for a specific crossing geometry and approach speeds.

Our distance-related sound dissipation criteria assumes:

- frequency sensitive absorption losses associated with 20ºC and 60 percent relative humidity;
- dissipation losses of 6 dB/distance doubling for warning along the track; and
- an incremental dissipation factor of 0.55 percent per degree of angle from track centreline (e.g. by 25 percent at 45 degrees to give 7.5 dB/distance doubling) to account for sound shielding obstacles.

The requirements of an auditory warning device for passive crossings include the same aspects as the pedestrian auditory warning device but must consider the additional factor of insertion losses (which are characteristic of sound transmission through an automobile) and noise levels inside the vehicle. Rapoza, et al. [1999] derived insertion losses and internal noise levels at 50 km/h (30 mph) for a range of personal road vehicles. We have used the averages for the seven 1991 vehicles tested.

Insertion losses increase with sound frequency. Low frequency sound tends to penetrate while high frequency signals are more readily reflected. The result is that the *bandpass* filter shape previously illustrated for the pedestrian alerting case (Figure 31) becomes a *low-pass* filter shape when insertion loss is included. However, the background noise level inside an automobile is significantly weighted to lower frequencies. When this factor is considered, the end result is flatter or even a *high-pass* filter. The effects are illustrated for a vehicle at 200 m warning distance in Figure 36.

The three curves in Figure 36 are normalized to have the same value at 1 kHz to better illustrate the relative contribution of insertion loss and masking. The square-symbol curve shows the impact of adding insertion loss to the atmospheric absorption losses and A-filtering that were shown for the pedestrian case of Figure 31. One can see that the 315 Hz band is most readily transmitted inside a vehicle. The other two curves show the incremental impact on audibility of the masking associated with internal noise for an idling vehicle with fan off (V0, F0) and for a vehicle moving at 60 km/h with fan set to position 3 (V60, F3).

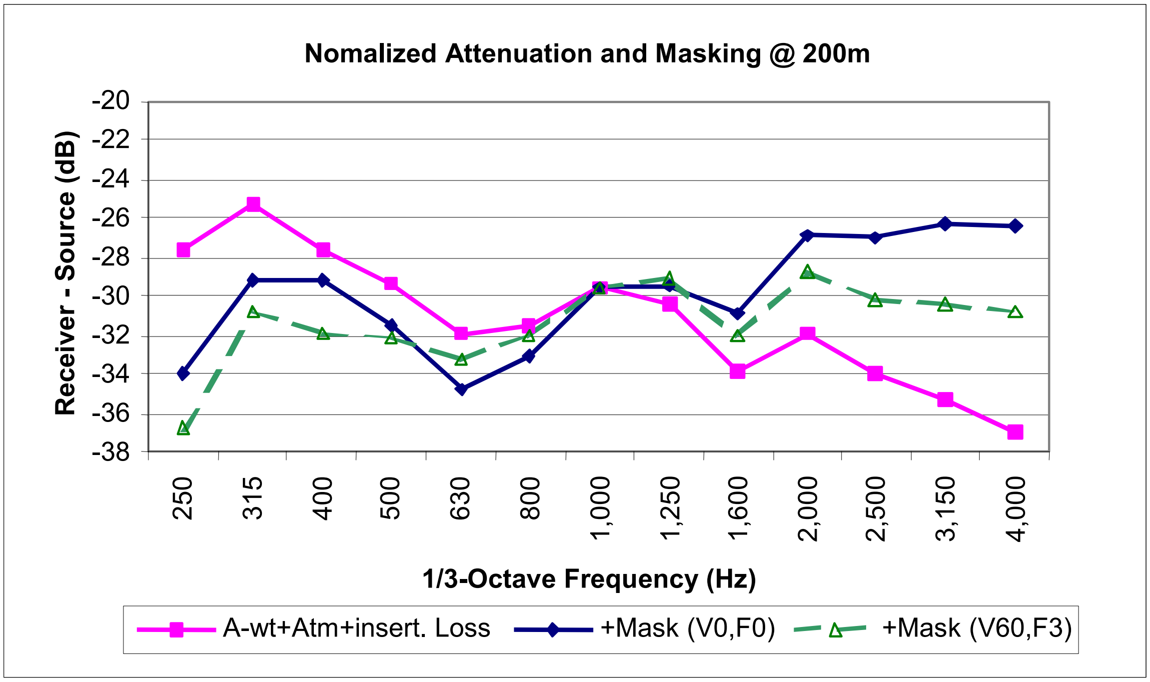


Figure 36 Effective filter of horn sound perceived by a motor vehicle driver

The masking noise associated with 60 km/h travel speed results in signals in the 1 to 4 kHz band being more readily transmitted from source to brain. The steeper masking noise of an idling vehicle with fan off accentuates the 2 to 4 kHz band. We note that the advantage in this frequency range for the stopped and quiet vehicle case would not exist for people with hearing loss of the 10th percentile 60-year-old male as illustrated in Figure 35.

Figure 37 compares the frequency characteristics of two horns relative to the masking criterion of a 60 km/h vehicle with fan set to position 3. One can see that the front-mounted 5-flute horn has a shape that allows it to take advantage of the lower SPL requirement in the 1 to 3.1 kHz range better than does the mid-locomotive horn characteristic. The upturn of the threshold at 4 kHz reflects the inclusion of the audibility constraint of a 10th percentile 60-year-old male. Without this constraint, the 4,000 and 5,000 Hz threshold would also be below the 5-flute front horn's characteristic.

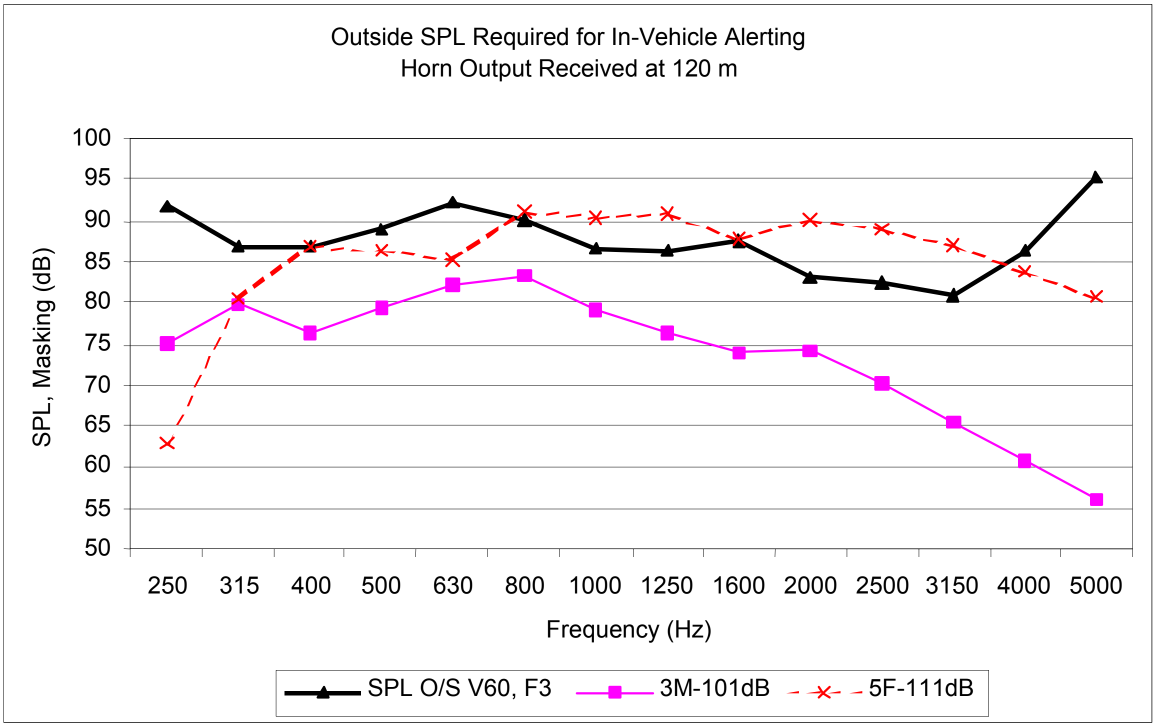


Figure 37 **Comparison of threshold and two horn characteristics**

As a consequence of its broader spectrum, the front-mounted horn can attain a given detection threshold with a lower sound level than the mid-locomotive positioned horns. The mid-locomotive horn requires an incremental SPL of 5.3 dB over that of the front-mounted 5-flute horn to achieve the same S/N criterion. This is independent of the incremental output required to accommodate the extra distance and other attenuation losses.

We confirmed the above masking effects/relationships for an idling automobile with measurements made at the point where the in-vehicle SPL was assessed to be close to the alerting threshold. The frequency spectrum of the received signal and the associated S/N ratios are presented in Figure 38. The bars show the horn signal SPL inside the vehicle as related on the left-side axis, while the line shows the S/N ratio for the horn as related on the right-side axis. One can see that even though the SPL was much lower in the range 1.6 to 3.2 kHz, the S/N level was highest in that range.

It is also noteworthy that the external signal was 78 dBA, but that much of the energy was concentrated at 800 Hz, which was still at a negative S/N value inside the vehicle. Without the 800 Hz component, the source SPL would have been 76 dBA and still detected.

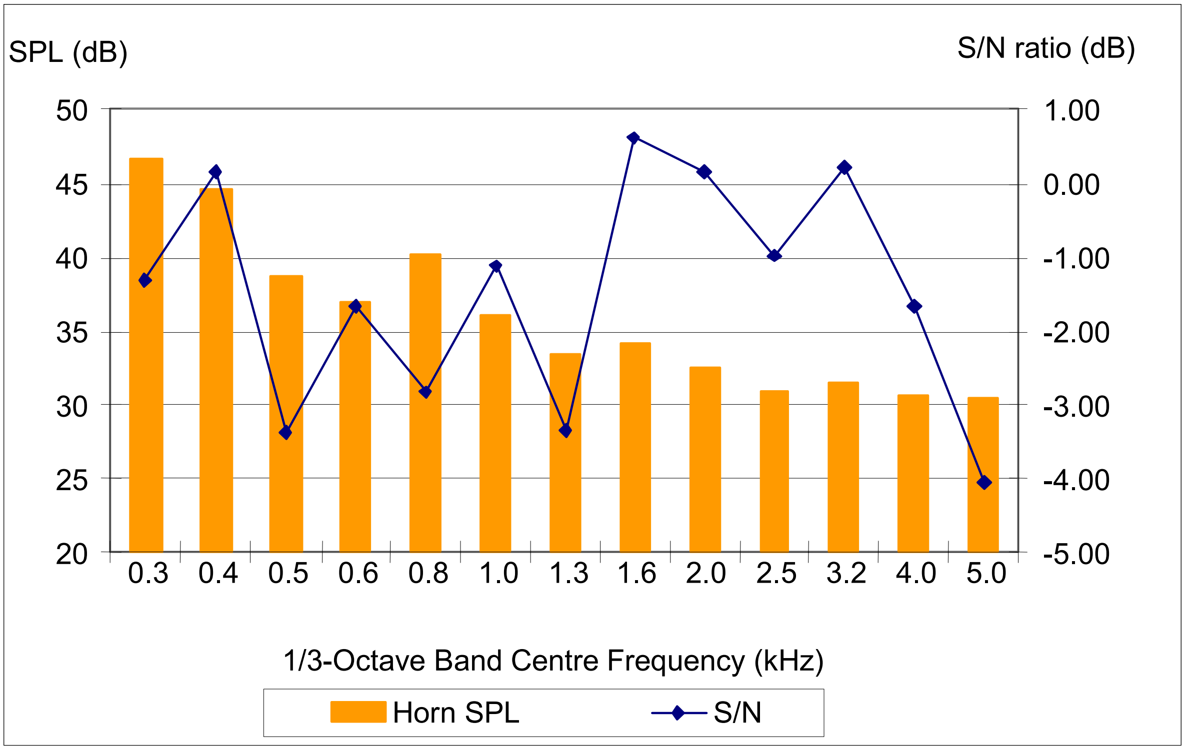


Figure 38 **In-vehicle sound pressure level and S/N ratios of audible horn**

5.2.1.3 Implications for Locomotive Horns' Frequency Spectra

Present Transport Canada regulations call for the locomotive horn to *sound like a steam whistle.* Steam whistles generate very few harmonics and have fundamental frequencies below 500 Hz. While a steam whistle might be an effective warning device in a quiet ambient, in the presence of background noise it would perform worse than any of the three horns evaluated here. The shift in the characteristic sound of a locomotive horn from the steam whistle's peak frequency of 400 Hz to today's air horn's peak frequency, while counter to the regulations, has led to a more effective auditory warning device.

The U.K regulations call for the following:

> *The tones of the audible warning device shall be recognisable as being from a train and not similar to warning devices used in road transport or as factory or other common warning devices.*

Existing locomotive horns vary widely in frequency spectra. There is considerable room in the existing spectra to consider focusing more on some horns' characteristics than others. On the other hand, a corollary to the wide variation in locomotive horn spectra is that the direction of 'sounding like a train' is in itself an uncertain guideline. The uncertainty is exacerbated by the fact that there are few regulations in other areas. We note that the SAE standard for truck horns simply states that the fundamental frequency should be stated on the horn.

The U.K. standard provides very specific limits on acceptable tones to clarify its dictate to sound like a train. It only accepts two horn systems, each with specific frequencies: a 2-flute separately sounded device with alternating 311 Hz and 370 Hz fundamentals, and a simultaneously sounded 3-flute horn with 370 Hz, 470 Hz and 622 Hz fundamentals. The U.K. standard also goes as far as constraining the number of flutes and specifying the fundamental frequencies as well as the relative magnitude of all harmonics up to 4,000 Hz.

We believe that such detail is too constraining to be included in a regulation, but agree that some additional detail on the sound level magnitude in the frequency range of the harmonics is desirable. Our analysis indicates that the spectrum of an unshielded front-mounted horn is much more effective than that of a mid-locomotive horn. We believe that manufacturers currently offer an adequate range of fundamental frequencies. While not necessarily part of a standard, we recommend that railways and locomotive builders include tighter tolerances in their purchase specifications. The U.K. standard, which accepts a +/- 20 Hz variation on fundamental frequency, seems reasonable. We note that the specifications for 470 Hz, 494 Hz and 512 Hz horns would require a tighter tolerance to be meaningful alternatives.

As noted above, the harmonic content is a more important aspect than the fundamental frequency. We believe that a new horn regulation should include a threshold for harmonic content. Railways would be required to maintain their horns such that the harmonic content above 1,250 Hz is met at all times. More importantly, they would have to position the horn such that the higher frequencies are not shielded.

Existing 3-flute and 5-flute horns can meet the following recommendation if mounted in a suitable location on the locomotive. There is no equivalent in the proposed FRA regulation. It is less specific than the U.K. recommended practice with respect to fundamental frequencies and more demanding with respect to harmonic spectrum.

- Locomotive horns should comprise fundamental frequencies consistent with at least two flutes and having fundamental frequencies no lower than 250 Hz and no higher than 660 Hz.
- The frequency content when measured in stationary tests at 61 m should be such that the minimum 1/3-octave-band SPL in the range 2,000 to 3,150 Hz is not lower than Φ below the maximum 1/3-octave band SPL in the range 250 to 1250 Hz, where Φ equals 12 dB for trains exceeding 70 mph and 15 dB otherwise.

If our laboratory findings of a 562 Hz sweet spot are independently verified, the first part of the recommendation should be modified to further state that at least one flute should have a fundamental frequency in the range of 470 Hz to 512 Hz. The second part of the recommendation could require that railways specify acoustic testing and possible re-furbishing of horn flute shapes in addition to the present overhaul of diaphragms when they are refurbished.

5.2.2 Stopped at Grade Crossing Warning Needs/Feasibility

Transport Canada has not yet updated its grade crossing accident database. We obtained some insight into grade crossing accidents by looking at FRA crossing accidents for the year 2000. The statistics show that active crossings involve many more stop-and-go type accidents than occur at passive crossings—40 percent for active versus 26 percent for passive—and the passive included more abandoned vehicles. Many collisions at active crossings involve vehicles that stopped but then decided to go. Of those vehicles hit by the train, the speed distribution of passive and active crossings covers a similar range.

The aspect of the horn that is more applicable for vehicles stopped at a grade crossing involves its influence on a driver's judgement of the time available to cross. To best judge the arrival time of a train, it might be better to have a fixed warning time from onset of blowing the horn than the existing fixed distance. Also, it would be desirable to have a louder output from faster trains so that a 7 second warning from a 95 mph train would sound the same to a driver as a 7 second warning from a 60 mph train. A 95 mph train would require an increased output sound level of 4.5 dB over that of a 60 mph train to provide the same loudness at fixed time warning.[8] If a high-speed output sound level were adopted, it would make sense to have it in the range of 4.5 dB louder than the output of a conventional freight locomotive horn.

The normal condition at a passive crossing is an approaching vehicle, but stopped vehicles and those vehicles such as school buses that stop as a matter of policy also exist at stop-signed grade crossings. The implications for an auditory warning device are that many stopped vehicles will have a lower background noise level, drivers are potentially listening for trains to decide whether to proceed through the crossing, and the angle of sound output is close to zero degrees, thereby avoiding wayside shielding influences. These influences on the requirements of an auditory warning device are more favourable than for moving vehicles.

On the other hand, those vehicles that stop at grade crossings as a matter of policy are often long vehicles that take longer to clear the crossing once the driver decides to proceed. The warning time calculation for a stopped vehicle is similar to the one shown in the previous section for pedestrians. Table 9 shows the minimum sound warning (MSW) SPL required to warn the three driver types identified in our criteria at three different train speeds. Each of these combinations is repeated for five different vehicle clearance times and two different horn positions. Thus, to warn a cautious driver (fan/radio off and listening) in a vehicle that takes 8 seconds to clear the grade crossing with a front-mounted 5-flute horn on a locomotive travelling at 90 mph would require a sound level output of 108.5 dBA (100 ft. equivalent).

Those cells that require an output above that expected from the horn are shaded. The 12-second-clearance/90-mph-train-speed cells are beyond the 1/4-mile whistle distance and not applicable to auditory warning. One can see that a 5-flute front-mounted horn is effective in more situations than the mid-locomotive horn. The shaded cells for the mid-locomotive horn are also based on the 101 dBA characteristic derived from static measurements. If one considers deterioration of

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[8] Assuming 6 dB loss per distance doubling and accounting for influence of the speed of sound (332 m/s), the increased loudness required at 95 mph (42.6 m/s) to have the same loudness to the receiver as a 60 mph (26.9 m/s) train is calculated as: 20 LOG(42.6 / (1-42.6/332) / (26.9 / (1-26.9/332))) = 4.45 dB.

output with speed for mid-locomotive horns as illustrated in section 4.4, only the *cautious driver* with lower train speeds and low clearance time cells are met.

We also note that drivers of vehicles that take longer than 8 seconds to clear the track would have to listen for a train going 60 mph even if a 5-flute front-mounted horn were used. It is important for drivers of vehicles to know that it is infeasible to alert them with auditory warning device technology and therefore cautionary proactive steps are required from drivers of vehicles at crossings. The sight lines provided at grade crossings extend beyond the ¼ mile whistle zone and education of drivers should reinforce their responsibility to look for trains.

We recommend that Transport Canada emphasize in its promotion of training of road vehicle drivers that it might be necessary to roll down both windows and turn off all noise sources to hear a train approaching a crossing in poor visibility conditions. It should also notify provincial and municipal highway authorities to bar school buses and tractor trailers from using passive grade crossings of high-speed rail lines in conditions of poor visibility (e.g. fog, heavy snow fall). We site Mowbray road grade crossing on the Kingston Subdivision (Ontario), which has stop sign protection on a 100 mph track, as one example where such steps should be taken.

Table 9 Warning (dBA @ 100′) required for vehicles stopped at a grade crossing

Horn Type		K5-Front-111 dB			Mid Loco.-101 dB		
Train Speed (mph)		30	60	90	30	60	90
Clear time (sec)	Driver Type						
4	Cautious	75.1	82.7	87.7	81.8	88.7	93.4
	Listening	87.4	95.0	100.0	94.0	100.9	105.7
	Distracted	96.4	104.0	109.0	103.0	109.9	114.7
6	Cautious	79.2	87.2	92.5	85.5	92.9	98.0
	Listening	91.5	99.4	104.8	97.7	105.2	110.3
	Distracted	100.5	108.4	113.8	106.7	114.2	119.3
8	Cautious	82.3	90.5	96.2	88.2	96.1	101.6
	Listening	94.5	102.8	108.5	100.5	108.4	113.9
	Distracted	103.5	111.8	117.5	109.5	117.4	122.9
10	Cautious	84.7	93.2	99.3	90.5	98.8	104.7
	Listening	96.9	105.5	111.5	102.8	111.0	116.9
	Distracted	105.9	114.5	120.5	111.8	120.0	125.9
12	Cautious	86.7	95.6	N/A	92.4	101.0	N/A
	Listening	99.0	107.8	N/A	104.7	113.3	N/A
	Distracted	108.0	116.8	N/A	113.7	122.3	N/A

5.2.3 Approaching Grade Crossing Warning Needs/Feasibility

5.2.3.1 Warning Distance for Approaching Vehicles

In addition to having different in-vehicle noise characteristics, a moving highway vehicle leads to a more complicated geometry involved in calculating the minimum warning distance at which a driver needs to hear a locomotive horn. We adopt (with one noted difference) the Aurelius and Korobow [1971] minimum warning distance formula. The distance between locomotive horn and highway vehicle is a combination of the minimum distance from the crossing that each vehicle must be at to have a safe warning. The critical distance for the highway vehicle is a combination of the distance travelled during the driver's reaction time (after being alerted to the presence of the train) and the minimum braking distance for its speed and the road friction conditions. Mathematically this minimum warning distance (MWD) is:

$$MWD = {}^{V_m}\!\big/_{3.6T_{br}} + {}^{V_m{}^2}\!\big/_{255(f \pm g)}$$

where

V_m = motor vehicle speed (km/h)
T_{br} = brake reaction time of the driver (s)
g = road approach gradient
f = assumed tire-ground friction coefficient

To determine the location of the train coincident with this point in time, Aurelius defines a critical time (T_{cr}). This is the time required for the highway vehicle to safely clear the crossing before the train crosses if the driver did not hear the warning a microsecond before the MWD was reached. This time is defined as:

$$T_{cr} = (MWD + CTZ + L_v)/V_m$$

where

V_m = motor vehicle speed (m/s)
CTZ = critical track zone length (m)
L_v = motor vehicle length (m).

The train's distance from the crossing associated with T_{cr} is the product of the train speed and T_{cr}. For higher speed trains, the speed of sound becomes a relevant delay. Thus, in a slight departure from Aurelius's methodology, we have taken one iterative step in determining the train's required warning distance. First, the travel distance of the horn sound waves is calculated as the hypotenuse associated with the two above distances and the crossing angle. We then adjust the train distance back an additional distance associated with the time delay in the sound leaving the horn and arriving at the motor vehicle.

In a further modification to Aurelius's methodology, we assess the following two levels of performance:

1. The generally accepted highway design standards in their calculations (2.5 s of reaction time and about a 0.35 coefficient of friction).
2. To determine the point at which a horn begins to have an influence, we adopt a less stringent effectiveness criteria of 0.6 s reaction time and 0.6 friction coefficient.

The first level of performance reflects the generally accepted highway design standards for response time and locked-wheel skidding friction. We note that as with most safety design criteria, the highway standards try to encompass the full range of conditions. A device that falls short of the design coefficients will still be effective in some circumstances. We adopt lower values in our second level of response. This is not to be interpreted as an argument to reduce the design criteria for visual sight lines, or even desirable auditory warning distances. It simply identifies criteria associated with an initial impact on some portion of crossing situations. The second level of performance reflects a higher rolling friction that is associated with antilock brake systems (ABS) on dry pavement and a faster response time.

The faster response time is drawn from the literature. Experimental investigations show outlying response levels of 2.5 s; however, the average response is usually lower. Fidell [1978] reported on the response times involved in an experimental investigation of driver response to sirens. The average response time (from start of signal at the detected level to brake application) was 0.62 s.

Beauchemin-Beaton-LaPointe Inc. [1978] reports on the work of Johansson and Rumar [1971], who found similar brake reaction times for drivers who expected a signal; median results were 0.66 s, with a range varying from 0.3 to 2.0 s. They also conducted follow-up tests with two sets of drivers, one expecting a signal and another with no anticipation. The mean times rose from 0.54 s for the expecting groups to 0.73 s for the surprised groups. On the basis of the tests, Johansson and Rumar estimated brake reaction times of 0.9 s or greater for 50 percent of drivers and 1.5 s or greater for 10 percent of drivers.

Najm, et al. [1995] derived a log-normal distribution for response time from driver simulation experiments. The distribution is characterized with a mean of 1.3 s, a mode of 1.07 s and a dispersion of 0.49 s. Olson and Sivak [1986] found that drivers of real cars take between 0.81 and 1.76 s to respond to unexpected roadway hazards.

We note that longer response times have also been recommended. Abrams and Lipscomb [1996] suggest that the typical perception/reaction time for both auditory and visual warnings is 2.5 s. For auditory signals, they allow one additional second for the receiving individual to conduct a visual scan to locate the source of the alerting signal. Their brake reaction time for an auditory warning device is thus 3.5 s. Their recommendation and the above review of the literature highlights the fact that our selected levels do not reflect the extreme bounds of expected performance variation.

5.2.3.2 Implications for Minimum Sound Warning

The three minimum sound warning scenarios applied to the stopped vehicle case are modified to accommodate response differences for the moving vehicle case. We replace the cautious driver (fans and radio off) with the fast-response scenario. The three moving vehicle scenarios are summarized in Table 10. The middle scenario, Fast-or-Listening, reflects two possible combinations. Since the difference between the fast response and base response conditions results in a minimum sound warning difference of about 9 dB, the same condition can be interpreted as a base response-but-listening driver.

Table 10 Assumptions for three moving-vehicle alerting scenarios

Scenario Description	Fast-and-Listening	Fast-or-Listening		Base-Distracted
Response (time/friction)	0.6 / 0.6	0.6 / 0.6	2.5 / 0.35	2.5 / 0.35
Background Noise Condition	fan set to 50%	fan set to 50%		fan set to 50%
Required Alerting S/M	+ 9 dB	+ 18 dB	+ 9 dB	+ 18 dB

The minimum sound warning requirements of the Base-Distracted scenario in a vehicle going 60 km/h on a paved road, with the internal 4-position fan set to position 2 are illustrated in Figure 39. Three train speeds and five crossing angles are illustrated in the data. The individual points on each curve represent a grade crossing angle.[9] The highest sound level and shallowest horn angle is associated with the fastest train speed of 145 km/h (90 mph) and a grade crossing angle of 150 degrees (i.e. road vehicle approaching the train). In sequence of decreasing sound level, the other data points represent the minimum sound warning for crossing angles of 120 degrees, 90 degrees, 60 degrees and 30 degrees. We note that the data points are based on the broad-spectrum sound characteristic of the front-mounted horns.

If one considers mid-locomotive horns, then an additional 5.2 dB is required (as explained in subsection 5.2.1). It is evident for all crossing angles that the required warning location is more focused to the front of the train as its speed increases. It is also evident that some crossing angles for trains going 90 mph are beyond the limits of auditory warning device technology under the demand of this minimum sound warning scenario. However, the plot is based on the most conservative of the three warning scenarios. The sensitivity to other scenarios is addressed in the next subsection.

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[9] In calculating the horn output required, crossing angles were measured on the basis of a zero degree angle for roads aligned with the track and travelling in the same direction.

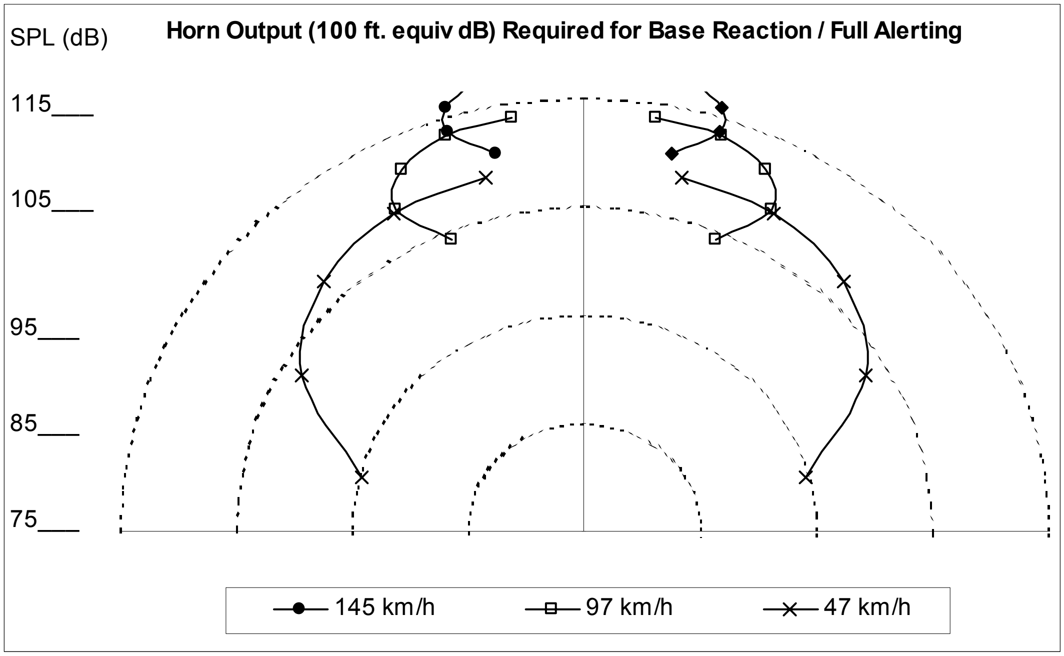

Figure 39 Horn output required for a range of speeds and crossing angles

5.2.3.3 Comparison of Needs/Feasibility

Figure 40 illustrates the sensitivity of the MSW level for a train speed of 90 mph (145 km/h) to the warning scenario selected. The Fast-or-Listening scenario brings the MSW levels into a feasible range. However, the present regulatory limit of 96 dB requires both a fast reaction and a listening driver for a broad-spectrum horn to be effective at shallow grade crossing angles when a train is travelling 90 mph. While the MSW of a fast-response, listening driver can be met with a 96 dB broad-spectrum horn signal, a narrow spectrum horn requires an additional 5 dB of output and thus is not a feasible auditory warning device for any of the scenarios shown in Figure 40. As shown in subsection 4.4.1, the output characteristic of a mid-locomotive horn changes significantly with polar angle.

Figure 40 also shows the output of the F40 locomotive's horn under conditions of train speed of 145 km/h (90 mph) and road vehicle speed of 60 km/h. One can see that the locomotive horn's output characteristic is ill-suited to warn vehicles approaching grade crossings, even under the most optimistic scenario. If the output of the horn that is realized in the lateral direction were also produced to the front of the locomotive, two of the scenarios and one crossing angle of the base-reaction scenario could be met.

Our analysis focused on 60 km/h highway speeds for two reasons. First, it covers many of the urban and a large number of the passive rural grade crossing situations. Second, it is near the limits of feasibility for an auditory warning device on high-speed trains. One can see that the requirements for the base-reaction/distracted-driver scenario are beyond the feasible range at combined speeds of 90 mph for train and 60 km/h road. We did not assess an 80 km/h highway speed because few scenarios lead to a feasible auditory warning device.

One cannot rely on locomotive horns as an effective warning device for passive crossings that involve high speeds on both the highway and the railway. One must depend on visual warnings for many of the speed/angle combinations. It is noteworthy that the crossing angles that position the highway vehicle farthest from the train are also the ones that have the best visual field of view to see the oncoming train. The more acute angles, where the driver would have to look to the rear to see the train are the ones that produce the shortest auditory warning distances. However, at high train and highway speeds, even the acute angle approach is beyond the feasible range of an auditory warning device.

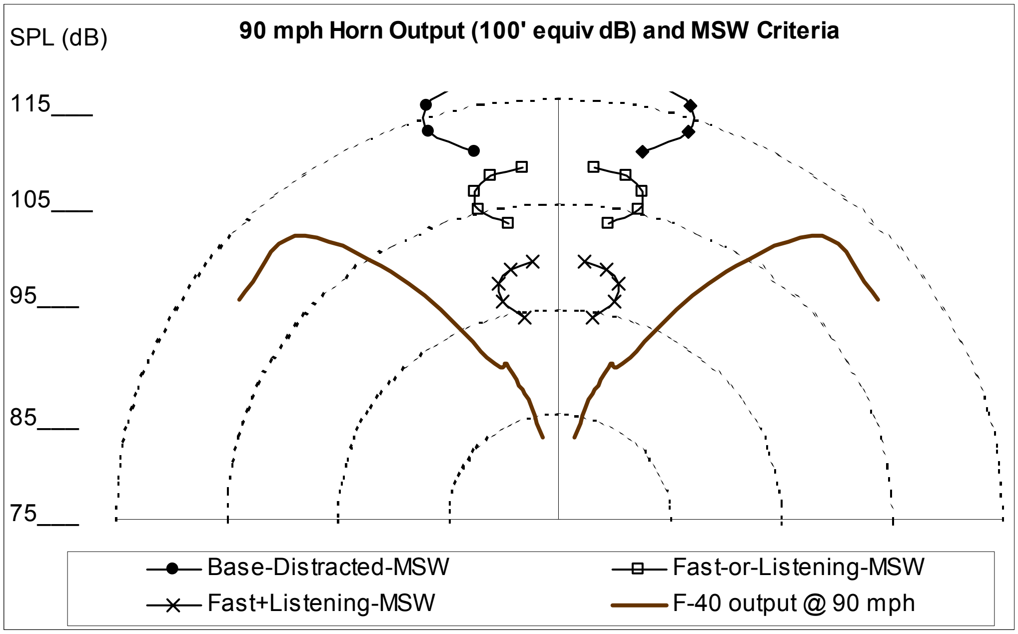

Figure 40 F40 horn output and requirement at 90 mph

We note that the worst case condition on VIA Rail’s high-speed corridor is a passive crossing with 80 km/h highway speed limit, 153 km/h (95 mph) train speed, and a 45°/135° crossing angle. For this speed combination, alerting a distracted driver is infeasible at either angle. The listening-or-fast scenario is feasible if the driver is in a quiet vehicle and on an approach angle of 90 degrees or less.

The results highlight the benefits of having an improved visual alerting component at passive crossings (see Appendix B). Another consideration is to reduce highway speed limits at passive crossings. Given the limitations of auditory warning devices, it is important to have speed limits at crossing approaches that are consistent with the road conditions. Highway speed limits at passive crossings with gravel roads should not exceed 60 km/h. The use of warning signs to reduce speed on wet pavement and in poor visibility conditions at all passive crossings should be investigated.

Figure 41 compares the measured output characteristics of several freight locomotive horns with the demands of the three minimum sound warning (MSW) scenarios for a highway speed of

60 km/h and a train speed of 97 km/h (60 mph). Pictures of the each of the locomotives, showing the horn position of each, can be found in Appendix E. The legend indicates the speed at which the locomotive's SPL characteristic was measured, and is assumed to be representative of the 60 mph (97 km/h) train speed MSW case it is being compared with. The GP9 locomotive (with horn behind and close to the exhaust stack) can be seen to meet only the requirements of the Fast-and-Listening scenario for two grade crossing angles. The SD-40 locomotive (horn positioned to the left side of the locomotive) meets the requirements of many of the scenario/grade-crossing angle combinations shown on the left side of the locomotive but fewer of the on the right side. The Dash-9 locomotive (horn located farther back from the shielding walls and in front of the exhaust) meets the requirements of all scenarios for grade crossing angles of 90 degrees and lower.

Figure 42 compares the MSW requirements for a train speed of 47 km/h (30 mph). Also shown is the polar output (100 ft. equivalent dB) of two locomotive horns measured in this speed range—an F59 passenger locomotive and a Dash-9 freight locomotive. One can see that at these speeds the attenuation of output to the front of the locomotive does not significantly affect its warning requirements for approaching highway vehicles.

5.3 Loudness Implications

The FRA's regulation for audible warning devices states that " . . . each locomotive shall be provided with an audible warning device that produces a minimum sound level of 96 dBA at 100 feet forward of the locomotive in its direction of travel" (Paragraph 229.129a in 49 CFR Part 229). The Canadian railways generally exceed this requirement.

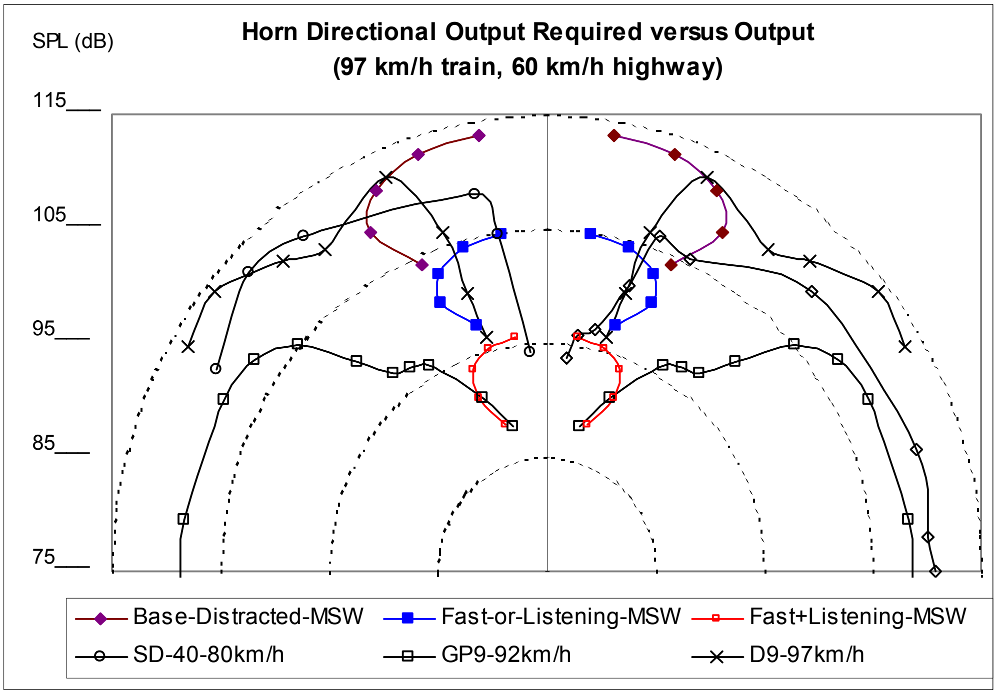

Figure 41 **Horn output and requirement at 97 km/h**

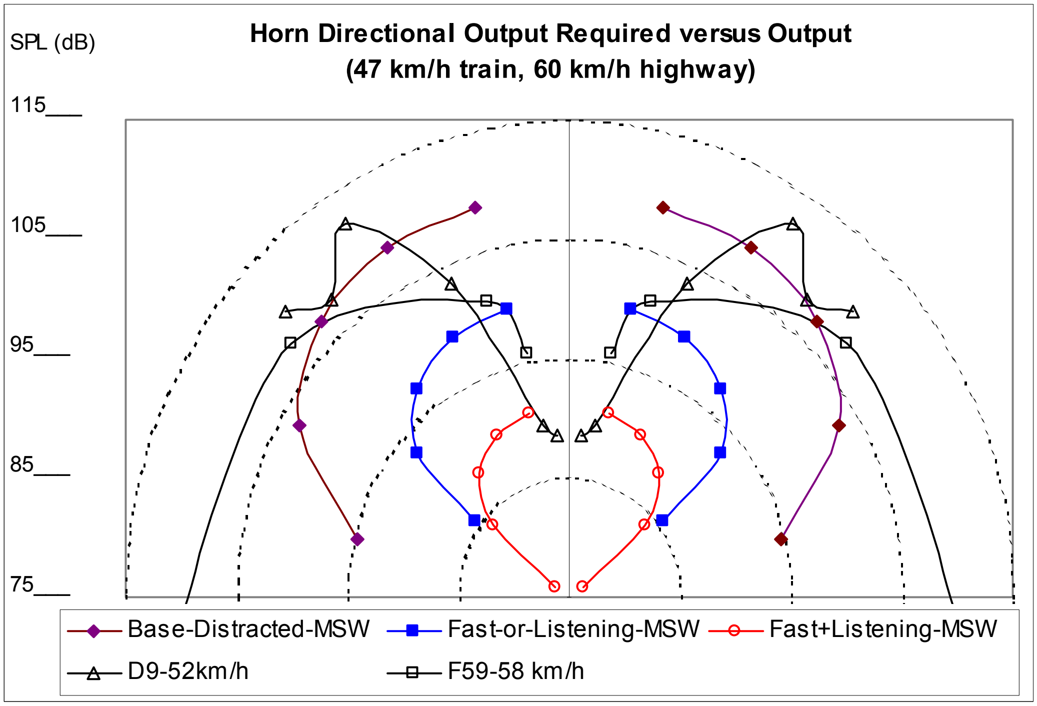

Figure 42 Horn output and requirement at 47 km/h

The FRA's proposed new rule [Federal Register, 2000] retains this minimum but removes the error margin that was previously allowed in test measurements of output. The new rule introduces for the first time a maximum allowable output.

Its discussion of the proposed rule considers the merits of having two operating upper limits:

1. one at 104 dBA that could be associated with night use and/or active crossings, and
2. a higher one at 111 dBA that could be associated with day use and/or passive crossings.

The discussion implies that the horn would operate within two operating ranges, a 96-to-104 dBA range under some conditions, and a 104-to-111 dB range under other conditions.

The U.K. horn regulations also call for a two-level horn and specify a maximum output. The dual output is only applicable to speeds over 160 km/h (100 mph), and the maximum limits are only measured at 5 m in front of the locomotive. The U.K. loudness regulations are summarized in Table 11. A minimum limit is specified at both 5 m and 100 m. The last column of Table 11 reflects our calculation of the 30.5 m equivalent on the basis of -6 dB/distance doubling (the same as reflected in their 5 m / 100 m relationship).

Table 11 U.K. standard for horn loudness

Distance in front of vehicle	5 metres		100 metres	30.5 metres (Our calculated equivalent)	
	Minimum (dBC)	Maximum (dBC)	Minimum (dBC)	Minimum (dBC)	Maximum (dBC)
Trains ≤ 160 km/h	120	125	94	104	109
Trains above 160 km/h					
"loud" mode	122	128	96	106	112
"soft" mode	115	119	89	99	103

Source (left 4 columns only): U.K. Railway Group, 1995

The U.K. regulation is for a C-weighted measure. The C weighting is flat over the horn spectrum and does not reduce the contribution of lower frequencies or enhance the contribution of mid-range frequencies as the A weighting does. However, as the horn spectrum includes both regions, we found that the pluses and minuses cancelled out in summation and produced SPLs that are very close in either scale.

Queensland Railways in Australia also has a two-level horn—higher for rural areas and lower for urban areas [Queensland Railways, 1997]. It uses a lower frequency 5-flute horn (K5LL), which is the same as the one the Long Island Railroad switched to (see subsection 6.2.2). Its standard (Table 12), when adapted to 30.5 m, calls for an output of 95 to 100 dBA in urban areas and 101 to 111 dBA in rural areas. It is noteworthy that the Australian standard also limits in-cab sound levels to 85 dBA with windows closed and 90 dBA with windows open.

We note that the part of the FRA's proposed new rule that has the largest potential impact and that has generated the most community reaction is the elimination of whistle bans (except under strict criteria). The FRA notes that setting a maximum limit of 111 dBA rather than 115 dBA would reduce community noise impacts by approximately 15 percent. On the other hand, Transport Canada is not proposing to eliminate whistle bans and already has regulations limiting the sound level in the cab. To specifically limit the warning level in front of the locomotive goes counter to our analytic findings. Taking the example of moving a horn from the middle of the locomotive to the front, the horn would be too loud under the FRA's new 104 dBA maximum, but moving it would not increase the community noise impact in non-whistle ban zones.

Table 12 Queensland, Australia's standards for horn loudness

Distance in front of vehicle	200 m		100 m		Our calculated equivalent at 30.5 m	
	Minimum (dBA)	Maximum (dBA)	Minimum (dBA)	Maximum (dBA)	Minimum (dBA)	Maximum (dBA)
"loud" mode	85	95	N.A.	N.A.	101	111
"soft" mode	N.A.	N.A.	85	90	95	100

Maximum limits are desirable from both pedestrian and community noise perspectives. We recommend that maximum limits be defined only for a 90-degree angle to the locomotive rather than in front of the locomotive. The close-range wayside limits included in U.K. regulations [U.K. Railway Group, 1995] call for a maximum limit of 135 dB at trackside on a 10 km/h pass-by test at 1.5 m above the top of rail and both 1.2 and 2.0 m horizontal from the nearest rail. U.K. locomotive horns are mounted near the coupler rather than at roof height. We recommend the 135 dB limit be measured at a height of 1.5 m above passenger platforms rather than top of rail.

Our findings indicate that the existing standard of 96 dBA at 30.5 m puts the onus on the motor vehicle driver to take noise reduction steps and to be actively listening for a horn in many situations. We did not find any horn measurements in the literature that were less than 101 dBA and our own measurements did not register less than 108 dB at a lateral angle from the locomotive. Almost all 3- and 5-flute horns were in the 108 to 110 dB range and reached 115 dB in some cases. Mid-locomotive horns measured 101 dBA in static tests. We see no reason to set a lower limit at 96 dBA. We recommend that all locomotives that have the ability to travel at speeds greater than 65 mph have a horn available to the crew that is mounted up front and has an output SPL of at least 110 dBA at 100 ft. If this horn is dictated by railway operating rules to be reserved for emergency use only, then the normal horn should be positioned on the locomotive such that it provides an output of at least 100 dB when measured at full speed at angles of 25 degrees and greater from the forward facing direction. Where two-level horns are used we recommend that the lower level of operation have a minimum output of 100 dB.

Our analytic results indicate that community noise impacts can be reduced by shortening the duration of the warning without significantly impacting its effectiveness. We recommend that warning time duration be shortened before horn intensity limits be considered as an all-encompassing rule. The warning heard inside a vehicle from a horn that is 400 m away is at the bottom of the detection threshold for a quiet vehicle. If it could be heard, warning times of 30 seconds from a train going 30 mph might lead to risky behaviour from those who believe a whistle means they have up to 30 seconds to *beat the train*. We recommend that railways change their operating rule 14(L)(ii) to give locomotive operators more flexibility in the sounding pattern of horns applied at rule-based grade crossings. They should be encouraged to initiate the first blow of the horn at a position they judge to be 15 s from the grade crossing, or at the present whistle post if their speed is greater than 60 mph. At crossings where there is a permanent track speed limit is 40 mph or lower, the whistle post should be at a location that provides 15 s warning at the first blow of the horn from a train travelling at the speed limit. Similarly, the effectiveness at the other end of the whistle pattern is of limited value. We recommend that locomotive operators be given the flexibility to stop sounding the horn at the entrance to gated grade crossings (rather than at the exit) when multiple vehicles are already stopped at the gates.

The idea of having two levels of output has merit. The main application of the loudest sound would be in cases of operator-perceived emergencies. However, it might also be desirable to consider day/night, active/passive, urban/rural and low/high-speed splits that exist in the other jurisdictions discussed above. As noted previously, a 4.5 dB increase in loudness would provide the same warning at a grade crossing from a 95 mph train as would be heard from a 60 mph train at an equal warning time from the crossing. If passenger trains that exceed 65 mph have a 5-flute front-mounted horn that can produce 111 to 115 dBA in perceived emergencies, it might be appropriate to consider an output level of 107 to 111 dBA at 30.5 m (100 ft.) for freight trains.

We encourage Canadian railways to ask the FRA to reconsider its limit on the louder level of two-level horns for locomotives that do not normally operate in the U.S. While the community noise vs. safety tradeoffs might justify this ruling when whistle bans are being lifted, the purpose of the two levels is to reduce the usage of the louder level. It seems counterintuitive to restrict the upper level to 111 dB when even 115 dB is not adequate for many alerting scenarios. We would rather see the upper limit at 115 dB. If the FRA retains its proposed 111 dB limit in its final rule, we recommend that Transport Canada seek a waiver to this limit for Canadian-based locomotives and particularly any high-speed VIA Rail locomotives that cross the border.

There is some additional support to this perspective in the accident data. From the FRA's crossing accident database for year 2000, we looked at the speed distribution of motor vehicles involved in grade crossing collisions where the train hit a moving vehicle. For passive crossings, 65 percent of the motor vehicles were reported to be going 10 mph or less. We would interpret this as indicating that 65 percent of the drivers were alerted to the presence of the train in time to apply the brakes but not in time to sufficiently slow down to stop short of the tracks. Some of these drivers may not have heard the locomotive horn, but had been visually alerted. However, the FRA's whistle ban studies indicate that at least some of these drivers were alerted by horns. A marginal increase in horn alerting capability would have an impact on those drivers. Referring back to our discussion of safe stopping distances (subsection 5.2.3.1) the incremental warning distance required for those drivers to have made a safe stop can be estimated as:

- 10 m to avoid the tracks,
- 8 m to accommodate vehicle length, and
- 3.5 m of additional stopping distance (i.e. $V^2 / [2 \times 0.35g]$, where $V = 5.4$ m/s (10 mph)).

At a highway speed of 60 km/h, the incremental distance, depending on response speed, is 26 to 56 percent of the desired *minimum warning distance*. For those drivers that were first alerted by the horn, a horn that was 2.5 dB louder would have provided the extra warning distance required for the base response case (5 dB for the fast response case).

5.4 Placement Implications

Our findings indicate that there is a speed-related attenuation of the sound output of mid-locomotive horns. The attenuation is greatest to the front of the locomotive and drops off with increasing lateral angle from the front. The area affected is greatest for horns located behind and close to the engine exhaust hood, and the magnitude of the attenuation increases at speeds beyond 65 mph. The mitigation of the sound is such that higher frequencies are affected more than lower frequencies. This reduces the horn's effectiveness in being detected inside a vehicle and in its alerting qualities. Horns located behind and close to the engine exhaust hood suffer further deterioration in the clarity of the sound, such that it can be perceived to be from a distant source.

We believe that all new locomotives should be built with horns located at the front of the locomotive. Ground effects, wayside shielding and debris considerations dictate that a higher position is preferable. We recommend that the horn's height should be at the roof level, but that hood-level heights are acceptable if such placement can lower community and/or in-cab noise impacts. In the event that a locomotive's horn is not positioned at the front of the locomotive, its effectiveness should be demonstrated at its highest operating speed.

We believe that the reduction of warning area exhibited by horns positioned behind and close to the engine exhaust hood of any locomotive that travels faster than 30 mph is large enough that the horn should be moved (or an alternative horn added) to another location. We have identified a number of alternatives, each with its own drawbacks that operating railways can assess against their own circumstances. An emergency-only horn is one option. An emergency-only horn combined with one or possibly two side-mounted *normal* horns would offer incremental coverage. A two-level horn is an option that has distinct advantages for trains operating in areas with community noise impacts. Extending the usage of the loud mode to high-speed, passive crossings would increase its safety impact but such a policy would have to weigh the in-cab noise impact against the benefits. A commuter operation with few passive crossings might adopt such a policy; an inter-city service with many passive crossings might not. Simply moving the horn to the front and providing better sound insulation and/or hearing protection devices for the crew is a third option.

6 ALTERNATIVE HORNS: EFFECTIVENESS AND NOISE CONCERNS

As noted in section 4.4, SPL measurements indicated there was an attenuation of sound output to the front of locomotives when the horn was positioned back from the front. The impact was worst at high speeds and when the horn was located behind and close to the exhaust hood. With the cooperation of VIA Rail and West Coast Express (WCE), the following three alternative horns were installed for evaluation:

1. Existing mid-locomotive horn elevated on VIA Rail's Genesis locomotives where the roofline in front of the horn was streamlined
2. Emergency-only horn over the cab of a VIA Rail F40 locomotive
3. Two-level horn over the cab of a WCE F59 locomotive

The main constraint to repositioning the horn is the impact on the in-cab noise level. The first alternative (involving VIA Rail's Genesis locomotive) avoided moving the horn any closer to the cab. The existing horn was elevated above the roofline and the outer high-frequency flutes were further elevated to get the most clearance from the most easily deflected frequencies. The horn position (relative to the roofline) of the existing horn and the position of the elevated horn are illustrated in Figure 43. The horn is situated on the left side of the locomotive, about 10 m back from the front end. It was thought that this elevation would be a sufficient measure since the Genesis locomotive has a streamlined roof and the amount of elevation available within VIA Rail's clearance envelope was enough to provide a line-of-sight path for the horn's emitted sound at most required warning distances.

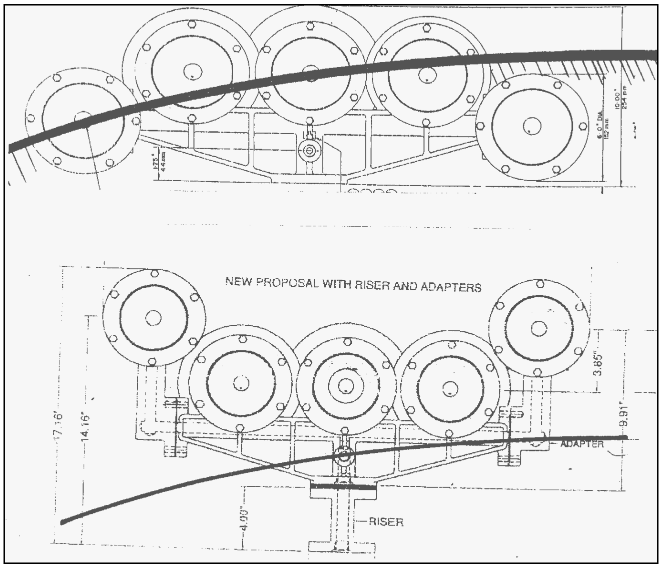

Figure 43 Illustration of the Genesis horn modification

The other two alternatives involved front-positioned horns and required in-cab noise mitigation measures. VIA Rail and WCE took different approaches to mitigating the in-cab noise impacts. VIA Rail's preferred approach was to make the front-mounted horn a second emergency-only horn, which it advised its crews to use only in cases of perceived emergencies. The existing horn was to be used in all other situations calling for horn usage.

WCE is a commuter railway operating between Mission and Vancouver, BC, with many whistle crossings in urban areas. It found the two-level horn attractive. The two-level horn had full output of 113 dBA (measured at 30.5 m in front of the locomotive) available when the operator perceived a need. For normal warnings it was restricted to an output of 102 dBA. This lower output level was superior to the output of the existing location when travelling at normal operating speed. It would therefore lower the community annoyance level associated with the existing horn. Residents would perceive the expected 10 dB reduction in sound level emitted to the side as a 50 percent reduction in noise. At the same time the warning effectiveness to the front is improved under 'normal' conditions and, like VIA Rail's alternative horn, attains the maximum SPL under perceived emergencies.

The three alternative horns were assessed in revenue service with the objective of assessing:

- the alerting effectiveness,
- community impacts (if relevant),
- the crew acceptance level.

In addition to the objective measurements of SPL, crew surveys were undertaken to solicit feedback on the perceived warning effectiveness and of other in-cab aspects of the horns. Unfortunately, the timeframe of the study and delays in getting equipment installed resulted in an insufficient number of survey responses. We recommend that the survey forms and video surveillance equipment be retained by the co-operating railways past this study's completion to assist the railways in assessing their crew's reaction to and perceptions of the alternative horns.

6.1 Alerting Effectiveness

The analyses of the horn's requirements in terms of urgency characteristics and directionality that led to the recommended alternative in the first place are the main basis of its safety effectiveness. The front-mounted horns have been found to produce an incremental loudness to the front of 10 to 20 dB, compared to mid-locomotive mounts located behind obstructions. The urgency content of the signal is also significantly improved. Nonetheless, sound measurements were made to confirm that the alternative horns produced the expected output characteristics.

Raising the Genesis's horn did not achieve as significant an improvement as expected. The results are discussed in subsection 4.4.1. There was an improvement in loudness, a reduced sensitivity to wind conditions and a significant improvement in higher frequency content at high train speeds. However, the SPL output to the front of the locomotive was not significantly improved. The level of output achieved to the front would be adequate for pedestrian situations but not for many of the stopped vehicle scenarios shown in Table 9.

Figure 44 compares the output of VIA Rail's emergency horn with its conventional horn at 90 mph. The results can be seen to meet expectations. The emergency horn's output characteristic at 90 mph is close to that of GO Transit's 5-flute front-mounted horn at 58 mph (illustrated in Figure 16).

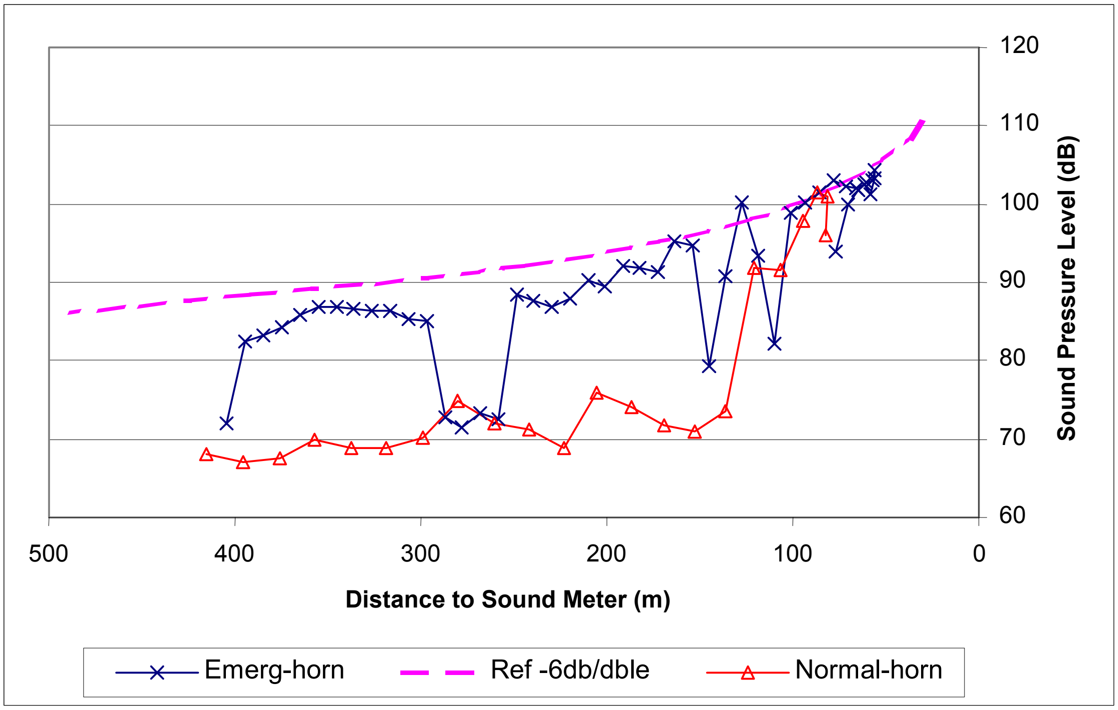

Figure 44 **Comparison of emergency and mid-locomotive horns at 90 mph**

One cautionary aspect of the prototype was that the retrofit led to situations where the emergency horn was not getting an adequate flow of air. The long feed line from the valve to the new horn might have produced condensation, which froze in the feed line. The findings further emphasize the importance of locating the valve close to the horn, and of providing an adequate sized feed line for a 5-flute horn's air requirements.

WCE's two-level horn was mounted on the cab roof about 1.5 m back from the front roof cowling to avoid potential antenna interference (Figure 45). It did not achieve the same performance as VIA Rail's emergency horn, which was mounted at the front of the locomotive.

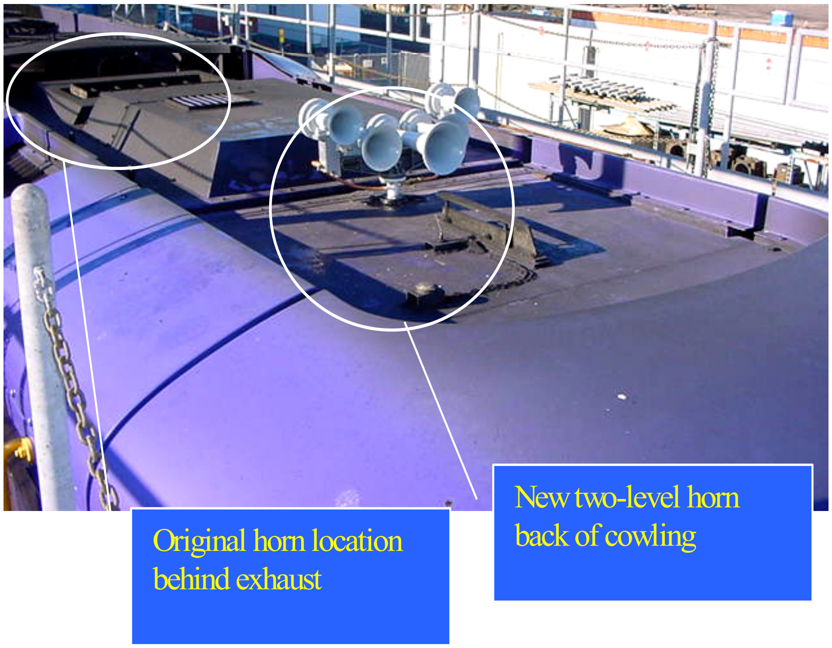

Figure 45 Two-level horn position on F59 roof

The individual outputs of WCE’s two-level horn are compared with its original horn’s output in Figure 46. One can see that the outputs to the front at both levels are about 6 dB below what the unattenuated output would be. The low setting is close to the existing horn’s output and the high setting is about 10 dB above the output from the previous location, but the output to the front is attenuated for both levels. We suspect that the turbulence from the cowling is the source of the attenuation in the forward direction; however, refraction might also play a role. The results reinforce the importance of mounting the horn at the front of the locomotive.

The front-mounted horn has clear advantages as an auditory warning device; however, the two alternatives tested are by necessity compromise solutions. Each weighs the warning benefits against impacts on in-cab sound levels and community annoyance. The safety compromise that results is similar for both of the front-mounted alternatives. While each provides the capacity to sound the loudest feasible warning, they depend on the operator recognizing an emergency condition. As such, they are adequate for trespass situations where the operator must first see the trespassers in time to warn them, but have limitations in areas where a rule-based warning is sounded. The NTSB [2000] in its comments on the FRA’s proposed horn rule states that, in its opinion, two-level horns “could place a burden on the train engineer to make the appropriate selection.”

For vehicles stopped at a passive crossing, the operator is in a position where he/she must decide whether an emergency situation exists. The results presented in Table 9 offer some guidance in this respect. One might consider it advisable to give a louder warning when vehicles with long clearance times (school buses, tractor trailers) are stopped at passive crossings. With respect to the same table, we note that this limitation is mitigated by the fact that at high train speeds, highway vehicles with long clearance times would not hear the emergency horn either.

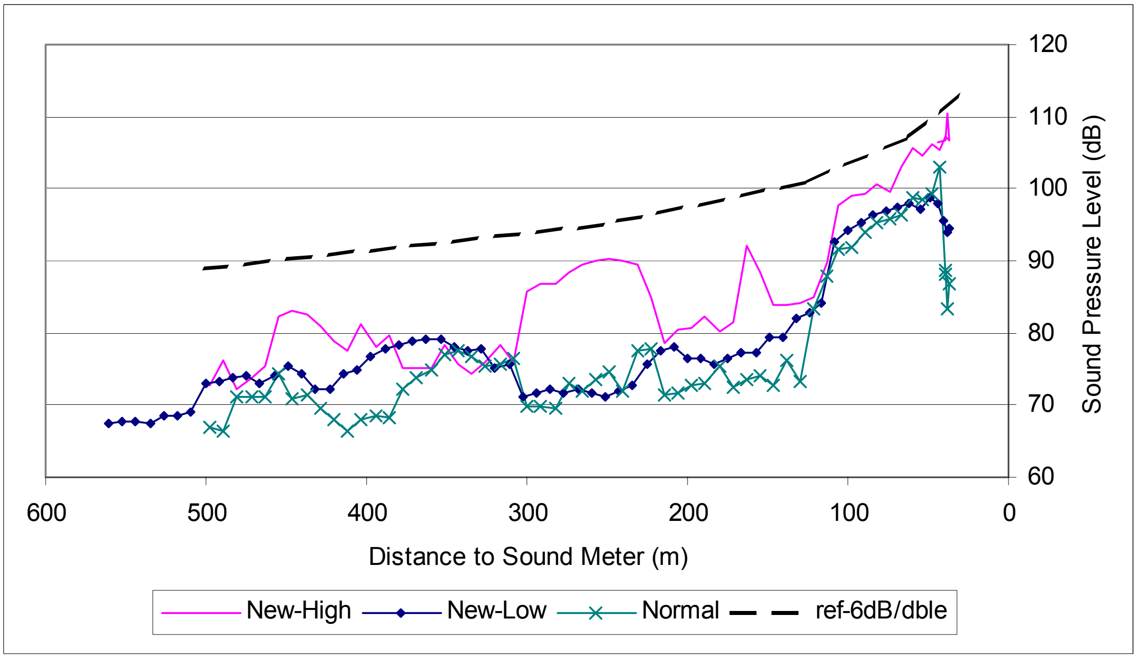

Figure 46 Comparison of two-level and mid-locomotive horns at 60 mph

Passive crossings with poor sight lines and potential hidden approach vehicles can pose a similar decision. Referring back to Figure 41, one can see that the Dash-9 locomotive and the SD-40's left side achieve full output at an angle that is adequate for vehicles approaching at 60 km/h, while the GP9 does not. The emergency-only concept will be effective if it is located on a locomotive (such as the Dash-9) where the normal horn's directional output rapidly rises to full effectiveness as the lateral angle increases. The normal horn's position on locomotives like the GP9 and F40 is such that it is effective in very few scenarios. The operator of these locomotives would have the sole responsibility of deciding whether to use the emergency horn or a horn that will only be effective at low train speeds.

The two-level horn has an advantage over the emergency-only horn on this type of locomotive because its lower output would offer sufficient warning for more speed/geometry conditions. Nonetheless, it has the capacity to offer a louder warning and the operator has the responsibility to decide when it is required. We believe that railways that adopt either the emergency-only or two-level horns should specify in their operating rules that the higher output level be used at passive grade crossings with poor visibility.

As noted in Section 5.4, the loss of output from horns positioned behind and close to the exhaust hood of locomotives (like the GP9 and F40) is so large that we believe corrective action is required. We do not have enough details on the types and frequency of accidents to gauge the impact of the reduced warning area to the front of newer locomotives such as the Dash-9 discussed above. We also do not have enough test data to assess whether these horns can be significantly improved with a height elevation. Adding an emergency-only horn up front would not significantly impact crew noise levels. If railways do not voluntarily add an emergency-only horn at the front of these locomotives, additional accident data analyses should be undertaken to assess the cost-benefits.

6.2 Community Noise Concerns

The unwanted effects of noise include loss of sleep, lower productivity, psychological discomfort and annoyance. These are hard to quantify, but because they are associated with a place, the quantity of damage is often viewed as resulting in lower property values. Many studies use a noise depreciation index (NDI), which is the percentage reduction of house price per dBA-above-some-base. The average NDI for all of the airport noise surveys between 1967 and 1990 is 0.62 percent/dBA, the same value as for highways surveyed over the same period [English, et al., 2000].

We note that the benefit derived from a social costing perspective using damage costs produces impacts that are higher than one can get by using prevention costs. The FRA in its analysis used a prevention-cost approach. The prevention costs were identified as the costs to municipalities of installing sufficient protection at crossings to allow whistle bans. On this basis the community noise impact was judged to be about 35 percent of the safety impact of prevented fatalities and injuries.

The data do not exist at this time to accurately calculate the number of residences affected by railway horns. We note that Transport Canada is developing a geographic database for crossings, which can potentially be tied to census data. Population and dwelling unit densities can be obtained from the 1996 Census Data on CD-ROM.[10] It is only possible to readily determine densities for political or major census divisions since these are the only units for which Statistics Canada includes the area. The areas of the smaller enumeration areas (EA) are not published. EAs typically contain 100 to 400 dwelling units. A GIS-coded file of EA boundaries can be purchased from Statistics Canada ($20,000 range for the whole of Canada) but was not in the scope of this project.

In the absence of exposure data, we quantify the impact area of the alternative two-level horn but do not take the analysis to the next level of assessing the community value realized by the alternative.

6.2.1 Relevant Definitions

Community annoyance with unwanted noise involves more than its loudness. The time of day that it occurs, its frequency spectrum, the duration/frequency of occurrence, and its tonal qualities all have an influence. The A-weighting scale is universally adopted to weight the relative annoyance of different frequencies within a noise signal. The following defined measures are used in this section:

- SPL (dBA) describes the *A-weighted Sound Pressure Level* in noise at any moment in time.
- Lmax is the *Maximum Sound Level* (or loudest part) of a single noise event.

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[10] Statistics Canada, GeoSuite, Catalogue No.: 92F0085XCB ISBN: 0-660-59272-X.

- SEL, the *Sound Exposure Level,* describes the cumulative noise exposure from a single noise event for its entire duration. In calculating SEL, the noise exposure is normalized to a time duration of one second so that different noise events can be compared in terms of their sound energy.
- Leq(p), the *Equivalent Sound Level,* describes the cumulative noise exposure from all events over a defined time period (p).
- Ldn, the *Day-Night Sound Level,* describes the cumulative noise exposure from all events over a full 24-hour period, with events occurring between 10 p.m. and 7 a.m. increased by 10 dB to account for greater nighttime sensitivity to noise. Ldn is the descriptor most commonly employed in environmental noise assessments.

In its draft environmental impact statement for its proposed horn rule [U.S. DOT, 1999], the FRA notes that a large number of community attitudinal surveys rank transportation noise among the most significant causes of community dissatisfaction. Surveys show that:

- at 45 Ldn, the level of high annoyance in a community averaged 0 percent,
- at 60 Ldn, approximately 10 percent of respondents reported being highly annoyed, while
- at 85 Ldn, the proportion of those being highly annoyed was approximately 70 percent.

The FRA identified two thresholds of community noise impacts, adopting U.S. Department of Housing and Urban Development (HUD) standards for a residential noise environment to qualify for funding of proposed housing developments. In the HUD Standards, Ldn below 65 dBA is considered “Acceptable”, while Ldn above 75 dBA is “Unacceptable”. We adopt the FRA’s interpretation of these standards as signifying thresholds of community annoyance as:

- Ldn = 65 dBA is the *impact* threshold*,* while
- Ldn = 75 dBA is the *severe impact* threshold.

While the focus of the FRA assessment was on the impact of eliminating whistle bans, our focus is on the impact of changing locomotive horn characteristics.

6.2.2 Community Noise Reduction Effectiveness

We looked at the community impacts of introducing a hypothetical pattern control 3-flute horn. The benefits of a pattern control horn (that are noted in section 6.3 with respect to in-cab noise levels) would also provide some level of reduction in community noise exposure. While an add-on pattern control device might be too large and too expensive to consider in locomotive retrofit applications, a similar effect might be achieved in new locomotive construction by recessing a horn into the body. The effectiveness of a hypothetical pattern control device on a 3-flute horn is assessed in Appendix F. It is shown to provide a reduction in Ldn such that 40 trains per day would represent the same severe Ldn impact as 10 trains per day with existing horns.

Of the alternative horns that were tested, only the two-level horn installed on WCE’s locomotive would lead to a reduced community impact. The other alternatives were driven by safety improvement without any increased community impact. Simply moving the existing horn up front and providing crew with hearing protection would also have a minimal change in community noise levels. The emergency horn as envisaged by VIA Rail would have a slight increased community impact, since the normal horn is unchanged and the emergency horn would be louder but (presumably) used infrequently.

We assessed the impact that the two-level horn would have on neighbouring community noise levels by analytic means. The two-level horn has an SPL that is 10 dB lower for normal operation than in emergency mode. Since the emergency mode is seldom required, the community impact is based on the normal SPL level and compares it with the SPL from the existing locomotive position. The existing horn position has a greater than 10 dB reduction to the front but emits full SPL to the sides.

The polar plots of the existing horn placement and the normal operation of the two-level horn were used as sound sources. We calculated the sound exposure level (SEL) on the basis of a 60 mph train blowing the rule 14(L)(ii) pattern (long, long, short, long) such that 11 s of application existed in the 15 s approach interval. We accounted for a nominal shielding effect of buildings in dissipating sound levels by calibrating the predicted open air sound propagation with published noise level measurements made in a study of Mundelein, Illinois [Lucke, et al., 2002]. Table 13 compares the measured values of maximum SEL reported for Mundelein with our analytic model predictions for the existing 3-flute mid-locomotive horn. The last two columns show the differences before and after a shielding adjustment factor is included. The averages of the differences shown in the last two columns of the table are 0.19 dB for the shield-calibrated model and 8.3 dB for the unadjusted model.

Table 13 Calibration of model SEL with Mundelein data

Site #	Track Distance (ft.)	Distance to Grade Crossing (ft.)	Max SEL (dB)	Model SEL (dB)	Shielded Difference (dB)	No-shield Difference (dB)
0	354	401	90.2	102.2	12.0	15.8
1	1,763	2,608	80.5	81.6	1.1	11.9
2*	1,354	1,383	94.5	88.1	-6.4	2.7
3	950	1,214	91.3	92.3	1.0	8.5
4	1,162	1,214	84.0	90.0	6.0	14.4
5	1,550	1,550	81.9	85.9	4.0	13.9
6**	544	597	88.6	98.2	-0.4	4.9
7	1,901	3,379	80.9	75.0	-5.9	5.9
8	422	1,943	91.5	83.9	-7.6	-1.7
9	1,531	1,848	88.4	86.4	-2.0	7.7

* This site was reported to be the only one with an unshielded view of the track.

** Indoor measurement, a 10 dB attenuation factor is included in our difference calculation.

As indicated in Table 13, the shielding calibration factor was based on a situation where maximum SELs were reported rather than averages. We made a similar comparison with average data from 14 sites reported in the Gering, Indiana study [Multer & Rapoza, 1998]. The model predictions for the existing 3-flute mid-locomotive horn with the shielding factor included were 6 dB higher than the average SEL data reported for Gering. As our intention is to make a relative comparison between two horn types, the use of averages or maximums is equally valid.

The front-mounted horn has a lower output but the fact that it is more focused to the front of the locomotive results in a higher SPL at shallower angles. As a consequence, the noise reduction impact of the two-level horn is greatest at larger distances from the track. At short lateral distances, the noise exposure from the two-level horns will be greater than it is with mid-locomotive horns. This is illustrated in Figure 47, which shows the impact along the track at fixed lateral distances of 200 m and 600 m. The values represent the average exposure from a train in each direction. For example, at 800 m along the track from the crossing, someone located 200 m away from the track would experience only a 1 dB reduction in noise exposure with the two-level horn, while someone 600 m away from the track would experience a 10 dB reduction.

Because we assume equal traffic by direction, the impact on the other side of the crossing will be the mirror image of the one shown. One can see that while the noise exposure is lower in all locations, the most effective location is that nearest the crossing. One must remember in looking at the SEL magnitudes, that SEL integrates the SPL over the time period. Thus, the SEL magnitudes are higher than the peak sound level attained during the horn sequence. Also, slower trains with longer whistle exposure times would produce higher SEL values and faster trains with shorter whistle exposure times would produce lower SEL values.

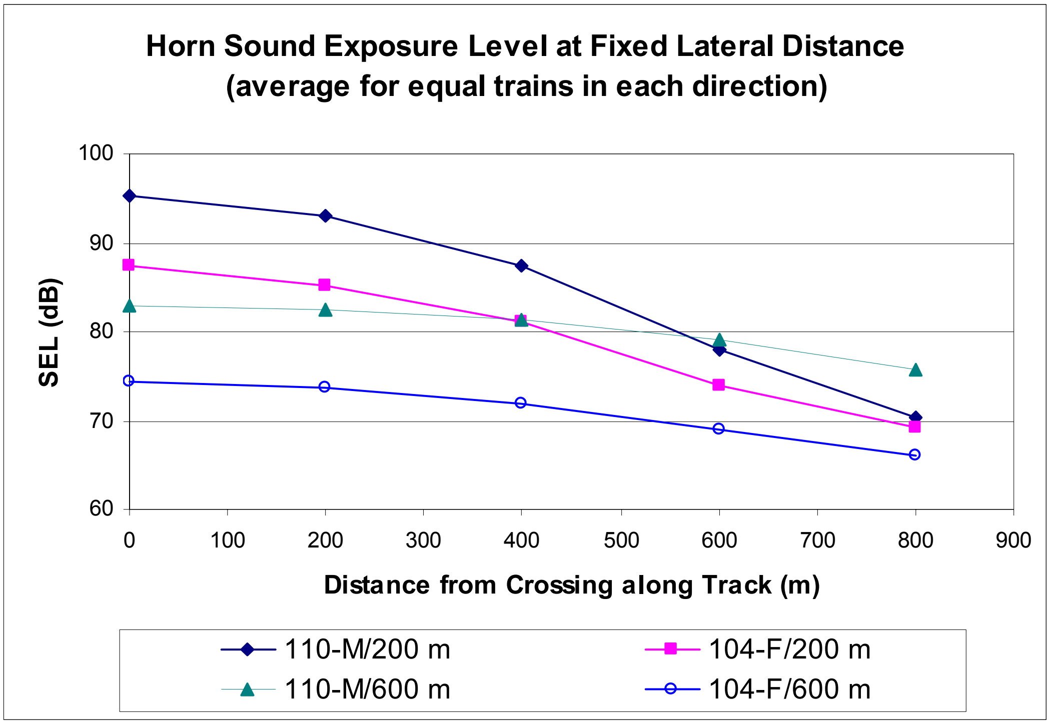


Figure 47 **Horn SEL comparison at fixed lateral distances**

The other community impact measure assessed was the day-night weighted exposure (Ldn). In calculating Ldn we have adopted some aspects of the procedure used by the FRA (*horn model* spreadsheet from the FRA's website—www.fra.dot.gov) in its environmental assessment of the proposed elimination of whistle bans. The FRA assumes that the train noise (excluding horn) is part of the ambient noise environment and is incremental to the baseline Leq. Its analysis of past noise measurements produced train noise at the crossing that has an Leq about 10 dB below the horn Leq. We used this number to increment the baseline Ldn with increasing train frequency and assessed the impact at a location 150 m and at a 90 degree angle to the track at the crossing. We assumed equal trains in each direction and equal trains in the 'night' and 'day' periods, all travelling at 60 mph and producing the same horn SEL discussed within this subsection. Figure 48 illustrates the resulting sensitivity of community noise with increasing train frequency for both normal and two-level horns. One can see that the two-level horn changes the train frequency at which a *severe* impact threshold is exceeded from below 10 trains per day to 40 trains per day.

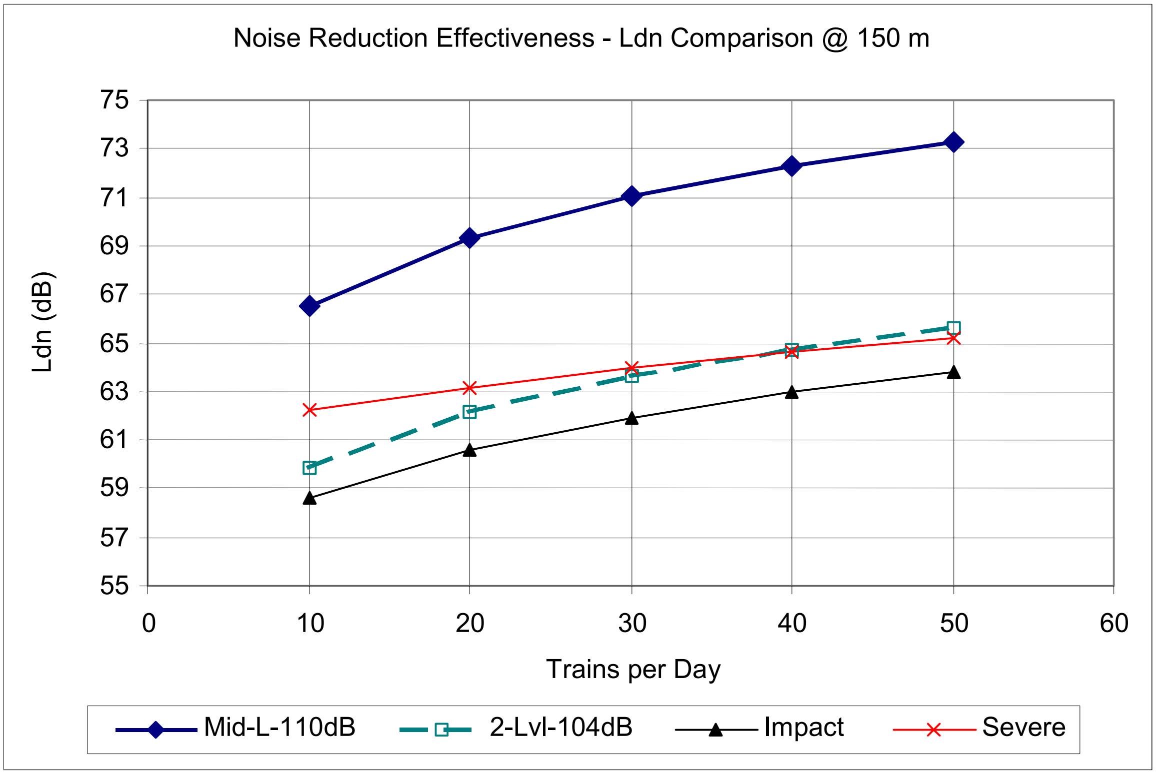
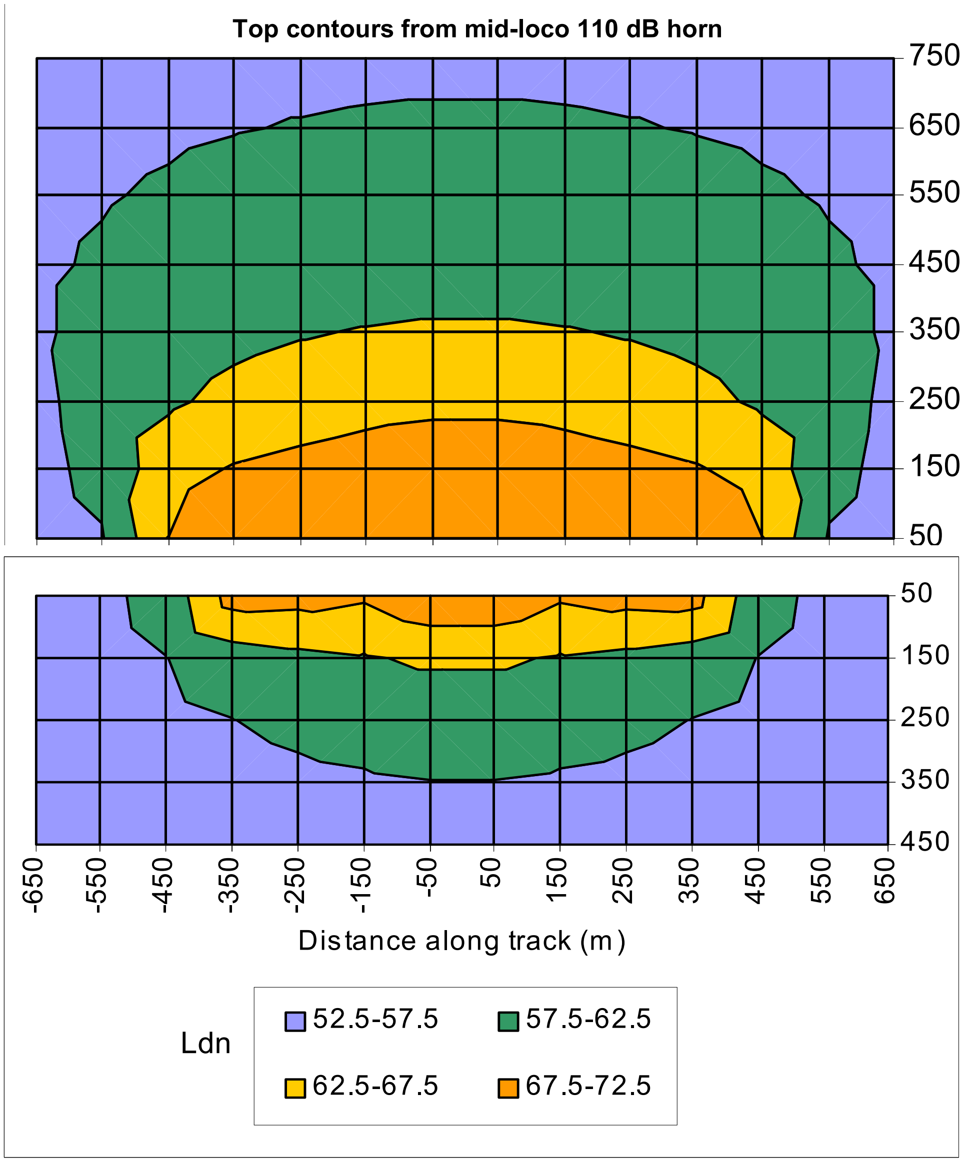


Figure 48 Trains-per-day comparison of community impact

Figure 49 illustrates the reduction in noise exposure in terms of surface area boundaries around a grade crossing. The upper part of the figure shows the Ldn impact of the existing mid-locomotive horn, while the bottom half of the figure illustrates the Ldn impact of the two-level horn.


Top contours from mid-loco 110 dB horn

Bottom contours from front-loco 104 dB horn

Figure 49 Ldn comparison of community impact surface area

The impact magnitude is not significantly changed for locations close to the track, but for a given threshold, the total area of impact from the two-level horn is about 40 percent of the area affected by the mid-locomotive horn. The total impacts for the affected areas are:

Reduction in *severe impact* region	2.73 dB-km^2
Reduction in *impact* region	2.89 dB-km^2
Total reduction	5.62 dB-km^2

There are other approaches to community annoyance issues with locomotive horns. The idea of wayside horns was noted in section 1.2. Another approach is to make the horn sound less annoying. The early work of Aurelius and Korobow [1971] produced a recommendation for 5-flute horns, in part because its sound was less annoying. The two-level horn tested by WCE had a harmonious sound with the normal 3-flute combination and a more alerting dissonant sound with the full 5-flute combination.

The Long Island Railroad (LIRR) recently made a number of changes to try to appease community annoyance.[11] Among the changes was a change to the chord that is played by the 5-flute K-5LA horn provided on the original locomotive. The equipment manufacturer had mounted the horn mid-locomotive in a depressed well. The specific changes included:

- moving it to the front over the cab,
- changing the magnet solenoid to a manual valve,
- changing the 622 Hz flute to 261 Hz, the 494 to 512 and the 415 to 470, and
- pointing the horn slightly downward.

The motivation for the changes was a combination of meeting the new FRA proposed rule and appeasing the high level of community complaints. Moving the horn to the front met the FRA's proposed new rule with respect to directionality (see Appendix A), while the shift to lower frequencies was considered to present a less annoying sound to the community. The use of a manual actuator allowed a reduced volume where the alerting needs were minimal. According to the LIRR, the warning effectiveness of either horn was not an issue.

LIRR considered a below-hood location but rejected it because of the complexity and cost of the conversion. A two-sound level horn (higher output at high speed) was also considered but rejected because it was believed the 5-chime horn would be acceptable to the community at high output.

6.3 Cab Workplace Constraints

Transport Canada has workplace regulations that govern noise levels inside the locomotive cab. The regulations generally follow occupational safety and health (OSH) regulations that require action to be taken to reduce the sound level before hearing protection is considered. Thus, the repositioning of the horn to mid-locomotive was prompted by a desire to meet the OSH recommendations.

Ultimately, the purpose of the horn is safety. Actions taken by the railways to date have recognized the safety constraint of the existing standard/regulation, which requires an output of 96 dBA measured in stationary tests at 100 ft. Industry followed the recommended tests to insure that any actions taken conformed with this established regulatory/recommended requirement, which was based on the knowledge at the time. Our findings indicate that the performance of the horn is influenced by its position when travelling at operating speeds. The findings shift the balance point, but still involve a necessary compromise among the safety objective and unwanted community and workplace noise levels.

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[11] Personal correspondence with Ron Leo, Long Island Railroad, Metropolitan Transportation Authority.

The crew aspect is further complicated by the fact that OSH regulations have been updated to more constraining level. These regulations are in the process of being revised to match Part VII of OSH Regulations that apply to other sectors of federal jurisdiction. The regulations cover sound level exposure intervals and are set to provide an 8 hour equivalent exposure limit. Current regulations permit exposure duration of 8 hours to sound levels up to 90 dBA. The exposure is cut in half only when the sound level increases by 5 dBA. The revised regulations (in the process of being adopted) will limit the 8 hour exposure to 87 dBA and reduce it by half for each 3 dBA increase in sound level.

The restriction placed on in-cab sound level from the horn by the existing and proposed regulations is illustrated in Figure 50. The figure depicts the absolute maximum horn sound level that would be allowed under conditions of a quiet ambient noise otherwise. While the old regulation would have allowed 105 dBA on VIA Rail's worst-case route, the proposed regulations restrict it to 96.9 dBA.

The equivalent 8 hour noise exposure *Lex(8)* is calculated as the integrated noise exposure over the work shift duration normalized to 8 hours. For an 8 hour shift it is simply the integrated noise measurement. In 1991 VIA Rail took in-cab noise measurements for a range of its locomotives at speeds up to 95 mph. Its most recently acquired locomotives exhibited an average background noise level above 80 mph of about 83 dBA. VIA Rail's recently purchased Genesis locomotives have an in-cab ambient noise level of about 78 dBA above 80 mph. On the other hand, its oldest locomotives are louder than the 83 dBA.

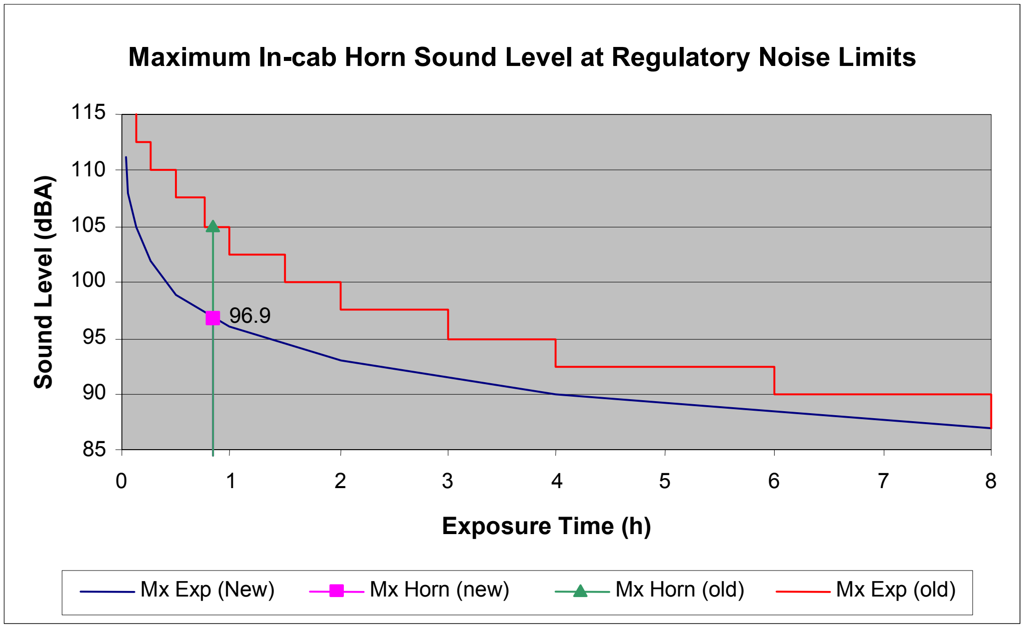

Figure 50 **Cab noise regulation influence on horn output**

To assess the effect of noise regulations on locomotive horns, we estimated horn exposure duration. VIA Rail provided data it had collected for several of its train runs. Horn exposure varied from 6 to 16 percent of the run time. We were also told that a typical work cycle includes 3.5 h of off-road time. On-road time varies from 4 to 5.5 h. We assume that the worst-case horn exposure is 0.83 h and that the ambient in-cab noise level is 83 dBA while on the road and 77 dBA when not. The ambient noise level in the cab influences the permitted horn sound level. The influence of ambient noise levels is illustrated in Figure 51.

We note that the placement of the horn at mid-locomotive was largely driven by crew noise level concerns, since the horn was able to meet the FRA guideline of 96 dBA at 30.5 m in either location. While Figure 51 illustrates that a quieter locomotive can accommodate a louder horn sound, the horn will also be more evident to the crew in a quieter locomotive. It is possible that the crew would still object to the locomotive horn even if the regulations were met. Thus, while 95 dBA for the horn might be acceptable for a locomotive ambient of 83 dBA, a target might be better set at 90 dBA.

Our in-cab sound measurements varied with the age of the locomotive/cab car. Figure 52 compares the in-cab sound spectrum of cab-mounted 5-flute horns on an F40 early 1980s locomotive, a mid 1980s GO cab car, and a late 1990s WCE cab car. The Volpe Center testing of over-cab positions was also sensitive to the locomotive vintage [Rapoza & Fleming, 2001]. While a new locomotive measured 91 dB and 97 dB for window closed and window open respectively, an older locomotive was about 6 dB higher at 97 dB and 105 dB, respectively.

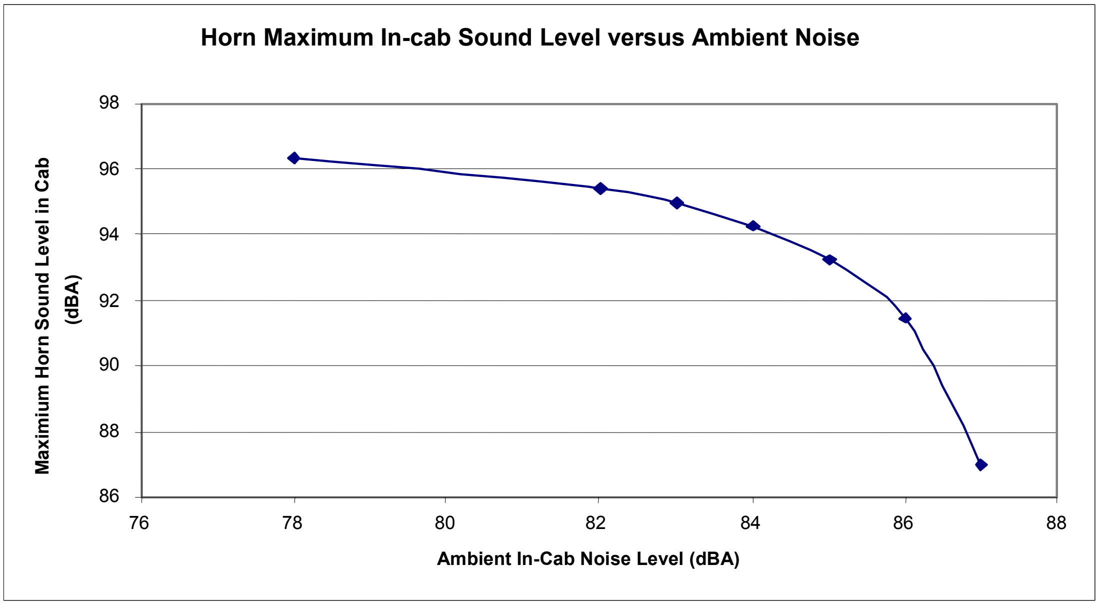

Figure 51 Influence of ambient noise on permitted horn sound level

Measurements made in-cab for the two-level horn installed on one of WCE's newer model F59 locomotives were:

- 87 dBA at normal and 94 dBA at emergency with windows closed.
- 93 dBA at normal and 104 dBA at emergency with windows open.

The WCE horn was positioned over the cab rather than in front of the cab because of structural limitations and concerns about airline feed length. If it were possible to mount it at the front of the cab, we believe the in-cab sound level would be closer to Rapoza's new-locomotive measurement of 97 dB with windows open.

The two-level horn would meet the new OSH regulations when operated at *normal* with the windows open. The regulation would also be met by the louder horn with windows closed. Older locomotives would meet the regulation with windows closed and horn operated at *normal*. Older locomotives and window-open situations with a single-level horn would require additional mitigation measures.

We also note that the objections to over-cab horn position were made at a time when neither hearing protection devices nor air conditioning were commonplace in locomotive cabs. Earplugs are becoming more common in the present in-cab environment of Canadian railways and the passenger railways have been installing air conditioning units in both old and new locomotives.

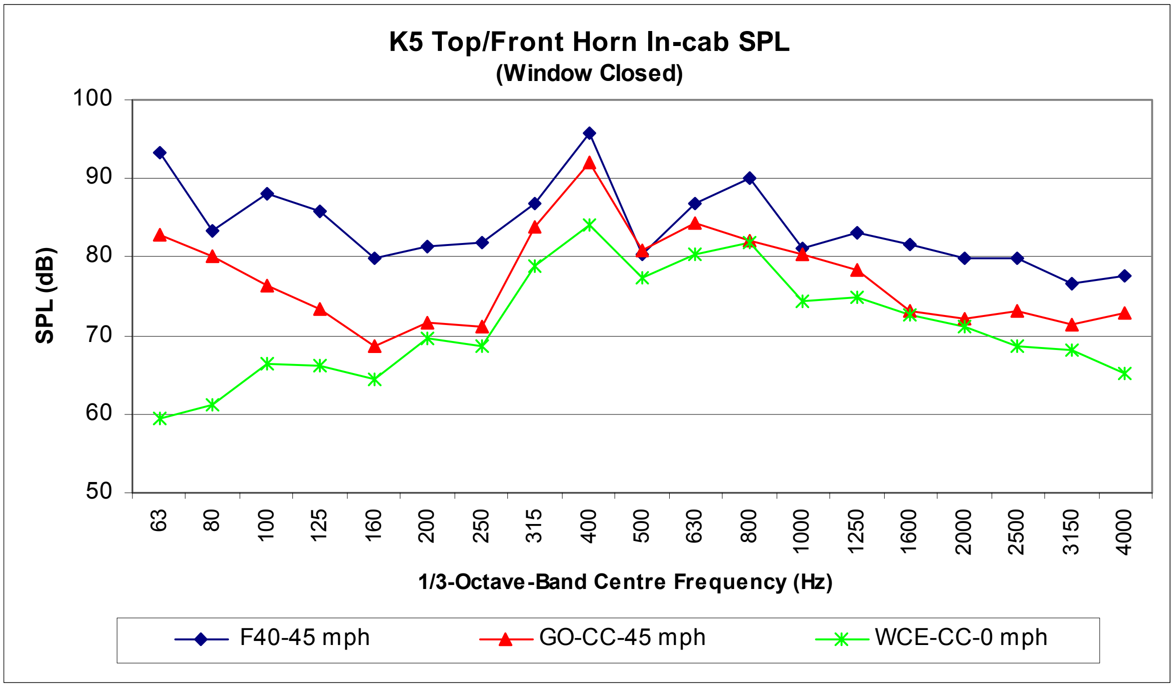

Figure 52 In-cab sound spectra of different vintage cabs

We assessed the effectiveness of hearing protective devices in mitigating horn sound levels. The attenuation properties were based on independent tests rather than manufacturer's claims. The ear plug attenuation is based on an average of six types of earplugs [Edwards, et al., 1983], the muffs on one brand [Robinson & Casali, 1999] and the active noise reduction plug on university laboratory tests [Matsubara, et al., 1999]. The effectiveness for the horn's sound spectrum is illustrated in Figure 53 and the aggregate results are summarized in Table 14.

Since the average of six different styles of earplug was used, it would be possible to select one from the range that best suits the locomotive noise environment and realize better results than the average results shown here.

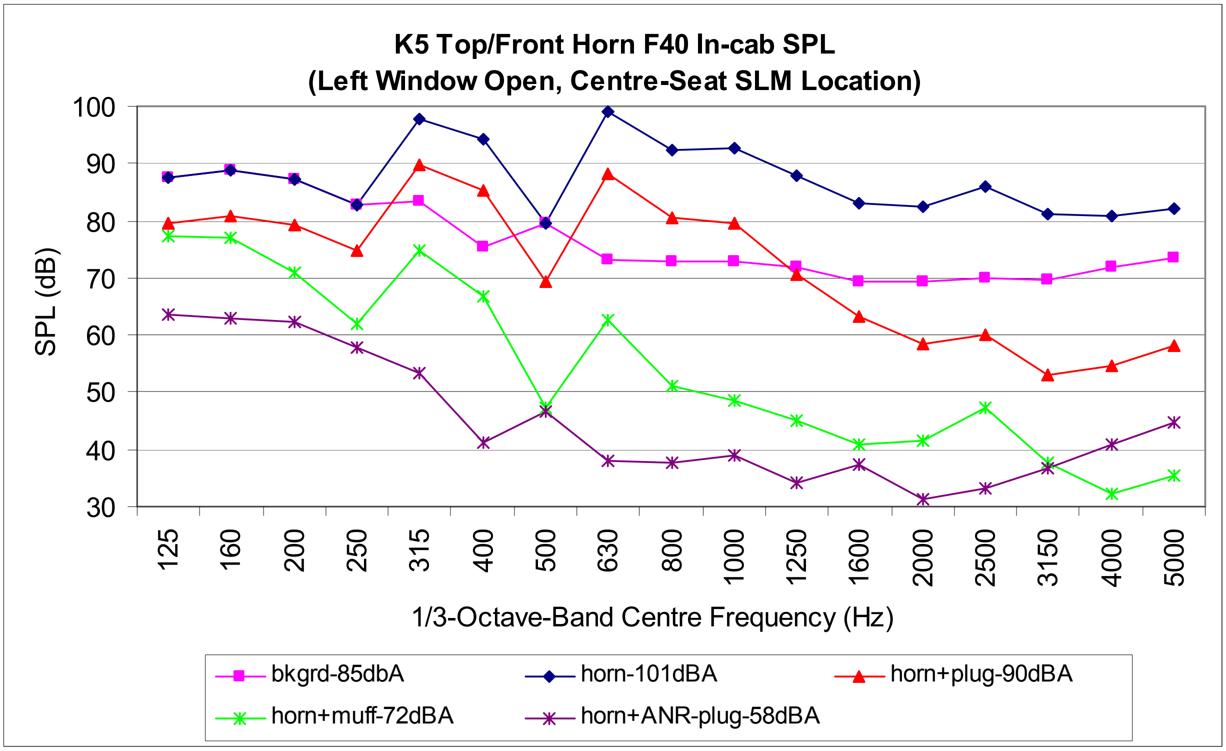

Figure 53 Effectiveness of hearing protectors

As seen in Figure 53, the background noise of the locomotive is higher than the horn at lower frequencies.[12] The earplugs bring the horn sound level to 90 dBA, which is below our estimated OSH requirement (93 dBA for an 85 dBA ambient from Figure 51). Muffs bring the sound level down to 72 dBA, well below the OSH requirement, and active noise reduction (ANR) plugs bring it down to 58 dBA. Muffs and ANR plugs are also adequate for the open-window condition as indicated in Table 14.

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[12] We had anecdotal evidence that the noise concerns are more with the engine sound level than with the horn. In testing in-cab sound levels on GO Transit, we observed that both crew members wore earplugs in the locomotive end of a commuter train trip but removed them on the cab car return trip. The background noise level in the locomotive end (engine/air compressor/radio) was high but was weighted on lower frequencies. The cab car had a much quieter background noise level of 78 dBA. The window was open with frequent horn activation on both legs of the trip and the horn SPL near the open window was about 105 dBA at both locations. The crew indicated that the engine noise was the main annoyance and the horn was in fact a harmonious relief to the other noise.

Table 14 In-cab sound level of K5 horn top/front position on an F40 locomotive

Window Condition	Sound Position	Sound Pressure Level (dBA)			
		No protection	Plugs	Muffs	ANR plugs
Closed	Centre	96	84	68	54
Open	Centre	101	90	72	58
Open	Window seat	107	95	77	64

The ANR plug is more effective than the muff and also lighter in weight. ANR devices have the ability to totally eliminate pure tones, such as the locomotive horn emits, and mitigate random noise. Such a device would have to be set to attenuate rather than eliminate pure tones so that the user could hear the horn and radio communications. The added initial cost and ongoing maintenance requirements are such that it is an unlikely choice over the standard plugs or muffs.

The plug style is sufficient for locomotives that have air conditioning (so that windows do not have to be opened) and would not attenuate radio and voice communication below the hearing threshold of the worst 10 percent of 60-year-old males. The *Detectsound* model [Laroche, et al., 1991] based on Zwicker's loudness summation [Zwicker & Scharf, 1965] considers the influence of age-related hearing loss. Laroche's application of the model to signal detection in noise with plug-style protectors found that the signal elevation required by the 10th percentile 60-year-old male over an 18-year-old was only 2 dB. The signal assessed was in the 800 to 2,500 Hz range.

The muff-style protector could bring radio communication close to the limit of intelligibility for persons with hearing loss. The ideal protector for the cab environment is one that falls between the plug style and the muff style. We reiterate that the plug-style data used in our analyses is the average of six types. It might be that one of the commercially available plugs would provide the required protection without affecting normal communications requirements. Alternatively, a muff-style protector that is designed to be less effective in the voice frequency range could be pursued. As shown in subsection 3.2.3, our masking model predicted the detection level of sound inside one brand of muff-style hearing protector reported in the literature. Laroche's *Detectsound* model, which has a more complex treatment of hearing loss, is another analytic screening tool that could assess the best type of hearing protector for the particular environment. Both analytic approaches are most reliable in situations of tone-related signal detection. The more complex requirement of voice intelligibility might require additional experimental investigation using railway crew members with some hearing loss for tests in a simulated cab environment. We note that the quality of the voice signal heard on in-cab radios is not always a high quality reproduction. It could be that an improved speaker and/or receiver would help to alleviate the intelligibility problem.

Another area of concern with respect to resolving the in-cab noise problem is the potential masking of radio communication by the horn itself. We do not have the data to resolve this issue. The possibility of radio voice signals being masked by horn noise needs to be assessed. We note that the horn is in the hands of the locomotive engineer and, if there is safety critical communication required at the same time as the normal warning sequence of the horn, we would suggest that the warning cycle be adjusted to accommodate the receipt of a radio message. In a perceived emergency, the horn would of course take precedence. We note that if the above issues are found to pose significant problems, the use of muff-style protectors with radio communication headsets and microphones is a possible solution.

OSH requires that hearing protection be considered when Lex(8) exceeds 84 dBA and be provided when Lex(8) exceeds 87 dBA and other methods of noise mitigation are not practicable. VIA Rail's F40 locomotives are close to the 87 dBA limit, while its Genesis locomotives are below it at about 78 dBA. Human Resources Development Canada [2000] conducted full duty cycle tests of freight railway locomotives. Its measurements indicate an average Leq of about 83 dBA with windows closed and 87 dBA with windows open. It is noteworthy that Volpe Center's in-cab measurements of the mid-locomotive horn position were 100 dB for the old locomotive and 95 dB for the new locomotive when the window was open. Thus, the window-open operating condition is a problem under the new OSH regulations, regardless of horn position.

Even though the OSH regulations prefer that action be taken to mitigate the noise source before hearing protective devices are used, we believe that the safety requirements of the horn override the drawbacks of using hearing protection. We recommend that Transport Canada (which has responsibility for both in-cab and external safety) implement standards that require horns to be positioned where their effectiveness cannot be unduly compromised at normal operating speeds.

We note that other mitigating steps are possible. The City of Calgary Fire Department undertook tests to investigate the effects of using electronic siren horns with more directional control [MC Squared, 1990]. A fire truck equipped with a standard flasher bar-mounted siren over the cab was measured at a level of 98 to 100 dBA in the driver's seat and 100 dBA at 50 ft. in front of the vehicle. The pattern control horn in the same location realized a 12 dBA reduction in the driver's seat (sound level dropped to 86 to 88 dBA). At the same time, the sound level at 50 ft. in front of the vehicle rose to 110 dBA**.** While the tests involved a horn with an electronic driver, a variation of such a device might be a feasible in some locomotive applications. Simply recessing the horn into the hood or roof could be an option for new locomotives. As noted in section 6.2, we assess the community impact of such a hypothetical device in Appendix F.

7 CONCLUSIONS AND RECOMMENDATIONS

We summarize our conclusions and recommendations in this section. Where recommendations relate to horn characteristics, we leave it to the railways and Transport Canada to determine which should be formalized in a rule and which should be adopted as railway standards. The focus of this study was on the position and sound characteristics of locomotive horns. It is much easier to implement changes in future-generation locomotives than in existing locomotives. Thus, the same finding can lead to different recommendations for new-build locomotives than for existing locomotives.

We found that a horn's location on the locomotive is extremely important to its effectiveness at operating speeds. The sound output to the front of the locomotive (and particularly that of the higher frequency components) deteriorates with increasing train speed if the horn is not mounted at the front of the locomotive. As a consequence, front-mounted horns were found to be more effective than those mounted in other locations.

We concluded that the undesirable in-cab noise impacts of a front-mounted horn could be accommodated. The optimal method requires analytic and experimental investigation, but methods are available today and this issue should not prevent action from being completed by the 2006 target of the *Direction 2006* initiative. We believe that the safety requirements of the horn override the drawbacks of hearing protection devices.

1. ***We recommend that Transport Canada (which has responsibility for both in-cab and external safety) implement rules that call for horns to be positioned where their effectiveness cannot be unduly compromised at normal operating speeds.***

The cost of providing horns at a front location and meeting in-cab noise constraints is not a major issue in new-build situations.

2. ***We recommend that all new locomotives be built with horns located at the front of the locomotive. In the event that a locomotive's horn is not positioned at the front of the locomotive, its effectiveness should be demonstrated at its highest operating speed.***
3. ***The horn's height should be at roof level, but hood-level heights are acceptable if such placement achieves lower community and/or in-cab noise impacts.***

Our findings indicate that the existing standard requiring a sound level output of 96 dBA at 30.5 m puts the onus on the motor vehicle driver to take noise reduction steps and to be actively listening for a horn in many situations. We did not find any horn measurements in the literature that were less than 101 dBA at 30.5 m, and our own measurements did not register less than 108 dB for lateral angles at 30.5 m from the locomotive. Almost all 3-flute and 5-flute horns were in the 108 to 110 dB range and reached 115 dB in some cases. In looking at two-level horns, the manufacturer could not provide a horn with an output lower than 102 dBA at 30.5 m. We see no reason to keep the lower limit at 96 dBA.

4. ***We recommend that all locomotives that can travel at speeds greater than 105 km/h (65 mph) have a horn available to the crew that is mounted up front and has an output sound pressure level of at least 110 dBA at 30.5 m (100 ft.). If this horn is dictated by railway operating rules to be reserved for emergency use only, then the normal horn should be positioned on the locomotive such that it provides a 30.5 m (100 ft.) equivalent output of at least 100 dB when measured at full speed at angles between 25 degrees and 45 degrees from the forward facing direction.***

If passenger trains that travel at speeds greater than 105 km/h (65 mph) have a capacity of 111 to 115 dBA in perceived emergencies, it might be appropriate to consider an output level of 107 to 111 dBA at 30.5 m (100 ft.) for freight trains that travel at speeds less than 105 km/h (65 mph). However, we hesitate to recommend a limit on available output for perceived emergencies.

5. ***We recommend that railways that frequently run at 100 km/h (60 mph) consider the same output level as recommended above for higher speed locomotives, and that all mainline locomotives with operating speeds lower than 105 km/h (65 mph) have a horn available to the crew that is mounted up front and has an output sound pressure level of at least 106 dBA at 30.5 m (100 ft.) with the same conditions noted above if it is an emergency-only horn.***

While the outputs recommended above are no louder than existing horns, positioning the horn up front will improve its effectiveness and offer some scope for a reduced output. A two-level horn would allow the normal rule-based warning to be sounded at a lower sound level and perceived emergencies to be responded to with the loudest sound level.

6. ***We recommend that any railway that frequently runs through urban areas without whistle bans consider the use of two-level horns.***
7. ***Where two level horns are used, we recommend that the lower level of operation have a minimum 30.5 m (100 ft.) equivalent output of 100 dBA.***

Maximum limits are desirable from both pedestrian and community noise perspectives but are relevant to lateral noise emissions from the locomotive. Existing railway horns have a maximum output capacity of about 145 dB at 1 m (3 ft.), which dissipates to about 115 dB at 30.5 m (100 ft.).

8. ***We recommend that maximum limits only be defined for lateral angles from the locomotive rather than in front of the locomotive.***
9. ***We recommend a maximum limit of 135 dB at trackside on a 10 km/h pass-by test at 1.5 m above the top of passenger platforms and 2.0 m horizontal from the nearest rail.***

We encourage the Canadian railways to ask the FRA to reconsider its maximum limit on the louder level of two-level horns for locomotives that do not normally operate in the U.S. While the community-noise versus safety tradeoffs might justify such rulings when whistle bans are being lifted, the purpose of the two levels is to reduce the usage of the louder level.

10. ***We recommend that Canadian railways seek a waiver to the proposed 111 dB limit on loud-mode output for Canadian-based locomotives and particularly any high-speed VIA Rail locomotives that cross the border if the FRA retains it in its final rule.***

We believe that existing air horn technology can provide the attributes required for an effective auditory warning device. The most important sound characteristic is its frequency spectrum, and the horn's harmonic content is more important than its fundamental frequencies. Our findings indicate that a typical narrow-spectrum characteristic needs to be 5 dB louder than a typical broad-spectrum horn to achieve the same signal alerting level inside a vehicle. A broader spectrum also adds to the perceived urgency associated with the sound warning. We found that, given other requirements, age-related hearing loss is not an issue for the horn spectra and does not significantly reduce the importance of higher frequency content.

11. ***We recommend that the frequency content of the assembled horn on the locomotive, when measured in stationary tests at 61 m, be such that the minimum 1/3-octave band SPL in the range 2,000 to 3,150 Hz is not less than Φ below the maximum 1/3-octave band SPL in the range 250 to 1250 Hz, where Φ equals 12 dB for trains exceeding 105 km/h and 15 dB otherwise.***[13]

There is a need to more clearly define what is currently known as the sound of a locomotive horn. We recommend that railways and locomotive builders borrow from and expand on the U.K standards in this regard.

12. ***We recommend that the tones of the locomotive's audible warning device be recognizable as being from a train and not similar to warning devices used in road transport or as factory or other common warning devices.***
13. ***We recommend that locomotive horns comprise fundamental frequencies consistent with at least two flutes and having fundamental frequencies no lower than 250 Hz and no higher than 660 Hz***
14. ***We recommend that fundamental frequency tolerances be +/- 20 Hz and that specifications on the harmonic content ensure the assembled and mounted horn meets the 1/3-octave requirements noted above.***

If our laboratory findings of a 562 Hz sweet spot are independently verified, the first part of the recommendation should be modified to further state that at least one flute should have a fundamental frequency in the range of 470 to 512 Hz.

Five-flute horns were found to have a broader spectrum than 3-flute horns and also realized a small incremental contribution to intensity and perceived urgency. We do not see a significant enough advantage in five flutes over three to recommend them as a standard for all locomotives. However, we believe the demands on an auditory warning device at high speeds warrant the available increase in effectiveness.

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[13] We note that this recommendation could require that railways specify acoustic testing and possible refurbishing of horn flute shapes in addition to the present overhaul of diaphragms when they are refurbished.

15. ***We recommend that railways consider the incremental benefits of 5-flute horns when purchasing new mainline locomotives.***
16. ***We recommend that any existing or future locomotives operating over 105 km/h have a front-mounted 5-flute horn available to the crew in emergency situations.***

We stress the importance of selecting frequency combinations and specifying the harmonic content at the time of purchase and refurbishing so that 3-flute horns provide a broad-spectrum warning signal.

Our findings indicated some increase in perceived urgency with increased dissonance. The effect was not as great as the frequency effect and its influence could not be statistically separated from an increase in the number of flutes.

17. ***We recommend that those railways that implement a two-level or emergency-only horn select the combination of frequencies such that some dissonance exists in the loud level.***

We do not see this as a regulatory requirement nor do we see it as desirable for a normal horn frequently used in a rule-based warning mode.

Additional factors come into play when considering the above findings with respect to existing locomotives. Of existing mid-locomotive horns, those mounted behind and close to the engine exhaust hood performed much worse than those mounted in other locations. Horns in this position would not provide an effective warning to motor vehicle drivers approaching a grade crossing at 60 km/h when a train is travelling at speeds of 97 km/h (60 mph). Few drivers stopped at grade crossings would be alerted by this horn if the train were travelling faster than 47 km/h (30 mph). We found that even though horns located behind the exhaust stack could be heard in time for a cautious pedestrian to react, the nature of the warning lacked effectiveness. A less cautious individual might not consider it to be from a nearby train and would have a lower perception of urgency than for the same horn mounted up front. We believe that the reduction of warning area exhibited by horns positioned behind and close to the engine exhaust hood is large enough that action is required.

18. ***We recommend that existing mainline locomotives with a horn positioned behind and close to the engine exhaust hood should either have its horn moved to the front or have an alternative emergency horn added at the front of the locomotive. If this alternative horn is dictated by railway operating rules to be reserved only for emergency use, then the normal horn(s) should be positioned on the locomotive such that it provides a 30.5 m (100 ft.) equivalent output of at least 100 dBA at angles between 25 degrees and 45 degrees from the forward facing direction when measured at full operating speed.***

We have identified a number of alternatives that operating railways can assess against their own circumstances. An emergency-only horn (which would only be initiated by the operator in situations of perceived emergency) is one option. An emergency-only horn combined with one or possibly two side-mounted *normal* horns might be required to get the incremental lateral coverage recommended above. A two-level horn is an option that has distinct advantages for trains operating in areas with community noise impacts. The normal warning would use a lower output level than the existing horn, but because of its up front positioning would still provide a louder and more effective warning to the front of the locomotive. The loud mode would be reserved for conditions of perceived emergency. Extending the usage of the loud mode to high-speed, passive crossings would increase its safety impact but such a policy would have to weigh the in-cab noise impact against the benefits. A commuter operation with few passive crossings might adopt such a policy; an inter-city service with many passive crossings might not. Simply moving the horn to the front and providing better sound insulation and/or hearing protection devices for the crew is a third option.

The measurement sample size for the behind-exhaust horn position was large enough and its performance poor enough that concrete conclusions and recommendations are possible. Other mid-locomotive horn positions, while not as effective as the up-front horn position, did perform better than those positioned behind and close to the exhaust. We found no alternative position that provided as effective a warning device as one mounted at the front of the locomotive. We do not have enough details on the types and frequency of accidents to gauge the impact of the reduced warning area to the front of these other horn positions (largely associated with newer locomotives). However, adding an emergency-only horn to the front of these locomotives would not significantly impact crew noise levels and we suggest that railways consider adding such a device.

19. ***We recommend that railways with existing locomotives that have horns that are mounted mid-body but not behind and close to the engine exhaust hood also consider adding an emergency-only horn at the front of the locomotives.***

We note that the increased line clearances generated on many mainline railways to accommodate double stack containers and tri-level auto-rack cars might allow elevation of mid-locomotive horns to a height where they can realize a warning effectiveness comparable to front-mounted horns. We were not able to conduct tests to determine the necessary height to fully achieve the performance of a front-mounted horn. Also, our tests were based on revenue trains rather than controlled testing. The railways might wish to seek verification of our findings with controlled tests. In addition, they might wish to assess, for a range of locomotive speeds, how high a horn needs to be elevated above the roofline to provide a warning signal to the front that is unattenuated at operating speeds.

We found that auditory warning devices are unable to meet the demands of all situations. Fast moving trains are not able to warn some long vehicles stopped at grade crossings.

20. ***We recommend that Transport Canada, in its promotion and training of road vehicle drivers, include material requiring that they know that it might be necessary to roll down both windows and turn off all noise sources in order to hear a train approaching a grade crossing in poor visibility conditions.***
21. ***We recommend that Transport Canada also notify provincial and municipal highway authorities to bar school buses and tractor trailers from using passive***

grade crossings of high-speed rail lines in conditions of poor visibility (e.g. fog, heavy snow fall).

We site Mowbray road grade crossing on the Kingston Subdivision in Ontario (stop sign protection on a 160 km/h track) as one example where such steps should be taken.

Similarly, the demands at passive grade crossings involving high speed on both road and rail approaches are beyond the feasible limits of auditory warning devices.

22. ***We recommend that highway speed limits at passive crossings with gravel roads not exceed 60 km/h.***
23 ***We recommend that the use of warning signs to reduce speed to 60 km/h on wet pavement and in poor visibility conditions at all passive crossings be investigated.***

We believe that community impacts can be mitigated without unduly compromising warning effectiveness. One option is the use of a two-level horn as previously recommended. A second option is to modify the existing fixed-distance warning sequence to a fixed-time warning.

24. ***We recommend that railways change their operating rule 14(L)(ii) to give locomotive operators more flexibility in the sounding pattern of horns applied at rule-based whistle crossings such that whistling is initiated 15 seconds from the crossing.***

Operators should be encouraged to initiate the first blow of the horn at a position they judge to be 15 seconds from the grade crossing, or at the present whistle post if their speed is greater than 100 km/h (60 mph). At crossings where the permanent track speed limit is 65 km/h (40 mph) or lower, the whistle post should be at a location that provides 15 seconds warning at the first blow of the horn from a train travelling at the speed limit.

Similarly, the effectiveness at the other end of the whistle pattern is of limited value.

25. ***We recommend that locomotive operators be given the flexibility to stop sounding the horn at the entrance to gated grade crossings (rather than at the exit) when multiple vehicles are already stopped at the gates.***

We have enough data on the performance of the behind-exhaust horn position to recommend that action be initiated without delay. Assuming the recommendations of this report are accepted, the first step forward is broad dissemination of the findings. In some cases this step has begun. The Brotherhood of Locomotive Engineers and United Transport Union are key players in any alternatives that involve increased noise in the cab. VIA Rail has initiated discussions with its employees concerning the performance issues raised and crew feedback has been solicited on aspects of the alternative horns installed on VIA and WCE locomotives. The railway has taken the responsibility of informing its employees of the safety issues involved and the noise mitigation approaches available.

Crew surveys were undertaken to solicit feedback on the perceived warning effectiveness and on other in-cab aspects of the alternative horns tested. The survey forms sought feedback on the type of actuator to be used for the two-level horns and whether loud activation should be tied into the emergency brake actuator. Unfortunately, the timeframe of the study and delays in getting equipment installed resulted in an insufficient number of survey responses.

26. ***We recommend that the survey forms and video surveillance equipment be retained by the co-operating railways past this study's completion to assist the railways in assessing their crew's reaction to and perceptions of the alternative horns.***

Two aspects of the emergency horn need further exploration. VIA Rail's and WCE's discussion with their locomotive engineers confirmed the preference for a single two-level horn button. The only style of two-level button that was available had no differentiation between first and second levels. The operator had to learn how far to push it without activating the emergency level. An improved button and further operational trials are required.

The survey form also asked for feedback on whether the emergency level should be tied into operator-initiated emergency brake applications. This issue is best addressed by the railways through discussions with their workers. We note that trains do experience undesirable emergency brake applications and operators also initiate emergency brakes in situations that do not require a horn warning. If automatically initiated, it should be tied to the brake lever and the operator should be able to regain control of the horn by pushing the horn button, either to stop it or to change the cadence.

These existing conversions can serve as a means of soliciting feedback and resolving acceptance issues that would provide valuable information to builders in the design and positioning of horns on future generation locomotives. It will also help the railways and their unions in assessing the need for, and/or methods of, repositioning horns on other better performing locomotives.

The dissemination of the findings needs to go beyond those involved in the above implementation steps.

27. ***We recommend that presentations be made to the locomotive builders, those railways not directly involved in this study and to any union officials that request it. We also recommend that a web site be developed that makes the audio-visual findings available to the public.***

We noted a number of areas of assessment that were raised but deferred in the course of this study.

28. ***We recommend that Transport Canada monitor the FRA's progress in its assessment of flashing versus steady burning lights. It might also be desirable to assess U.S. grade crossing accident data in a time series analysis of before/after the switch to strobe light or ditch light usage and to assess the relative fog-penetrating effectiveness of different lights.***

29. ***We recommend that further analyses of the U.S. studies of the impacts of whistle bans be undertaken to better classify the parameters and situations where locomotive horns were found to have an influence.***

Our focus in this study was on safety performance and the steering committee recommended that a more rigorous assessment of community impacts and solutions be deferred. Community impacts can be pursued on a number of fronts, including:

- development of better data on housing density near grade crossings,
- policy development on the application of social cost principles,
- evaluation of the performance of wayside horns, and
- ongoing implementation/evaluations of two level horns.

Other issues arising in this study that warrant further assessment include:

- verification of a 562 Hz sweet spot,
- exploration of conditions under which lower frequencies have an elevated effectiveness,
- determination of the relationship between perceived urgency and response time for in-vehicle noise environments, and
- better characterization of refraction and turbulence impacts (and their boundary of influence) on moving vehicles' auditory warning devices.

The Canadian railways and Transport Canada initiated this project as part of the *Direction 2006* initiative. We believe that implementation of the recommendations contained herein by January 1, 2006, will make a contribution to the *Direction 2006* goal of reducing crossing accidents by 50 percent by 2006.

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APPENDIX A

U.S. FRA Notice of Proposed Rule for Locomotive Horns

Source: (Federal Register, Vol. 65, No. 9 / Thursday, January 13, 2000)
(extract of key elements)

…. under most circumstances of crossing configuration and train speed, a train horn set in the range of 104–105 dB(A) at 100 feet in front of the locomotive may provide a sufficient auditory cue to alert the motorist who pauses at a crossing with active warning systems that the arrival of the train is imminent.

The greater challenge is presented by passively signed crossings. Depending upon the train horn harmonics, the Volpe Center estimates that a horn sound level in the range of 111–114 dB(A) may be sufficient to warn most motorists at passive crossings for all conventional train speeds, despite the fact that the horn sound as inserted into the vehicle must exceed the background noise by a larger margin than at crossings with automated warning devices in order to seize the motorists' attention.

Community impacts are also highly sensitive to train horn levels—but in the opposite direction. Volpe Center calculations suggest, for instance, that just reducing train horn levels from 114 dB(A) to 111 dB(A) would almost double the number of train movements permitted before a common 24-hour measure of acceptable community noise levels (Ldn=65 dB(A)) is exceeded at any given distance from the railroad right-of-way.

FRA is proposing two specific options, with a third concept suggested for comment. Under both options the minimum level would remain at 96 dB(A). However, in order to avoid significant loss of warning effectiveness, field tests would not include the current ''plus or minus'' allowance for error. Tests in the field would be required to demonstrate a sound level of at least 96 dB(A) at 100 feet in front of the locomotive and to comply with a specified maximum level. To avoid non-representative results caused by environmental extremes, testing would be required to be conducted within a range of temperature of 36 and 95 degrees Fahrenheit with relative humidity between 20 and 90 percent. Both temperature and humidity affect the propagation of sound waves.

Options for maximum level. Under the first option, the maximum permissible train horn sound level would not exceed 104 dB(A), which is believed to be sufficient in most circumstances to provide adequate warning at crossings using automated warning devices (where the motorist makes a decision while at rest near the crossing, expecting the train to arrive).

Under the second option, the train horn could be set at up to 111 dB(A), which is in the range where the horn is believed to be effective under many circumstances at passively signed crossings (where the motor vehicle is in motion at the decision point and the motorist have been provided no contemporaneous reason to expect to see a train). As soon as they are completed, FRA will place in the docket Volpe Center studies providing information pertinent to this analysis.

Variable level option. FRA notes that one possible approach to addressing this issue is a variable horn level. Under this approach, train horns would be required to be capable of sounding within a low range *(e.g.,* 96–104 dB(A)) approaching any crossing with active warning devices and within a higher range *(e.g.,* 104–111 dB(A)) at any crossing not equipped with automated warning systems. FRA notes concern that this could place an additional burden on the locomotive engineer and that sounding the horn in this pattern would not be feasible where crossings are closely spaced and are not uniformly treated with automated warning devices. Accordingly, at a minimum simplified procedures requiring the engineer to take the safe course would be required in these circumstances. Commenters are asked to evaluate this approach as a third option.

Directionality. Under current regulations, some locomotive horns have been placed near the center of the locomotive in order to reduce crew noise exposure. Although providing at least 96 dB(A) at 100 feet in front of the locomotive, these arrangements have sometimes led to higher sound levels at right angles to the locomotive than to the front or rear. This has resulted from obstructions such as diesel exhaust stacks and air conditioning units causing the horn noise to disperse. FRA believes that this approach is not necessary for crew safety and is inconsistent with the responsibility of the transportation company to limit community noise impacts. Accordingly, the proposed rule would require that the sound levels at 90 degrees and 100 feet from the center of the locomotive not exceed the value 100 feet in front of the locomotive. FRA also requests comment whether this community exposure should be measured at 90 degrees from the horn placement location, rather than the center of the locomotive.

APPENDIX B

Wayside Horn Reviews

The systems tested thus far have involved electronic horns mounted at the crossing. They play a simulated locomotive horn sound and are enclosed/shielded such that the sound output is focused along the highway rather than along the track (see Figure B.1). The horns are initiated by the crossing signal system and include a strobe light, which indicates to the locomotive crew that the horn has activated.

In light of ongoing tests of such devices in the U.S., the project steering committee believed it was best to focus this study on on-board systems. We note that the principal impetus for wayside horns in the U.S. is that of communities seeking alternatives to their existing whistle bans that will be lifted under proposed new FRA regulations. Transport Canada is not proposing to lift whistle bans in Canada but is focusing on potential improvements to on-board systems as it considers new locomotive horn regulations.

While we are not including wayside horns in our review, we comment on two aspects of the work done to date.

One drawback of the previous studies of wayside horns is that they all appear to be based on low-intensity devices. While the devices had improved community acceptance, it was not clear how much was due to the sound-focus along the road-approach and how much was due to the lower intensity and/or different frequency spectrum.

The lower intensity and the narrower frequency spectrum of the wayside horns tested (Figure B.2) resulted in the devices being assessed by some as less effective in alerting drivers. Rapoza and Rickley (1995), using acoustical data, determined that a wayside horn with a single tone and a maximum sound level of 87 dBA would be less detectable inside a moving motor vehicle than 5-chime and 3-chime locomotive air horns.

The FRA, in more recent evaluations of horn effectiveness (Rapoza, et al., 1999, pp. 35), predicted that wayside horns (of the type previously characterized) would be ineffective in alerting drivers at approach speeds of 30 mph (48 km/h) and higher. We note that if the wayside horns tested were proven to be effective, then it implies that locomotive horns are being operated at much higher sound intensities than necessary.

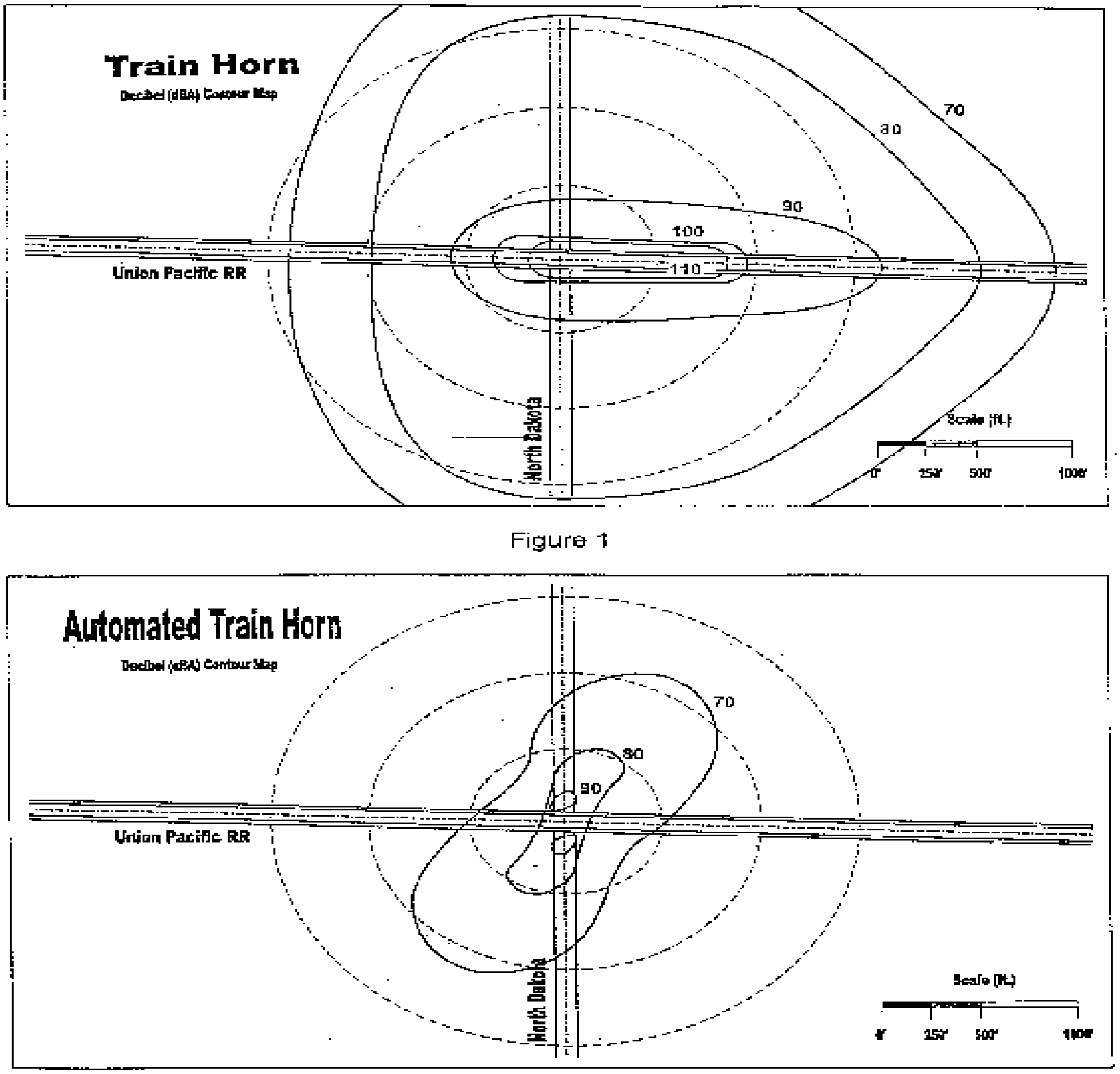

Figure B.1 Sound Intensity Contours for Wayside and Train-borne Horns
Source: Gent et al., 1999

Another aspect of the wayside horn work done to date is that the horns have been tied to the crossing signal system. There is a concern that tying the horn to the normal crossing protection system's activation could have a detrimental safety impact. Today's locomotive horn is clearly associated with a train, and people already ignore crossing lights and gates. If the horn becomes another device associated with the crossing signal system, then motorists might begin to ignore the horn as well as the gates. There is a trade-off to be made between false alarms and unpredictability associated with a horn tied the crossing signal systems and potential missed alarms if the horn is tied to the locomotive engineer.

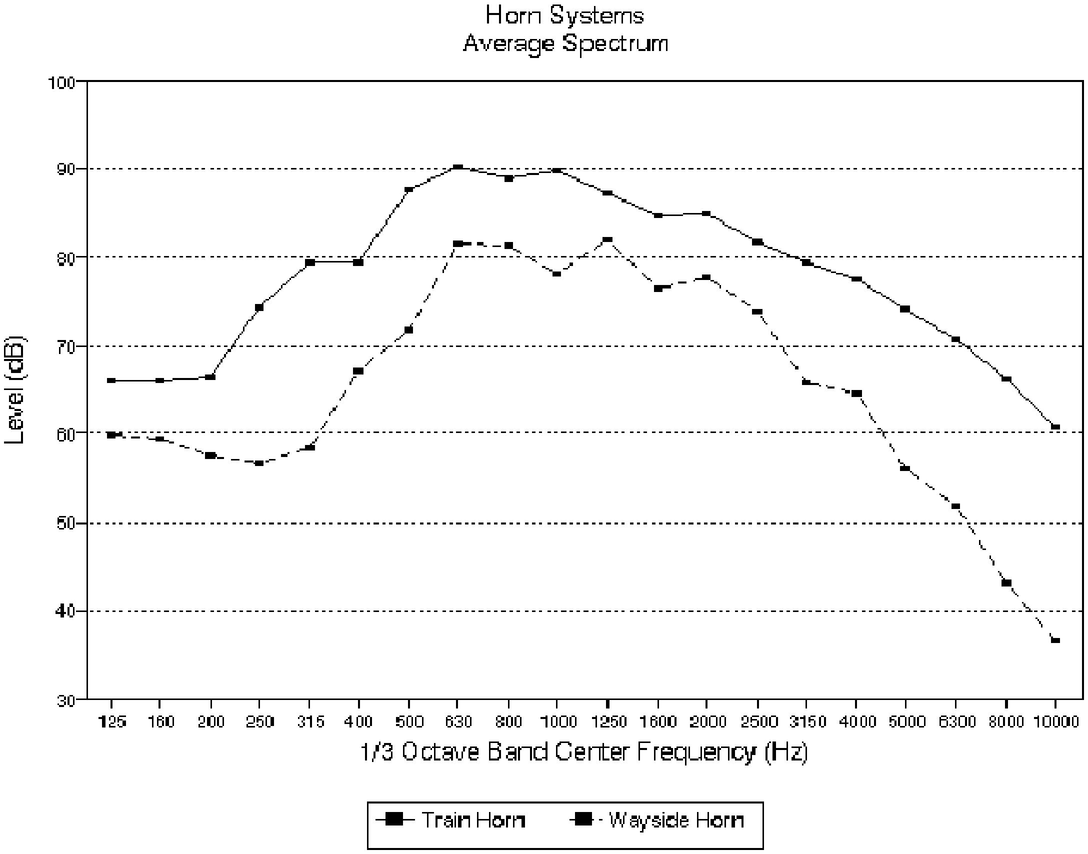

Figure B.2 Horn Spectra for Wayside and Locomotive Horns
Source: Multer and Rapoza, 1998

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APPENDIX C

U.S. FRA Regulations to Improve Locomotive Visual Conspicuity

U.S. railroads have been using various forms of auxiliary lighting systems for some years now. Figure C.1 is a picture of an Amtrak 40PH locomotive with two Star 200BC roof mounted strobes and a centre strobe between the number boards. The five-flute horn is also quite evident.

Figure C.1 Amtrak Strobe Light Configuration
Photo by: Dick Leonhardt (source – www.trainweb.com*)*

We found that the U.S. FRA has conducted evaluations of strobe lights and other light systems to raise the conspicuity of a locomotive [Carroll, et al., 1995] and subsequently introduced a regulatory requirement. The experimental field tests compared the performance of a lone headlight with combinations of a headlight and each of the following:

1. pulsing *crossing lights* that were aligned straight down the track,
2. steady burning *ditch lights* that were outwardly aligned at 15 degrees, and
3. dual *strobe lights* mounted on the top of the locomotive.

The following were among the principal findings:

- All three types of auxiliary lights outperformed the lone headlight by significantly increasing the distance a train can be detected and improving an observer’s ability to estimate a train’s arrival time at the crossing. For detection distance, the crossing light performed best, followed by the ditch and strobe lights.
- Although desirable effects can be achieved with pulsating strobe lights, particularly those lights operated in pairs, extensive use of strobe and oscillating-type lights on emergency vehicles has reduced their usefulness as a distinct warning of an approaching train. Further, strobe lights can tend to wash out against a light background and may not compete well for attention in a nighttime environment with a variety of light sources. Research in support of this proceeding indicates that crossing lights and ditch lights—the auxiliary lights most widely used by U.S. railroads—also appear to perform well under both experimental conditions and in revenue service.
- With respect to estimation of time of arrival, the crossing lights were judged to result in the smallest estimation errors for actual arrival time intervals between 7 and 22 seconds. However, the ditch lights clearly aided estimation of arrival, as well. In the field tests, observers wore headphones to mask noise from the oncoming locomotive.

- The limited accident data set suggest that the use of crossing lights may result in a greater than 50 percent reduction in accident rates.

The regulation is presented in Annex C.1. In its development of the new rule [Federal Register, 1995] the FRA notes:

> *FRA believes that a uniform light configuration on locomotives will help the public become familiar with and quickly recognize the appearance of an approaching locomotive. A configuration of three front-mounted lights (defined in the interim rule, together with the headlight, as "ditch lights" or "crossing lights") is the most common system adopted by the railroad industry since the issuance of the first interim rule in 1993. Those three lights form a triangle with one major dimension (base or vertical axis) of at least 60 inches. The normal human eye can discern two objects as separate when the objects are spaced to form a visual angle of approximately one-half of one degree. When the lights are seen as separate, the observer can better estimate the speed of an approaching train because as the locomotive moves closer the lights will appear to move further apart. A space of 60 inches between lights causes the lights to appear separate at 572 feet from the observer. Beyond 572 feet the lights are commonly seen as one. This distance corresponds to an approach time of 13 seconds for a train moving at 30 miles per hour, or 6.5 seconds for a train moving at 60 miles per hour.*
>
> *Given the prevalence and practicality of the three-light triangle system, the desire for a uniform appearance of an approaching locomotive, and the physical advantages of this system, FRA believes it to be the best lighting system to accomplish the purpose of this rule.*

In the same discussion of the new rule the FRA noted:

> *Information available to FRA suggests that about 7,946 locomotives are currently equipped with auxiliary lights that comply with the proposed rule. About 52.84 percent of these locomotives have pulsing lights. The remaining 47.16 percent have steady beams. Assuming the industry continues to install auxiliary lights in this proportion, FRA expects costs to reach approximately $97 million over the next twenty years. Although specifications for pulsing and steady beam lights differ, data are not available to establish that one light system is the more effective. Assuming both are equally effective, to justify incurring $97 million in costs, auxiliary lights must provide a benefit of preventing an average of at least 11 accidents annually. FRA estimates that auxiliary lights will prevent approximately 6,300 accidents (involving 1,493 fatalities and 3,056 injuries) valued at $2.424 billion over twenty years.*

Annex C.1

U.S. FRA Regulations to Improve Locomotive Visual Conspicuity

Source (Federal Register, Volume 60, Number 166, 1995)

FRA Regulation Sec. 229.125 Headlights and auxiliary lights. * * * * *

d) Effective December 31, 1997, each lead locomotive operated at a speed greater than 20 miles per hour over one or more public highway-rail crossings shall be equipped with operative auxiliary lights, in addition to the headlight required by paragraph (a) or (b) of this section. A locomotive equipped on [date of publication of final rule] with auxiliary lights in conformance with Sec. 229.133 shall be deemed to conform to the requirements of this section until [date four years after date of publication of final rule].

Auxiliary lights shall be composed as follows:

(1) Two white auxiliary lights shall be placed at the front of the locomotive to form a triangle with the headlight.
  (i) The auxiliary lights shall be at least 36 inches above the top of the rail, except on MU locomotives and control cab locomotives where such placement would compromise the integrity of the car body or be otherwise impractical. Auxiliary lights on such MU locomotives and control cab locomotives shall be at least 24 inches above the top of the rail.
  (ii) The auxiliary lights shall be spaced at least 36 inches apart if the vertical distance from the headlight to the horizontal axis of the auxiliary lights is 60 inches or more.
  (iii) The auxiliary lights shall be spaced at least 60 inches apart if the vertical distance from the headlight to the horizontal axis of the auxiliary lights is less than 60 inches.

(2) Each auxiliary light shall produce at least 200,000 candela.

(3) The auxiliary lights shall be focused horizontally within 15 degrees of the longitudinal centerline of the locomotive.

e) Auxiliary lights required by paragraph (d) of this section may be arranged to burn steadily or flash on approach to a crossing. If the auxiliary lights are arranged to flash, they shall flash alternately at a rate of at least 40 flashes per minute and at most 180 flashes per minute, for at least 20 seconds before the front of the train occupies the crossing. The flashing feature may be activated automatically and shall be capable of manual activation and deactivation by the locomotive engineer.

f) Auxiliary lights required by paragraph (d) of this section shall be illuminated not less than 20 seconds before the locomotive arrives at a public highway-rail grade crossing.

g) For the safety of persons along the right of way, including **railroad** employees and contractors

  (1) Railroads may elect to operate auxiliary lights when the speed over the crossing is less than 20 miles per hour; and

  (2) Railroads shall have the discretion to illuminate locomotive auxiliary lights in other circumstances in addition to approaching a public highway-rail grade crossing.

h) When one required auxiliary light and the headlight of a locomotive remain operative after the train has departed its initial terminal, the locomotive may proceed as an equipped locomotive until reaching the next point at which repairs to the inoperative light can be made. If no required auxiliary light remains operative, the locomotive may be moved only if the requirements of Sec. 229.9 are met.

Donald M. Itzkoff, Deputy Federal Railroad Administrator. [FR Doc. 95-21143 Filed 8-25-95; 8:45 am]

References

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Federal Register, Volume 60, Number 166 [Page 44457-44463], *Locomotive Visibility: Minimum Standards for Auxiliary Lights*, Department of Transportation, Federal Railroad Administration 49 CFR Part 229 August 28, 1995.

APPENDIX D

Laboratory Experiments in Detection and Perceived Urgency

D.1 PURE-TONE AUDIBILITY IN CAR NOISE

This experiment was designed to assess frequency regions that allow for maximum audibility in the presence of a car-noise mask. Pure-tone signals were presented that consisted of all combinations of eight frequencies and six intensities relative to the mask. The eight frequencies span the spectral bandwidth in which substantial energy may be generated by currently manufactured locomotive horns (261 to 4,000 Hz).

Participants

Nine participants were recruited from Queen's University and the Kingston (Ontario) area. These participants included four females and five males ranging in age from 18 to 40 years with a mean age of 25.8 years. All participants reported normal hearing and were able to detect all test signals when presented in quiet. Participants received course credit or cash payment for their participation.

Apparatus

Testing Environment

A sound attenuated chamber was used for testing. The configuration of the chamber and equipment inside the chamber is schematically depicted in Figure D.1.

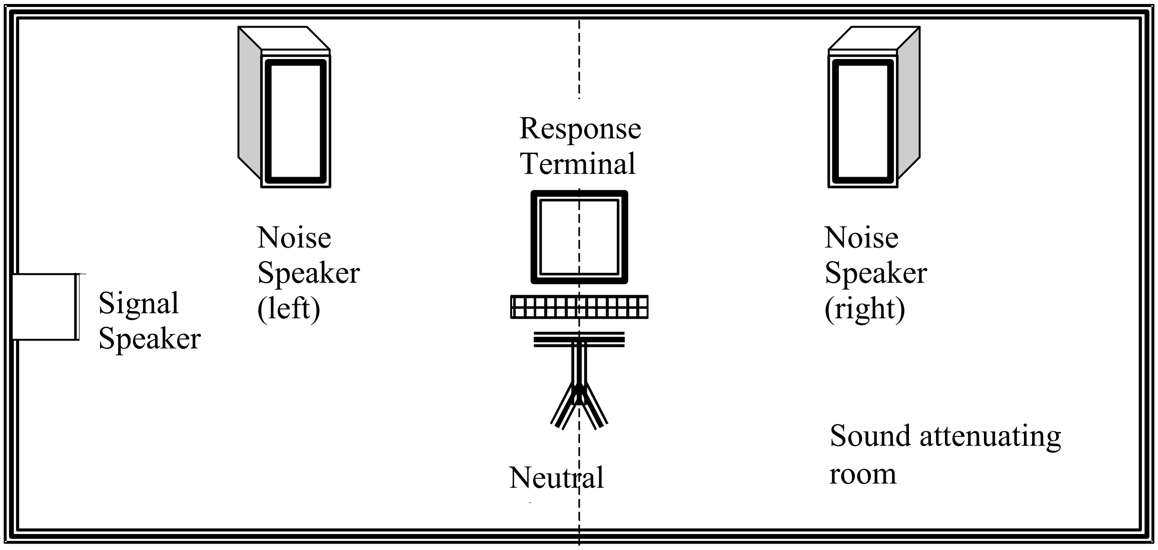

Figure D.1 Schematic depiction of the test environment

Participants were seated on an adjustable stool that was positioned in the middle of the chamber in front of a response terminal. The two loudspeakers that carried the noise mask were seated 0.5 m above the floor on stands. These stands were situated 2 m from the participant at 45 degrees to the left and right of the neutral plane (the participant's line of fixation). The single loudspeaker that carried the signal was seated 1 m above the floor on a stand. This stand was situated 3 m from the participant at 90 degrees to the left of the neutral plane.

Noise Mask

The noise mask was modelled after the average spectrum of in-car noise reported by Rapoza, et al. [1999]. In order for the noise mask to approximate the average spectrum, white noise was iteratively generated, recorded, and filtered from the vantage point of the participant. This iterative process was stopped once the recorded spectrum approximated the average spectrum such that the difference between spectra was less than 0.5 dB within any 1/3-octave band in the frequency range spanning 31.5 to 10,000 Hz. White noise was generated using a Macintosh Power PC running SoundEdit16 software (Macromedia, 2000) and projected through a NAD 3020A amplifier connected to B & W loudspeakers. The white noise was recorded and filtered using an IBM Pentium running CoolEdit software (Syntrillium, 2000). The overall intensity level of the noise mask at the participant's head was approximately 85 dB.

Signals

Forty-eight 1 s pure-tone signals spanning 8 frequencies (261, 400, 500, 562, 630, 1000, 2000, 4000 Hz) and 6 intensity levels relative to the noise mask (0, -3, -6, -9, -12, -15 dB) were tested. The intensity level (dB) for each of the 48 signals is listed in Table D.1. Signals were presented using Judge software (Nyvalla, 1998) running on an IBM PENTIUM computer with output via 16-bit sound card to a Fostex 6301 speaker monitor.

Table D.1 Intensity levels of test signals (dB)

Intensity Relative to Mask	261 Hz	400 Hz	500 Hz	562 Hz	630 Hz	1,000 Hz	2,000 Hz	4,000 Hz
0 dB	57.8	53.2	50.2	48.9	46.6	43.8	36.2	30.2
-3 dB	54.2	50.4	47.5	46.6	44	40.7	33.7	26.8
-6 dB	51.8	47	44.6	43.3	40.5	37.5	30	24.2
-9 dB	48.1	44.1	41.3	39.8	37.9	34.9	27.4	21.1
-12 dB	45.8	41.3	39.1	36.8	35	32.1	24.4	18.3
-15 dB	42.2	38.2	35.7	33.6	32	29.4	21.4	15.1

Procedure

The height of the stool was adjusted such that the distance from the ground to the midpoint of the participant's head was always 1.5 m. Participants were told that they would be detecting signals in a noise mask. To familiarize participants with the task, the experimenter provided the participant with feedback regarding a sample of signal and no-signal trials that were presented with the noise mask. Participants were told that following each trial they would be prompted with the following question: Was a signal present in this trial? 1 = "Yes", 2 = "No". They were told to expect there would be an equal number of signal and no-signal trials. Responses were entered using the response terminal. Each of the 48 signals was presented 10 times resulting in 480 signal trials. In addition, an equal number of no-signal trials ("catch trials") were presented. The order of trials was independently randomized for each participant.

Results and Discussion

The false alarm rate (i.e., percentage of “yes” responses on no-signal trials) was low (*M* = .025, *SE* = 0.1) with no participant exceeding .01. Because of the low false-alarm rate, subsequent analyses only considered hit rates (i.e., percentage of “yes” responses on signal trials).

In Figure D.2, the mean hit rate collapsed across participants is plotted as a function of frequency and signal/noise ratio. Mean hit rates were subjected to a within-subject analysis of variance. The main effect of intensity was significant, F (5, 40) = 19.30, p < .0001.

As seen in Figure D.2, hit rates were best for higher signal/noise ratios. The main effect of frequency was significant, F (7, 56) = 5.89, p < .0001. As seen in Figure D.2, hit rates were best for mid-frequency signals with peak accuracy centred at 562 Hz. There was also a significant interaction between intensity and frequency, F (35, 280) = 2.51, p < .0001. This interaction was due to an advantage of mid-frequency signals for low signal/noise ratios only. Post-hoc tests revealed that variability in hit rates across frequency was not significant for signal/noise ratios -9 dB or higher.

Mid-frequency signals may have an advantage in low signal/noise ratios because of a compromise between two psychoacoustic factors. First, participants are most sensitive to high-frequency signals, particularly those that fall between 2,000 and 4,000 Hz (Fletcher & Munson, 1933). Second, masking studies have shown that high-frequency signals are particularly vulnerable to masking effects in the presence of broadband noise (Egan & Hake, 1950; Zwicker & Fastl, 1990). In this experiment, the powerful masking effect of low-frequency noise may have been further amplified by the spectrum of the noise mask, which was heavily weighted toward the lower frequencies. Thus, mid-frequency signals may have led to higher hit rates because they were more audible than lower frequency signals but less vulnerable to masking than higher frequency signals.

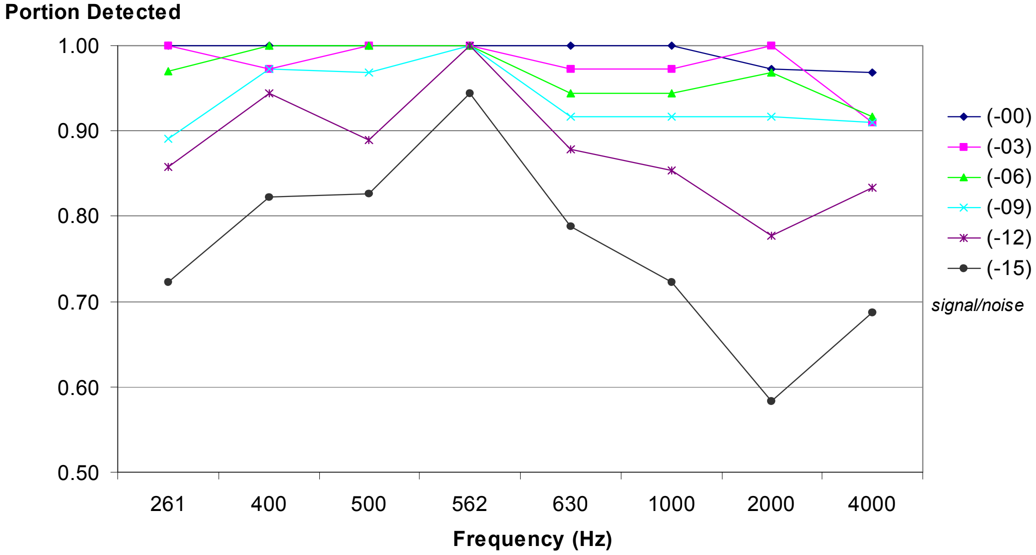

Figure D.2 **Mean hit rate plotted as a function of frequency and signal/noise ratio**

D.2 PERCEIVED URGENCY OF PURE-TONES IN CAR NOISE

Previous tests have shown that the perceived urgency of pure-tone signals will vary with respect to a signal's frequency and intensity (Hellier, et al., 1993). The purpose of the current experiment was to assess whether such variability in perceived urgency may be obtained in the presence of car noise.

Participants

Eleven participants were recruited from Queen's University and the Kingston (Ontario) area. These participants included eight females and three males ranging in age from 17 to 39 years with a mean age of 25.5 years. All participants reported normal hearing and were able to detect all test signals when presented in quiet. Participants received course credit or cash payment for their participation.

Apparatus

The testing environment and noise mask was identical to that described in Experiment 1 (see section D.1). The 12 test signals consisted of all combinations of 4 frequencies (500, 1000, 2000, 4000 Hz) and 3 intensity levels relative to threshold (0, 3, 6 dB). The criterion for threshold at a given frequency was a hit rate of .9 or better as determined in Experiment 1. For example, a review of Figure D.2 reveals that threshold for a 500 Hz signal was -9 dB.

Procedure

As in Experiment 1, the height of the stool was adjusted such that the distance from the ground to the midpoint of the participant's head was always 1.5 m. The task was free modulus magnitude estimation for urgency (adapted from Hellier, et al., 1995). Participants were told that they would be rating the urgency of signals presented in a noise mask and were asked to adhere to the following instructions:

> *You will be presented, in irregular order, a series of sounds. Your task is to respond to how urgent they are by moving the slider appropriately. When you have the heard the first sound, give its urgency a rating – any rating that you think appropriate. Once you have made your rating, you may initiate the next sound by clicking the NEXT button. Let positions to the far right of the slider represent the most urgent sounds and positions to the far left represent the least urgent sound. Try to make the ratios between the ratings that you assign to the different sounds correspond to the ratios between the urgency of the sounds. In other words, try to make the ratings proportional to the urgency of the sound as you perceive it.*

There were two trials for each signal. The order of trials was independently randomized for each participant.

Results and Discussion

All ratings were given an integer value between 1 and 100 relative to the final position of the slider on a given trial. The mean urgency rating for the 12 signals is reported in Figure D.3 as a function of frequency and intensity relative to threshold.

The urgency ratings were subjected to a within-subject analysis of variance. The main effect of frequency was significant, F (3, 30) = 7.55, p < .001. Higher ratings of urgency were associated with higher frequencies. The main effect of intensity relative to threshold was also significant, F (2, 20). Higher ratings of urgency were associated with higher intensities relative to threshold. The interaction between the two factors was not significant.

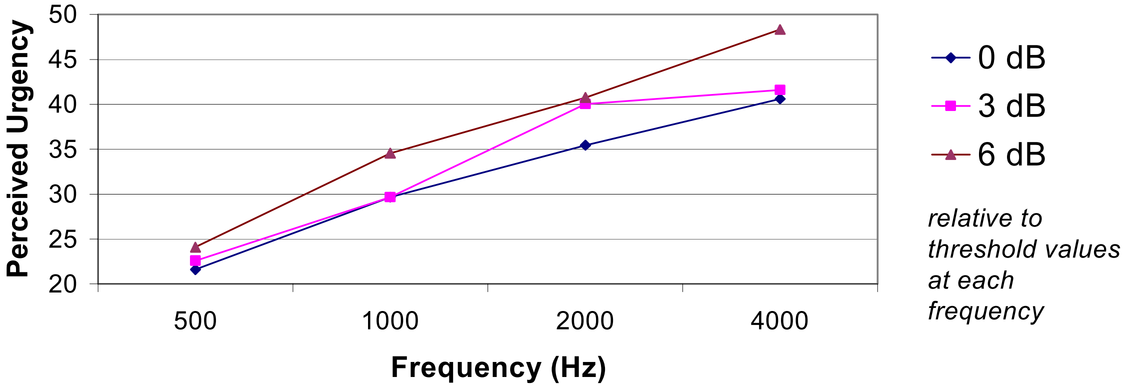

Figure D.3 Mean urgency as a function of frequency and intensity relative to threshold

D.3 PERCEIVED URGENCY OF MULTI-FLUTE HORNS

Based on the findings of Experiment 2 (D.2), we may conclude that changes to a horn's frequency and intensity should have influence over its perceived urgency. The objective of this experiment was to determine whether perceived urgency of locomotive horns varies as a function of acoustic and psychoacoustic factors other than frequency and intensity of component flutes.

Participants
Fourteen participants were recruited from Queen's University and the Kingston (Ontario) area. These participants included nine females and five males ranging in age from 17 to 45 years with a mean age of 24.5 years. All participants reported normal hearing. Participants received course credit or cash payment for their participation.

Apparatus
The testing environment was identical to that described in Experiment 1 (D.1). Seven railway horn single-flute recordings provided the raw ingredients. All flutes had comparable spectra but varied with respect to fundamental frequency: 311, 370, 415, 440, 470, 494, 622 Hz. The intensity of each flute was adjusted such that loudness from the vantage point of the participant was equalized (66 dBC). The loudness-adjusted flutes were mixed together to form 23 novel horn signals. The 23 novel horns represented all 3-, 4- and 5-flute combinations that were possible if the frequency bandwidth of horns was fixed. The bandwidth of horns was fixed by imposing a simple constraint: the lowest flute in any novel horn was always 311 Hz and the highest flute in any novel horn was always 622 Hz. Although novel horns were equalized with respect to loudness and bandwidth, they varied with respect to other important characteristics –

in particular, the number of flutes, spectral centroid (i.e., amplitude-weighted mean of the spectrum) and musical dissonance.

The musical dissonance of each novel horn was determined using three steps. First, the component intervals generated by the novel horn were specified. Second, a dissonance value for each component interval was calculated by collapsing across the corresponding values from four dissonance scales reported by Krumhansl (1990). Finally, the average of all dissonance values was used as the musical dissonance value for the novel horn. To corroborate the validity of the musical dissonance value, four musically trained listeners were asked to rate the musical dissonance in each novel horn. The average value of their ratings was well correlated with the computed musical dissonance values, r (21) = .82, p < .0001.

Procedure

The procedure was identical to that described in Experiment 2 (D.2).

Results and Discussion

All ratings were given an integer value between 1 and 100 relative to the final position of the slider on a given trial. In Table D.2, acoustic and psychoacoustic parameters of each novel horn are reported along with mean urgency ratings.

Mean urgency ratings ranged from a minimum of 37.40 (SE = 6.12) to 72.02 (SE = 4.68). The relative influence of number of horns, spectral centroid and musical dissonance on perceived urgency was evaluated by subjecting mean urgency ratings to a multiple regression analysis. The resulting model accounted for 63 percent of the variance, F (3, 19) = 10.57, p < .00026. This model suggests that perceive urgency in locomotive horns may be increased without change to loudness (dBC) or spectral bandwidth by adding flutes (BETA = .39), increasing the spectral centroid (BETA = .60) and/or increasing musical dissonance (BETA = .37).

To ensure that the results of this experiment were not due to properties of the test chamber or localization of sound, the experiment was replicated using headphones. All flutes were equalized for loudness over headphones (at 66 dBC) and remixed to create 23 novel horns. The model described above (number of horns, spectral centroid and dissonance) was again highly significant, accounting for 76 percent of the variance, F (3, 19) = 20.51, p < .0001 with all beta weights significant (p < .05). The results of this experiment suggest that perceive urgency in locomotive horns may be increased without change to intensity (dBC) or spectral bandwidth by increasing the spectral centroid and possibly by adding flutes and /or increasing musical dissonance. The individual contribution of number of flutes and musical dissonance for perceived urgency of locomotive horns requires an additional experiment in which these two variables are independently manipulated. However, it is reasonable to conclude that correlated increases in the number of flutes and musical dissonance of locomotive horns increases perceived urgency.

Table D.2 Acoustic and psychoacoustic parameters of each horn, and mean urgency rating

Novel Horn	Flutes	Spectral Centroid	Musical Dissonance Value	Urgency Rating	
				Loudspeaker	Headphone
1	3	4,650	-0.64	37.40	27.55
2	3	4,694	-1.07	38.86	29.1
3	3	4,657	-0.35	46.63	35.69
4	3	4,619	-1.07	47.15	35.35
5	3	4,716	-0.61	66.42	49.25
6	4	4,697	-0.48	47.93	45.75
7	4	4,658	-0.25	51.89	45.61
8	4	4,626	-0.68	48.83	35.22
9	4	4,710	-0.5	62.57	51.24
10	4	4,683	-0.14	50.80	51.42
11	4	4,664	-0.7	54.01	39.28
12	4	4,737	-0.59	68.85	50.82
13	4	4,623	-0.14	50.85	53.96
14	4	4,705	-0.11	68.47	66.06
15	4	4,695	-0.27	65.25	53.97
16	5	4,466	-0.05	41.06	48.42
17	5	4,663	-0.43	48.73	43.78
18	5	4,718	-0.39	64.99	57.46
19	5	4,654	0.02	55.28	61.21
20	5	4,709	-0.04	72.02	60.8
21	5	4,671	0.15	65.20	67.78
22	5	4,629	-0.17	54.58	51.85
23	5	4,688	-0.32	68.34	60.86

D.4 LOCOMOTIVE HORN IDENTIFICATION

The objective of this experiment was to empirically document the rate of identifying different horns as locomotive horns when they are presented in a car noise mask.

Participants

Seventeen participants were recruited from Queen’s University and the Kingston (Ontario) area. These participants included 11 females and 6 males ranging in age from 17 to 45 years with a mean age of 25.7 years. All participants reported normal hearing. Participants received course credit or cash payment for their participation.

Apparatus

The testing environment was identical to that described in Experiment 1 (D.1). Signals included three warning sounds that were not horns (police siren, ambulance siren, and crossing bell), two field recordings of non-locomotive horns (Truck Horn, Car Horn), two field recordings of locomotive horns (VIA Rail Horn, GO Transit Horn), and three synthesized locomotive horns from Experiment 3 (Novel Horn 3, Novel Horn 6 and Novel Horn 21). The synthesized locomotive horns represented minimum, intermediate, and maximum urgency, respectively. All signals were presented in the presence of the noise mask described in Experiment 1.

Procedure

Each signal was presented once only in a free-identification task. Participants were told that they would be responsible for identifying warning signals while immersed in a sonic environment similar to what they might experience while driving a car. There were no other clues given to indicate that any of the sounds had anything to do with grade crossings or locomotive horns. All responses were recorded using pen and paper.

Results and Discussion

Figure D.4 is a plot of the identification rate of each horn as a locomotive horn, non-locomotive horn, or something else. The field recordings of locomotive horns were identified as locomotive horns more frequently than were the novel horns, however the rate was well below 100% (65% GO Transit and 59% VIA Rail). The novel horns were identified as locomotive horns more frequently than were the non-locomotive horns. It is important to note that identification rates of the three novel locomotive horns were quite comparable (i.e., 24% to 35%). This finding suggests that for the range of horn parameters manipulated in this study, a compromise does not exist between urgency and identifiably. The higher rates of identification for real locomotive horns are likely due to in part to the availability of non-source cues (e.g., environmental filtering and Doppler shift).

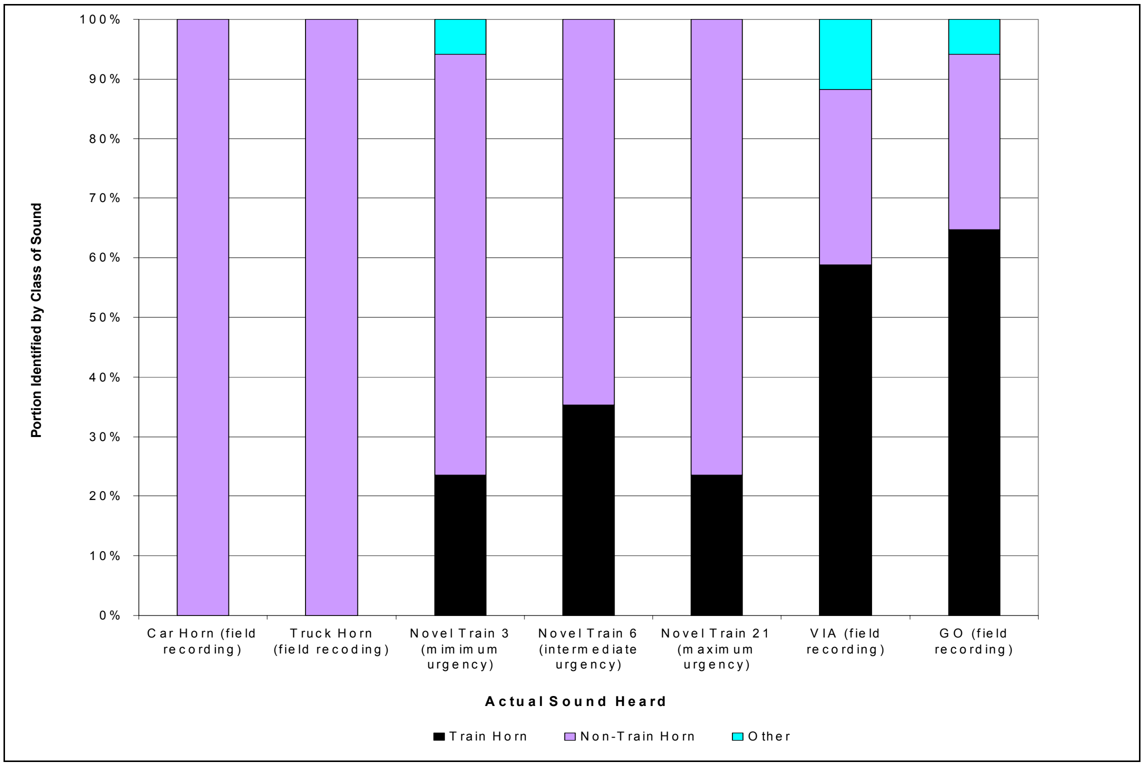

Figure D.4 Identification of locomotive horn sounds

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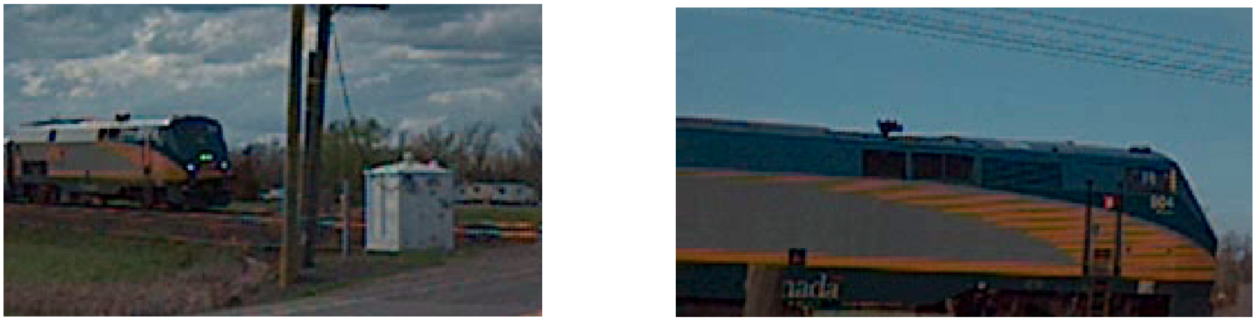
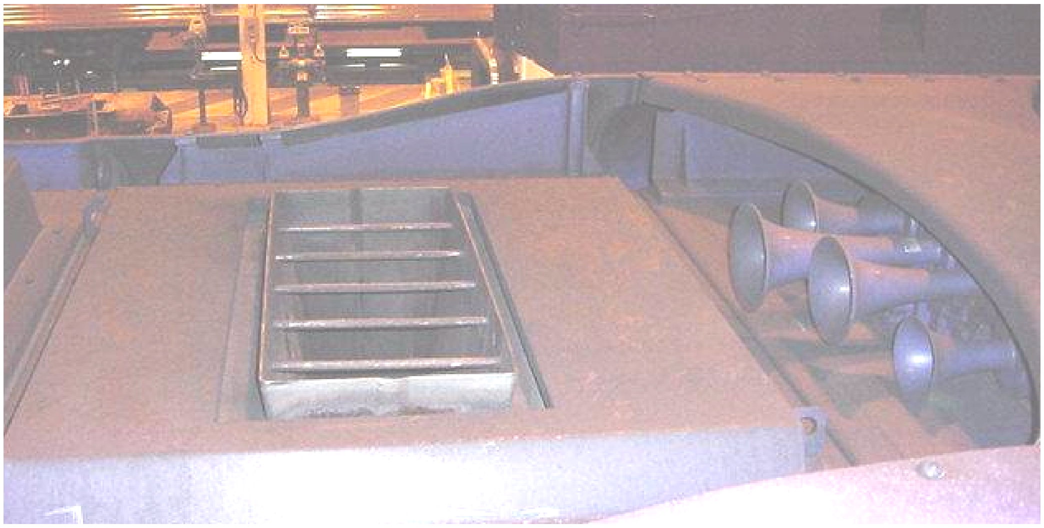
APPENDIX E

Revenue Service Test Locomotives and Selected Measurements

E.1 Locomotive pictures illustrating horn positions



Genesis locomotive raised horn position



West Coast Express F59 normal horn position

SD-40

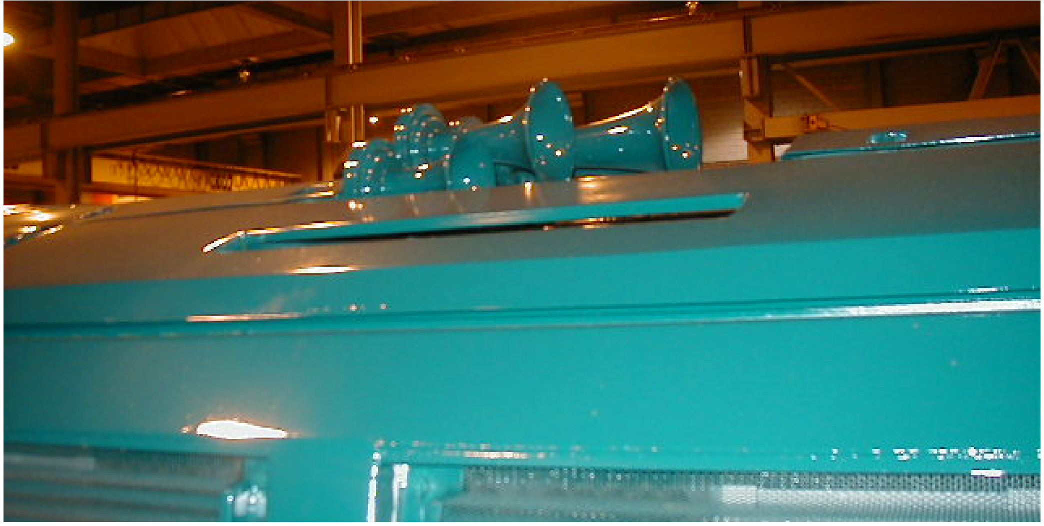
Dash-9

GP-9

Photo credits this page: Shane Stewart, stewart.railfan.net

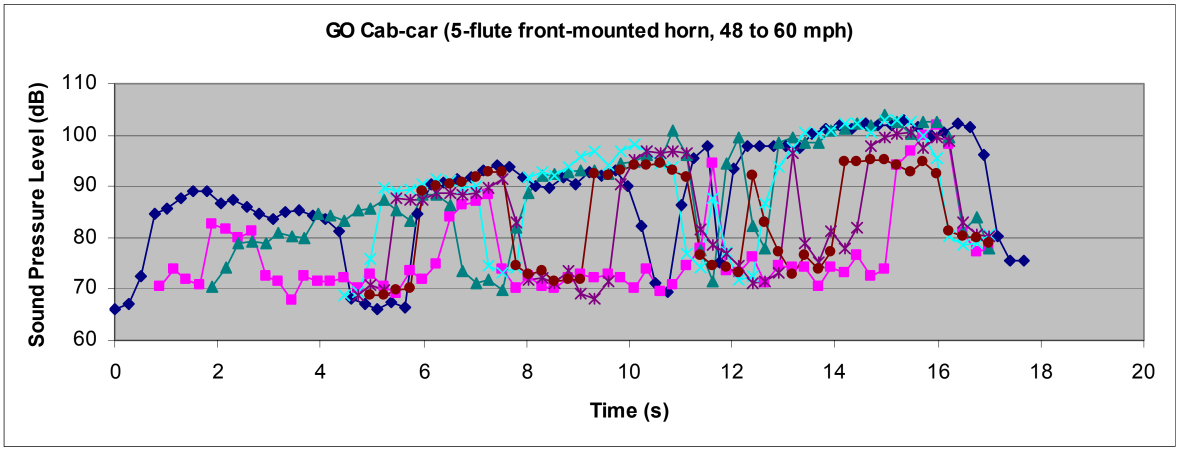
F40 (Photo credit: Shane Stewart, stewart.railfan.net)

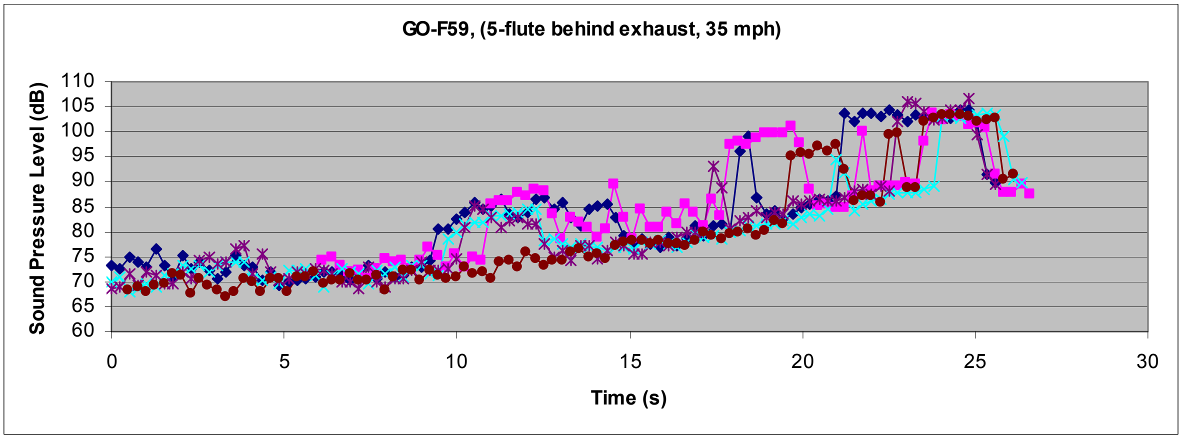
LRC (Photo credit: Shane Stewart, stewart.railfan.net)

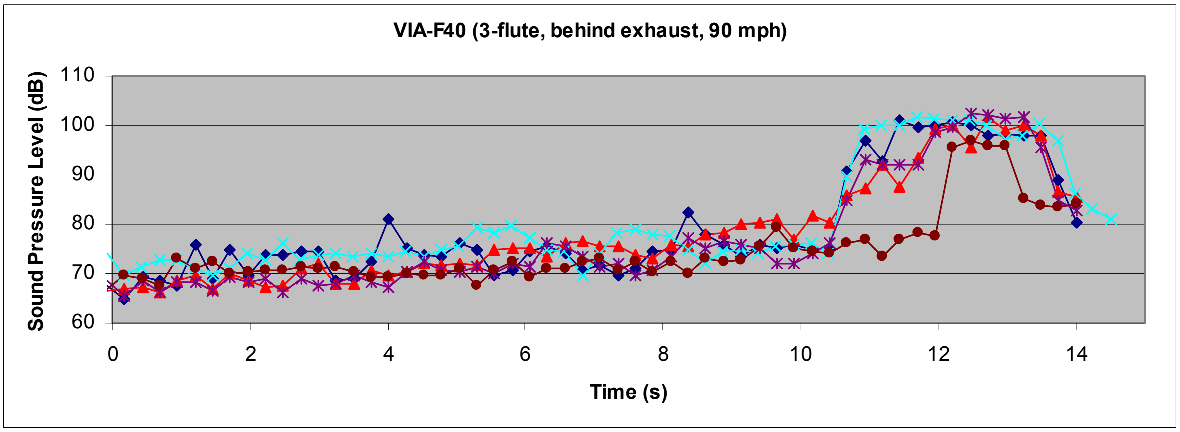


Genesis locomotive normal horn position

E.2 Sound Measurements at South Blair Crossing for 400 m Train Approach







APPENDIX F

Hypothetical Pattern Control Horn

We look at the community impacts of introducing a hypothetical pattern control 3-flute horn. Figure F.1 illustrates the effectiveness of one particular design in reducing sound level over the frequency range 400 to 10,000 Hz. The vertical axis is the degrees rotation relative to straight ahead (down the track in our case). The plots show the threshold rotation angle at which the sound output is decreased by 6 dB. Plots are presented for both the horizontal (community impact) plane and the vertical (cab impact) plane.

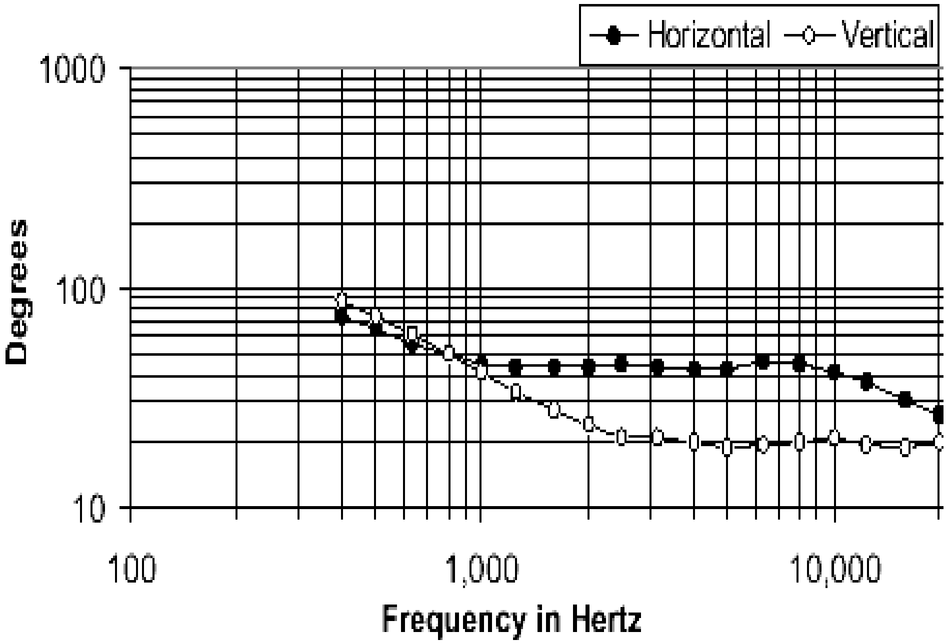


Figure F.1 Beamwidth (-6dB contour) of a pattern control horn
Source: Community Professional Loudspeakers, Brochure # HD242-991020.

We assessed the impact of a hypothetical pattern control railway horn by assuming that the characteristics of the illustrated device can be achieved in a railway application. The affect of the frequency dependent performance on the 3-flute horn's characteristic spectrum is illustrated in Figure F.2. The impact is calculated at 90 degrees and at 91 m (assuming a 7 dB/distance doubling). The spectrum shifts from one that has a broad peak between 500 and 1250 Hz to one that peaks at 400 Hz. In addition to shifting to a more 'pleasant' frequency, the overall sound level is reduced from 95 to 84 dBA.

The influence on A-weighted noise level reduction is further illustrated in Figure F.3. One can see that a 75 dBA annoyance threshold is reduced from a distance of about 580 m lateral to the track to about 210 m. Since the trains are moving and travelling in both directions, the wayside impact will vary by location. A residence lateral to the whistle post for one direction will see a significant reduction for horns blown at that whistle post but will see no reduction from horns blown by trains travelling in the opposite direction.

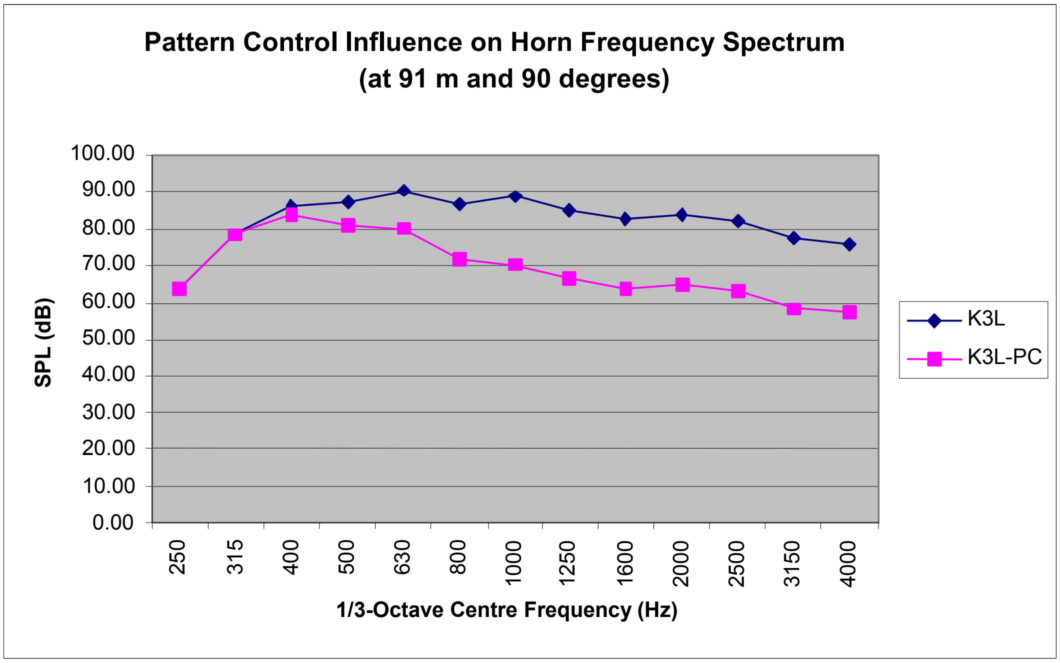


Figure F.2 **Pattern control impact on horn spectrum at 90 degrees**

We assessed the impact along the track at a fixed lateral distance of 600 m and assuming equal trains in each direction. We calculated the sound exposure level (SEL) on the basis of a 60 mph train blowing the rule 14 (L)(ii) pattern (long, long, short, long) such that 11 s of application existed in the 15 s approach interval. The results are illustrated in Figure F.4.

Because we assume equal traffic by direction, the impact on the other side of the crossing will be the mirror image of the one shown. One can see that while the noise exposure is lower in all locations the most effective location is that nearest the crossing. One must remember in looking at the SEL magnitudes that the measure involves integration of the SPL over the time period rather than an average SPL. Thus, the SEL magnitudes are higher than the peak sound level attained during the horn sequence. Also, slower trains with longer whistle exposure times would produce higher SEL values. Similarly, faster trains with shorter whistle exposure times would produce lower SEL values.

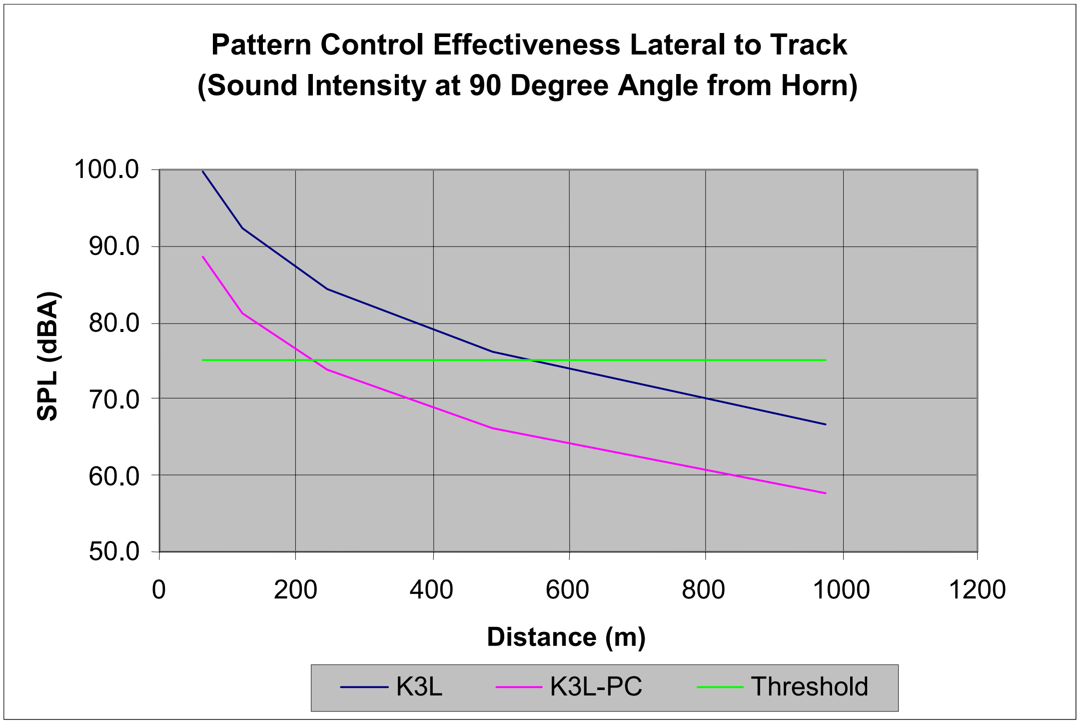


Figure F.3 Noise impact at increasing lateral distance from the track

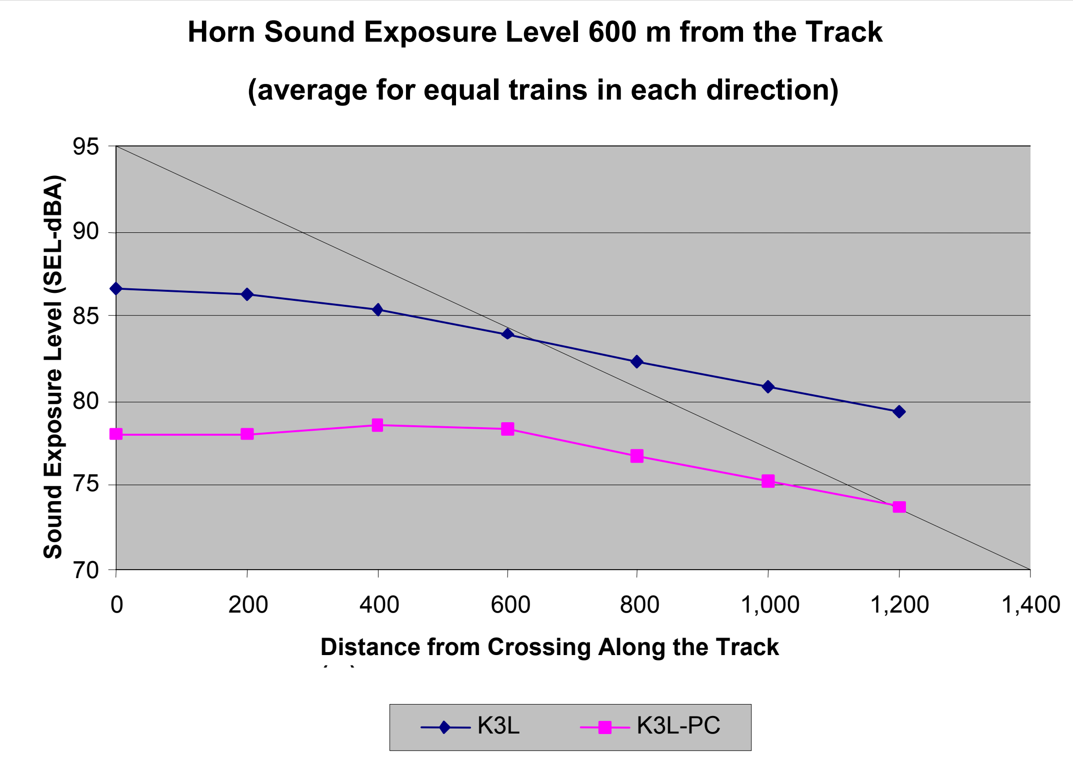


Figure F.4 Sound exposure level noise impact comparison

The final community impact measure we assessed was the day-night weighted exposure (Ldn). In calculating Ldn we adopted some aspects of the procedure used by the FRA (*horn model* spreadsheet from the FRA website (www.fra.dot.gov)) in its environmental assessment of the proposed elimination of whistle bans. The FRA assumes that the train noise (excluding horn) is part of the ambient noise environment and is incremental to the baseline Leq. Its analysis of past noise measurements produced train noise at the crossing that has a Leq about 10 dB below the horn Leq.

We used this number to increment the baseline Ldn with increasing train frequency and assessed the impact at a location 300 m and at a 90 degree angle to the track at the crossing. We assumed equal trains in each direction and equal trains in the 'night' and 'day' periods all travelling at 60 mph producing the same horn SEL as previously discussed. Figure F.5 illustrates the resulting effect of a pattern control horn on community noise at increasing train frequency. One can see that the hypothetical pattern control horn changes the train frequency at which a *severe* impact threshold is exceeded from 10 trains per day to 45 trains per day.

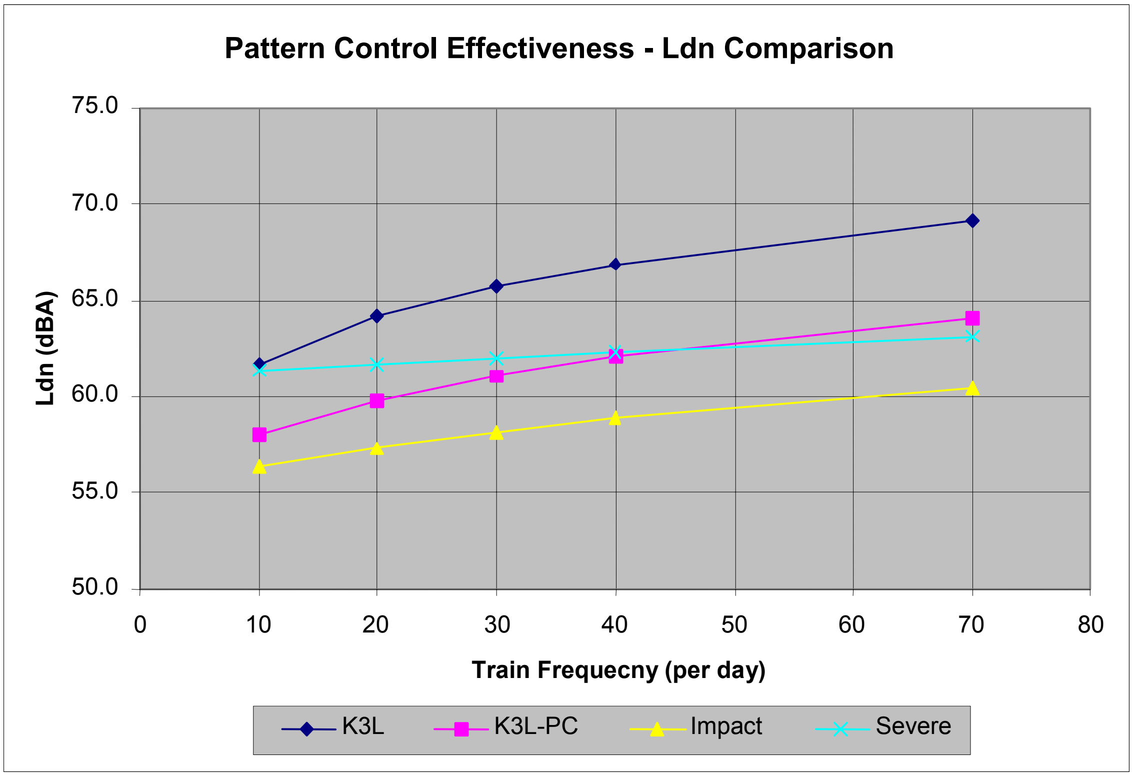


Figure F.5 **Ldn Noise impact at increasing train frequency**