# A Review of Four Studies of FM Receiver Adjacent-Channel Immunity

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## Executive Summary

We were asked by the National Association of Broadcasters (NAB) to review four studies of the susceptibility of consumer FM receivers to adjacent-channel interference. These studies were sponsored or performed by the Office of Engineering and Technology (OET) of the Federal Communications Commission (FCC), the NAB, the National Lawyers Guild (NLG), and National Public Radio together with the Corporation for Public Broadcasting (CPB) and the Consumer Electronics Manufacturing Association (NPR et al.).

Each of these four studies examined the same technical question, but the studies are being used to support contradictory conclusions. Even so, there are great areas of agreement among the studies. The methods used to test receivers are quite similar. Every study reported that car radios out perform other FM broadcast receivers. When we reformatted the data from each study into a consistent format, we found the four sets of measured data to be quite consistent.

The significant differences among the studies were not in the measurements or in the performance of the radio receivers tested. Rather, the most important difference among the studies was the criterion used to decide whether the effects of an interfering signal on an adjacent channel caused harm to the desired signal. The difference among these studies lies in the definition of impaired reception. The NLG defined impaired reception to mean badly broken reception. The NAB used the same definition of impaired reception as had the FCC when it developed the FM service—that a broadcast service suffers from interference when it is degraded to the level many observers would characterize as slightly annoying. NPR et al. used a definition similar to that used by the NAB. The OET used a distortion measure that, while not as flawed as

that used by NLG, could bias the testing and required that an audio signal be substantially degraded to be counted as impaired.

Table 8 of our report is reproduced below. It compares the four reports and confirms that the differences among the studies arise from the definition of impairment and not the measurement process or the characteristics of the radios tested. Specifically, it shows that if the measurements of each study are interpreted consistently using the 50-dB criterion of harmful interference, each study predicts that the vast majority of receivers will fail when receiving interference at the interference level implied by the FCC's ratios.

**TABLE 8—Percentage of Receivers Not Meeting FCC Ratios in the Four Reports and Using 50-dB Output SNR Criterion**

| Report | Criterion in SNR terms | Tested radios failing under authors' criterion | Tested radios failing under 50-dB SNR criterion |
|---|---|---|---|
| NPR et al. | 45 dB | 81% (13/16) | 100% (16/16) |
| NLG | 20–30 dB | 27% (3/11) | 73% (16/22) |
| OET | 25–30 dB | 10% (2/21) | 79% (16.5/21) |
| NAB | 50-dB or 5-dB degradation if receiver cannot reach 50 dB | 79% (22/28) | 79% (22/28) |

*Note:* SNR = signal-to-noise ratio.

The results of these tests are no surprise. In radio engineering, as in most other engineering activities, there is always a tradeoff between cost and performance. It makes little economic sense to build radios that are capable of rejecting more adjacent-channel interference than those radios will actually experience in use. Consequently, we would expect to see radios engineered to perform reasonably well in the radio environment created under the FCC's rules. The FCC's rules set the adjacent-channel-interference environment, and radios are built to perform well in that environment. But, there is little or no point to building in better adjacent-channel protection than is needed.

All four studies made the mistake of reporting the results of tests of car radios along with other radios. Every report showed that car radios outperform other radios with respect to adjacent-channel interference rejection. In fact, car radios need this capability if they are to provide reasonable performance. At the very least, car radios should have been tested and reported separately. Including car radio performance in these studies provides misleading signals about the overall performance of receiving systems.

To sum up, decision makers should understand the tradeoff between added adjacent-channel interference and reduced performance of broadcast receivers. Listen to music at signal-to-noise ratios of 70, 60, 50, 40, and 30 dB. Consider the literature on subjective testing of audio systems, and consider consumer preferences. Finally, decide what quality of FM broadcast service the FCC's rules should protect.

## About the Authors

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# 1 Introduction and Overview

We were asked by the National Association of Broadcasters (NAB) to review four studies of the susceptibility of consumer FM receivers to adjacent-channel interference. Three of these studies were filed by parties in the comment round of pleadings in MM Docket 99-25. These three parties were the NAB, the National Lawyers Guild (NLG), and National Public Radio (NPR) together with the Corporation for Public Broadcasting (CPB) and the Consumer Electronics Manufacturing Association, collectively referred to as NPR et al. Two staff members in the Office of Engineering and Technology prepared the fourth study.[1]

Each of these four studies examined the same technical question, but the studies are being used to support contradictory conclusions. For example, CPB wrote, "The tests show that, in many situations, adding a new LPFM station by eliminating the 2nd and 3rd adjacent channel protections would significantly impair both the existing and the new stations."[2] In contrast, NLG wrote, "These results strongly indicate that, at least for Low Power FM stations of 100 watts ERP or less, regulation of second and third adjacencies should also be eliminated."[3] Obviously, CPB and NLG cannot both be right. Either some of the tests are flawed or someone is arguing improperly from the data.

The NAB requested that we review and compare these studies. They asked us—as experts who had not been previously involved with this proceeding and who had no involvement with the design or execution of these four studies—to perform a cross between a *Consumer Reports*

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1 *TRB 99-3 Interim Report*, July 19, 1999.
2 Comments of CPB, MM Docket 99-25, p. 16.
3 Comments of NLG, MM Docket 99-25, p. 19.

product evaluation and a book review. Based upon this general request from the NAB, we formulated our own specific directives:

- Examine and compare the studies, identifying the strengths and weaknesses of each;
- Comment on appropriate criteria for defining unacceptable interference and methods of interference measurement;
- Identify conclusions supported by all the studies;
- Identify conflicts among the conclusions of the various studies; and
- Offer our explanation for any conflicts identified in the step above and provide our opinion as to the likely correct conclusions.

This report presents the results from our undertaking the above five tasks. We begin by discussing briefly the role engineering can play in helping the Commission understand the implications of the decisions it will make in this docket. Next, we discuss how one measures the effects of interference. After that, we look at each of the four studies. Finally, we offer our conclusions.

# 2 Engineering Insights for Policymakers

Many important policy issues today depend upon scientific and technological factors that require specialized knowledge and training to fully understand or evaluate. This section considers briefly this general dilemma and then focuses on the specific concerns created by the four studies of adjacent-channel interference.

## 2.1 General Considerations

Science and engineering must contribute to the policy process when the policy in question involves a technical subject like radio broadcasting. Their most profound contribution is the creation of new ways of doing things or new alternatives. There would be no concern about funding childhood immunizations if immunization technology did not exist. Science and engineering can also illuminate the choices before policy makers. Congress, the FCC, the Environmental Protection Agency (EPA), judges, and state legislators face the problem of choosing policies the outcomes of which depend upon technical facts that the policy makers cannot be expected to master. Often, as in this case, policy makers face the problem of making policy choices based upon engineering or scientific studies they cannot replicate, verify, or sometimes, even fully understand. What should policy makers do when faced with incomprehensible, conflicting, ambiguous, or weak technical advice?

## 2.2 Engineering and the Decisions in MM Docket 99-25

In the case at hand, technologists can provide data and analysis that allow the policy makers to understand the tradeoffs, if any, in choosing among the alternative courses of action in this docket. Good engineering studies should assist informed choice in the political process. The fundamental issues are not so difficult or esoteric that a nontechnologist cannot master them with modest effort.

In the Notice of Proposed Rulemaking (NPRM) in this docket, the FCC articulated the specific question at hand. The Commission stated, "We seek comment and analysis on our tentative conclusion not to include 3rd-adjacent channel protection requirements for any LPFM service"[4] and "We also seek comment on the state of receiver technology and the ability of receivers to operate satisfactorily in the absence of 2nd-adjacent channel protection."[5] The theory needed to understand and explain the performance of receivers under adjacent-channel interference is well understood. Measurement of the performance of receivers suffering from adjacent-channel interference requires care and is a moderately exacting technical process. In fact, the studies we reviewed used similar test methods and test equipment. The studies differed in the way they measured and reported the impairments caused by interference and in the type and number of receivers tested. Before we review these studies, some background on measuring audio impairments would be helpful.

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4 NPRM, para. 45.
5 NPRM, para. 46.

## 3 Measuring Audio Impairments

Before reviewing the individual studies, we believe a quick review of the key technology—the measurement and characterization of the quality of audio system performance—is in order. This is hardly a new field. Investigators in the nineteenth century such as Rayleigh and Helmholtz conducted significant research on this topic.[6] Throughout this century, other investigators have extended their understanding. For example, in the 1930s scientists at Bell Labs tested the human response to sounds at various intensities and levels—leading to the Fletcher/Munson curves familiar to most audiophiles.[7] There is now an extensive literature on effects of noise and distortion on human perception of speech and music. Proper measurement of these effects is important in both the telephone industry and in broadcasting, as well as in sound recording and now the computer industry. We can draw on over a century of research and experience. Colleges teach courses in the subject (e.g., MIT's Subject 6.182 Psychoacoustics Project Laboratory, USC's EE 522 Immersive Audio Signal Processing). There exists a broad library of standards in this area—including many ITU-R standards. Recent years have seen an expansion of work in this area due to the need to perfect and verify the performance of audio compression techniques.[8] In this proceeding, it is radio interference we are looking at that *results* in audio imperfections.[9]

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6 Amazon.com ranks Helmholtz's book, *On the Sensations of Tone,* as number 35,154 in their sales rankings of more than 1.5 million titles. Not bad for a science book first published in 1863.

**7** Fletcher, H., & Munson, W. A. (1933). "Loudness, its definition, measurement, and calculation," *Journal of the Acoustical Society of America*, 5, 82-108.

8 Speech compression is essential to modern digital wireless devices such as digital cellular phones. The more general audio compression is used in digital broadcasting (terrestrial digital

Examination of the literature and standards leads to a few conclusions. First, *subjective testing*—the use of a panel of listeners to compare and grade the performance of alternative systems—is the gold standard of audio system evaluation.[10] Second, although they may be the gold standard, subjective listening tests are, like gold, very expensive—requiring significant time and staff. Consequently, other objective test methods have been developed. These objective measurements may or may not be monotonically related to subjective quality, but they are close enough for many applications. A primary measurement used to assess the performance of analog broadcasting and recording systems is the audio or output *signal-to-noise* ratio (SNR). This ratio compares the energy in the desired signal with the energy in the obscuring or impairing noise signal. Often the SNR is calculated using a weighting procedure that attaches more weight to noise at the most easily heard frequencies and less weight to noise at frequencies that are less irritating. Informally speaking, SNR is a measure of the static that has been added to a signal.

Table 1 below shows SNR for some familiar audio systems. In this table, a higher number is better and SNR is reported in dB—a logarithmic measure that matches well with the human hearing process. A difference of about 3 dB in SNR is usually regarded as the smallest size

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television, digital audio broadcasting, DirecTV's service) as well as in consumer products such as MP3 players.

9 The Audio Engineering Society maintains a web site at http://www.aes.org/ that contains many pointers to the literature on audio system measurement. Other useful web sites are those of the Acoustical Society of America, http://asa.aip.org, and the European Broadcasting Union, http://www.ebu.ch/.

10 It may seem strange to some that engineers rank a subjective test as the highest performance standard. Despite stereotypes, engineers actually have normal endowments of common sense and they recognize that the proper measure of a system designed to serve consumers is the consumer reaction to that system.

difference a typical observer will notice. Thus, there is not much difference in the typical subjective evaluation of the performance of two audio systems—one operating with 40-dB SNR and the other with 43-dB SNR. However, there is a big difference between a system operating with 40-dB SNR and one operating with 60-dB SNR.

**TABLE 1—Signal-to-Noise Ratio for some Familiar Audio Systems**

| System | Approximate SNR |
|---|---|
| Compact disc | 100 dB |
| Sony Walkman digital audio tape | Better than 87 dB |
| FM broadcasting (best conditions) | 60–80 dB |
| Consumer audio taping equipment[11] | 60 dB |
| Telephone call | 30-50 dB |

A second measure of audio system performance is *harmonic distortion*. Harmonic distortion is most often used to measure the performance of audio devices such as amplifiers or recording systems. It is a measure of how accurately an audio system reproduces the input signal. Harmonic distortion is often used to characterize the performance of amplifiers. It is caused by nonlinearity in the amplification chain that creates frequency components that are harmonics of the original frequencies (integer multiples of the original frequencies, also called overtones). If the output signal from an amplifier is the same as the input signal, except bigger, then there is no distortion. With music or pure tones, distortion can be noticed by the presence of overtones. For example, if a real-world amplifier has as input a 1,000-Hz tone, the output will consist primarily of a 1,000-Hz tone, but tones at 2,000 and 3,000 Hz (and other frequencies) will also be present

11 For example, the Sony TC-KE500S.

in the amplifier output. These unintended overtones produced by the amplifier are called harmonic distortion. It is hard for the human ear to hear harmonic distortion. The human ear's response to a 2,000-Hz tone is reduced when a strong signal is also present at 1,000 Hz. Similarly, people often think they hear a sound at 2,000 Hz when they only hear a sound at 1,000 Hz.[12] Most music sources, such as a piano or violin note, contain overtones that are only slightly modified by the overtones created by distortion.

Hence, given both the reaction of the human hearing system and the content of most music, harmonic distortion is harder to hear than unrelated noise.[13] It is generally accepted that harmonic distortion has to rise to about 1 to 2% before people find it objectionable.[14] Some people would find 1% harmonic distortion hard to notice.[15] The nonlinearities in the signal processing chain that cause harmonic distortion also cause intermodulation distortion that produces other, unintended frequency components. The usual test procedures for audio

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12 See, for example, A. Gersho, "Advances in speech and audio compression," *Proceedings of The IEEE*, vol. 82, pp. 900-918, June 1994. P. Noll, "Wideband speech and audio coding," *IEEE Communication Magazine*, vol. 26, pp. 34-44, November 1993. J. J. N. Jayant and Y. Shoham, "Coding of wideband speech," *Speech Communication*, vol. 11, pp. 127-138, 1992.

13 It is easier to hear someone cough at an orchestra concert than to tell that one of the violinists is playing an octave high. Indeed, everybody in the audience can hear the person coughing, but only audience members with unusual musical acuity will notice that one violin is an octave high.

14 See H.F. Olson, *Elements of Acoustical Engineering*, Van Nostrand, New York, 1947 as quoted in Electronics Engineers' Handbook, 2nd Edition, Donald G. Fink and Donald Christiansen, eds., McGraw-Hill, 1982, at pp. 19-18.

15 While engineers are good, they are not perfect. Engineers often use different units to measure SNR and harmonic distortion. Although SNR is normally measured as a power ratio and expressed in dB, harmonic distortion is often measured as a voltage ratio and expressed in percent. This notational difference makes it harder for the nonexpert to keep track of what is going on in the four studies we consider. This confusion adds an unintended shell-game element to reading the engineering studies in this docket.

equipment use the measure of total harmonic distortion plus noise (THD+N) as shorthand for all nonlinear impairments.

Although it may be possible, albeit rare, for interference to drive the signal into the nonlinear region and cause harmonic distortion, that is not usually the principal concern when considering the effects of interference. Interference is best treated as a different, extraneous source of additive noise. Thus, we measure its effects by considering the signal-to-noise plus interference ratio (SNIR). The *noise* we refer to here is due to thermal, environmental, or receiver noise that we cannot overcome and is not the interference from like signals residing in a co- or adjacent channel. The interference of concern here is external and produced by other emissions in the radio spectrum by other than the desired transmitter. It is what can be controlled by regulation. It is therefore our considered opinion that the deleterious effects caused by this interference must be measured. Other undesirable effects, inherent in the imperfections in the signal chain may also be present, but they are a red herring when the objective is to determine whether controllable external additional emissions such as second and third adjacent channel interference should be permitted to degrade expected reception quality.

SNR and SNIR and harmonic distortion can be easily and quickly measured by modern test equipment. One could measure all of these quantities on 10 audio systems in much less time and at much lower cost than it would take to conduct subjective listening tests of those same audio systems. In some of its rules, the FCC uses audio SNR as a criterion of system performance and requires equipment to meet minimum SNR levels.[16]

16 See, for example, 47 CFR 80.961(b).

## 4 The Proper Standard for Measuring Interference Effects

We believe that the audio output SNIR (often called SNR and measured in the same fashion) is the appropriate measure in this context.[17] We note that it is often used for such comparisons. The ITU-R, and before it the CCIR, recommended that measurement of the degradation of SNR by the interfering signal be used in this situation. Three of the four studies we review (NAB, NLG, and NPR et al.) measured and reported the effects of interference on SNR. The measuring process for determining harmonic distortion does not measure all the extraneous energy delivered in the output signal; rather there is a hole of no measurement around the test tone. In most circumstances, this hole would not be disabling, but it may alter some measurements. Distortion, specifically harmonic distortion, is normally used to measure the accuracy of the reproduction of a signal rather than the presence of extraneous signals.

The FCC and the broadcast industry have long used SNR as a measure of system performance. For example, in 1979, the FCC authorized the CPB/NPR satellite interconnection system. In the order, the FCC stated, "NPR states that the satellite interconnection system has been designed to provide a minimum end-to-end channel performance that satisfies all requirements for radio broadcasting transmissions set forth in the Commission's Rules and Regulations. Specifically, the public radio satellite interconnection is designed to provide a subjective signal-to-noise ratio greater than 65 dB."[18]

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[17] For the rest of this report we use SNR to refer to SNIR in order to make our notation consistent with that used by NAB, NLG, and NPR et al.

[18] 70 FCC 2d 1858 (footnote omitted).

The comments in this proceeding by the AFCCE and the NAB contain histories of the development of the FCC's FM technical standards. Those histories show quite convincingly that the FCC designed the FM broadcast service to permit broadcasters to deliver signals good enough to permit reasonably priced receivers to provide a 50-dB SNR output signal. We note that in 1949 the FCC's NPRM in Docket No. 9407 stated, "The laboratory tests were based upon a 50 decibel rejection of the undesired signal. . . ."[19]

We also note that receiver manufacturers measure and report SNR and harmonic distortion separately. Figure 1 below is an excerpt from the data sheet for the Denon DRA-375RD receiver. Notice that this data sheet reports both an SNR (82 dB mono, 78 dB stereo) representing the output SNR ratio under ideal conditions and the level of total harmonic distortion (0.1% mono, 0.15% stereo). If the energy measured in the 0.1% harmonic number were noise instead of distortion, then the SNR would be only 60 dB. It is well known that 0.1% harmonic distortion is imperceptible to most observers but that almost all observers can tell the difference between 82-dB SNR and 60-dB SNR. Denon, like other hi-fi manufacturers, reports these measurements separately because they measure separate aspects of the performance of receiving systems. If the energy created by harmonic distortion were measured as noise, then there would be no reported difference in the performance of 80-dB and 60-dB SNR FM receivers with 0.1% harmonic distortion.

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19 14 FR 4986. (F.R. Doc. 49-6556. Filed, Aug. 11, 1949, 8:48 a.m.)

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|---|---|
| FM Section | |
| Tuning frequency range | 87.5 - 108 MHz |
| Usable sensitivity | 0.9 µV (10.3 dBf) |
| S/N 50 dB sensitivity (µV at 75 ohms) | Mono : 1.6 µV (15.3 dBf)<br>Stereo : 23 µV (38.5 dBf) |
| Signal-to-noise ratio (A-weighting) | Mono : 82 dB, Stereo : 78 dB |
| Total harmonic distortion | Mono : 0.1%, Stereo: 0.15% |
| Capture ratio | 1.5 dB |
| AM suppression | 50 dB |
| Image rejection | 42 dB |
| Effective selectivity | 55 dB (± 400 kHz) |
| Frequency response | 30 Hz - 15 kHz, -0.2, -1.5 dB |
| Stereo separation | 40 dB (1 kHz) |

**Figure 1. Denon data sheet excerpt.**

There is still a question of what changes in SNR constitute unacceptable interference. We return to this point in more detail later. Note that the ITU-R in Recommendation 641 defines the interfering level to be that level of interference that degrades receiver performance to the 50-dB SNR level. This ITU-R level is not overly demanding—for example, it is much lower than audiophile standards or CD quality. It is a big step below the performance capabilities of the Denon receiver shown above.

## 5 Examination of the Four Studies

In this section, we consider each of the four studies. All four studies addressed the FCC's two questions regarding their tentative conclusion not to include 3rd-adjacent-channel protection requirements for any low-power FM service and on the state of receiver technology and the ability of receivers to operate satisfactorily in the absence of 2nd-adjacent-channel protection. All four studies used the same essential approach—the engineers obtained several consumer FM broadcast receivers and tested the performance of those receivers in the presence of interfering signals. None of the studies examined the economics of receiver manufacturing or the various tradeoffs (cost, receiver size, etc.) associated with improving the resistance of consumer receivers to interference from signals on the 2nd- and 3rd-adjacent channels. None of the studies explained why automobile receivers should be expected to outperform the FCC ratios.

Beyond this essential similarity, the four studies vary greatly—many of the differences appear to be consequences of limitations on the time and resources available for the studies rather than of positions of the sponsors of the studies. However, some of the differences do appear to reflect the position of the sponsoring party. Specifically, the NLG and OET studies use relatively poor measures of receiver performance—ones not supported by traditional engineering practice or accepted standards—that have the consequence of minimizing the observed effects of interference. Even so, all four studies show that some current receivers suffer interference at the signal levels currently embodied in the FCC rules. The studies differ on the proportion of receivers that suffer such interference. The NAB study showed 22 of 28 receivers (79%) failing to provide acceptable performance when subjected to an interfering signal right at the FCC's limits. The OET study showed only 2 of 21 receivers (10%) failing to meet their 3% added-distortion criterion in the presence of 2nd-adjacent-channel interference at the FCC limit and 6 of the 21 (20%) failed to meet the 1% added-distortion criterion.[20] Three of the 11 (27%) receivers tested by the NLG study failed (by its definition) with a 2nd-adjacent channel signal at the FCC limit. A full 13 of 16 (81%) receivers tested in the NPR et al. study were driven below the 45-dB SNR operating point before the interfering signal rose to the FCC's limit.[21]

## 5.1 OET Study

William H. Inglis and David L. Means prepared the OET study dated July 19, 1999.[22] They tested 21 receivers for resistance to interfering signals on the 2nd- and 3rd-adjacent channels. The interference criteria the OET team used was a 1% or 3% increase in distortion—by which they meant the quantity of total harmonic distortion plus noise (THD+N) as measured by an Audio Precision System One.[23] They measured the levels of adjacent-channel signal necessary to degrade receiver performance to one of two levels—a 1% increase in THD+N and a 3% increase in THD+N.

We believe that such increases in THD+N are inappropriate criteria for determining the onset of interference. Harmonic distortion can arise from many subsystems in the receiver. Yet, the base level of THD+N defines the results of the OET test. Consider two receivers, alike in every way, except that the first has an audio output stage that generates 1.0% harmonic distortion and the second has an output stage that generates 0.1% harmonic distortion. The harmonic distortion in

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20 See OET report p. 31 and Table 2.
21 NPR et al., p. 4, Chart # 6 2nd Adj D/U with 45 dB Audio S/N
22 *Second and Third Adjacent Channel Interference Study of FM Broadcast Receivers*, Project TRB-99-3, Interim Report, FCC/OET TRB-99-1, July 19, 1999.

the first receiver would not be objectionable to many consumers, and few consumers could even notice the harmonic distortion in the second receiver. But, the OET's test methodology would require the measured THD+N to rise to 2% in the first receiver, versus rising to only 1.1% in the second receiver, for a finding of interference. In this case, the OET would not define the first receiver to be receiving interference until its performance was driven down to an SNR of 34 dB, whereas the second receiver would be defined to be receiving interference when operating at an SNR of 39 dB. The SNR due solely to interference effects would be 35 dB in the first receiver and 39 dB in the second.[24] That is, the higher audio distortion in the second receiver, although imperceptible to some consumers and probably not found objectionable by most, causes the OET methodology to judge its listeners to be willing to accept 4 dB more service degradation from interference.

It seems to us unlikely that this actually represents consumer preferences. This definition biases the testing process against all FM receivers that have higher levels of harmonic distortion in the audio amplifier stages. That is, all other things being equal, the OET's procedures determine that a receiver that has higher harmonic distortion in the audio amplifier stage is more resistant to interference. This is just the opposite of what one would expect from listening tests or other measures of consumer preference. All other things being equal and at the same levels of

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[23] Personal communication, William Inglis, September 9, 1999.

[24] THD+N of 0.1% corresponds to an SNR of 60 dB (assuming no distortion or treating all distortion as noise) and THD+N of 1% corresponds to an SNR of 40 dB . THD+N of 1.1% corresponds to an SNR of 39.2 dB [20 Log(1/0.011)] and THD+N of 2% corresponds to SNR of 34 dB. The added noise needed to drive a signal from 40-dB SNR to 34-dB SNR would create an SNR of 35 dB on its own. The calculation is 10 $\text{Log}(10^{-3.4}-10^{-4}) = 35.3$.

adjacent-channel interference, we would expect subjective measures of audio quality to be lower for the radio with the higher level of harmonic distortion.[25]

One can use data from the NPR et al. report to illustrate this shift in the measurement base. That report gave the level of THD generated by the receiver in normal operation. For example, they showed a Sony Walkman as having a THD of 1.7%. Applying the OET test procedure to this receiver would require setting the level of the interfering signal high enough to force the measured THD+N to 2.7%. This requires that the SNR from the interference impairments alone be only 31 dB! Using data from the NPR et al. report, we generated Table 2 below that shows the SNR necessary to cause interference for each receiver as interference is defined in the OET report. Notice that the average SNR associated with the OET 3% criterion is 28 dB and that associated with the 1% criterion is 34 dB. Even using measurements of THD+N, rather than measurements of SNR, the OET could have adjusted its test procedure to measure a consistent level of audio impairment from the interference effects.[26]

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[25] For the levels of harmonic distortion in typical consumer receivers, the consumer preference for the radio with less harmonic distortion would probably be slight—indeed hard to measure.

[26] For example, if one wanted to determine the level of interference required to drive the SNR down to 50 dB, one could calculate the impact of adding noise at the –50 dB level to the measured THD of the receiver. Or, because the Audio Precision System One can measure SNR, the researcher could measure that level directly.

**TABLE 2—Implied Output SNR for OET Test Methodology**

| Manufacturer | THD in % (Average) | Equivalent SNR of OET 3% Test (dB) | Equivalent SNR of OET 1% Test (dB) |
|---|---|---|---|
| | | *Automotive* | |
| Delco | 0.55 | 28 | 35 |
| Ford | 1.00 | 27 | 33 |
| Audiovox | 0.74 | 27 | 34 |
| Koss | 0.88 | 27 | 33 |
| Ford | 1.60 | 25 | 31 |
| | | *Portable* | |
| Panasonic | 0.55 | 28 | 35 |
| Sony Walkman | 1.70 | 25 | 31 |
| Sanyo | 0.38 | 29 | 36 |
| SonyTR | 3.50 | 23 | 28 |
| Magnavox | 0.90 | 27 | 33 |
| Radio Shack | 0.34 | 29 | 36 |
| | | *Home HiFi* | |
| Den380 | 0.16 | 30 | 38 |
| Pioneer | 0.93 | 27 | 33 |
| Den680 | 0.05 | 30 | 39 |
| SonyHIFI | 0.22 | 29 | 37 |
| TechHiFI | 0.26 | 29 | 37 |
| Average | | 28 | 34 |

*Data Source:* NPR et al. report, Table A1, Test Status.
*Note:* SNR = signal-to-noise ratio.

Although we have a few other concerns with the OET's testing procedures, our most significant concern is with the use of THD+N as the criterion of impairment in the presence of interference. This is not the conventional measure of interference effects in the engineering community; it is unlikely to match consumer preferences; and, when increments in THD+N are measured as defined by the OET, the test process is biased.

The results reported in the OET Table 2 for receiver 11 appear suspicious. Receiver 11 required an interfering signal 43.5 dB stronger than the desired signal to raise the distortion 1% but required an interfering signal 63.5 dB stronger than the desired signal to raise the distortion 3%. Going from 1% to 3% distortion is no more than a 10-dB decrease in output SNR, and, if the receiver is delivering reasonable quality audio output, no more than 10-dB increase in the interfering signal should be needed to cause such an impairment. In the OET tests the average increase in interfering signal strength required to go from 1% added distortion to 3% added distortion was 5.6 dB, and the average for all receivers other than 11 was only 4.9 dB. Yet, receiver 11 required a 20-dB increase in the level of the interfering signal to go from 1% to 3% added distortion.

The OET did not test low-cost receivers (e.g., the Sony Walkman) even though such receivers are widely used. There is no question that testing these units properly would have been more difficult and that time limits on the OET study may have precluded such testing.[27] It is better not to do something than to do something wrong. However, the exclusion of an important class of widely used receivers could bias the results of the study. In this case, one would expect that these physically small, lower-cost units would perform more poorly than average.[28]

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[27] See the discussion below regarding the testing of personal receivers in the NAB and NLG studies.

[28] Improving IF filter selectivity increases the cost of a receiver and may also increase its bulk.

Consequently, omitting such receivers from testing would show that the population of receivers perform better than is actually the case.[29]

We can calculate adjustments to the OET results to estimate approximately the level of interfering signals the OET would have identified had they used the 50-dB SNR measure of interference recommended by the ITU-R for this circumstance. We adjusted the OET measurements as follows. First, we took the averages calculated in Table 2 above for the 1% and 3% added distortion levels as the assumed audio output SNR for the OET radios (34 and 28 dB, respectively). We also examined the results from the NPR et al. report and determined that an average increase of 16 dB in the level of the interfering signal was associated with an 20-dB increase in the audio output noise (output SNR falling from 50 to 30 dB). If we make the further assumption that the changes in output SNR are linear functions of the changes in the strength of the interfering signal (an assumption that is reasonable but not perfect, provided that the receiver is operating above threshold), then we can calculate the level of the interfering signal that would have resulted in an output SNR of 50 dB. Consider one specific example, Table 2 in the OET report shows that receiver 1 had an interfering signal 36.2 dB stronger than the desired signal when the receiver suffered 1% distortion. Based upon our average value of 34-dB SNR associated with 1% distortion, we see that we have to reduce the interfering signal enough to increase the output SNR by 16 dB. Using the ratio of 16/20 seen in the NPR et al. data, this requires decreasing the interfering signal by 16 dB * (16/20) = 12.8 dB. So, the adjusted level of the interfering signal must fall to 36.2 - 12.8 = 23.4 dB above the level of the desired carrier in

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[29] Of course, because the OET procedure requires receivers with greater audio distortion to accept stronger interfering signals, the OET tests would have been more likely to find that personal receivers performed adequately in the presence of interfering signals.

order to improve the output SNR to 50 dB. Table 3 shows the result of applying this adjustment to all the entries in the OET's Table 2, for 75-kHz deviation of the interfering signal. The shaded entries represent estimates of receiver performance in the presence of interference that fall below the levels assumed in the FCC's rules.

**TABLE 3—Adjusted OET Data to Show Estimated U/D Ratios at 60-dB Contour Desired Signal Stereo L+R, Undesired Stereo L Only, 75 kHz deviation, with 50-dB Output Signal-to-Noise Ratio**

| Sample # | Adjusted 1% data | Adjusted 3% data |
|---|---|---|
| 1 | 23.4 | 27.7 |
| 2 | 12.0 | 8.7 |
| 3 | 39.5 | 37.5 |
| 4 | 29.8 | 29.1 |
| 5 | 17.4 | 18.9 |
| 6 | 42.3 | 39.5 |
| 7 | 45.4 | 44.1 |
| 8 | 44.7 | 43.5 |
| 9 | 54.7 | 49.9 |
| 10 | 34.6 | 35.6 |
| 11 | 30.7 | 45.9 |
| 12 | 42.2 | 38.3 |
| 13 | 31.9 | 35.3 |
| 14 | 34.4 | 36.2 |
| 15 | 23.6 | 24.1 |
| 16 | 23.7 | 28.3 |
| 17 | 36.3 | 34.0 |
| 18 | 23.2 | 29.5 |
| 19 | 32.0 | 32.9 |
| 20 | 36.0 | 38.7 |
| 21 | 29.8 | 27.1 |

*Note:* Entries in shaded areas do not meet the FCC ratios.

Several observations about the table are immediately apparent. If our procedure is correct, the two estimated interference levels in each row should be the same—they are estimates of the same quantity. In most cases, the numbers are quite close, except for the case of receiver number 11. The wide disparity in the two estimates for receiver 11 is a consequence of the anomalous measurements we discussed above. Fully 33 of the 42 estimates, or 79% of the receiver performance estimates, indicate that the receivers did not perform at the levels assumed in the FCC rules. If the OET receiver samples are numbered in the same order as shown in Table 1 of the OET report, then receivers 7, 8, and 9 are all car radios. These three radios are the only radios that performed above the FCC ratio for both estimates. But, as we discuss below, car radios need to reject adjacent channel interference by at least 10 dB more than other radios if car radios are to yield equivalent service.

We must emphasize that the estimation procedure we used to generate Table 3 is very rough—it compounds two sets of assumptions—and the reader should keep the relative weakness of our estimation process in this case in mind. We used the best method we could design to adjust the OET test results to make them comparable with the others, but we recognize that it may have produced flawed results. We expect that measurement of the actual output SNR of the receivers would create a table somewhat like the one we have prepared, but several of the entries in the table would probably be quite different.

As with the other studies, the OET tests showed that car radios outperformed other radios with respect to the ability to reject adjacent-channel interference.[30]

## 5.2 NAB Study

The NAB filing contains three separate studies or reports. The first is a study by Moffet, Larson, and Johnson (MLJ Report 1), entitled *Standard of Service*, that examined the proper standard to use to identify the presence of interference. After consideration of historical practice, including an interesting examination of the standards used by the FCC in establishing the FM broadcasting service, and of current practice and regulation, the authors concluded that a reasonable measure of interference is that contained in the ITU-R Recommendation 641. The second report was by Carl T. Jones Corporation (CTJ); it reported the results of testing 28 receivers according to the criteria specified in the MLJ report. The third report in the NAB trilogy was again by MLJ (MLJ Report 2). This report described how the receivers were selected for testing and provided an analysis of the results of those tests.

### 5.2.1 MLJ Report 1

MLJ recommended two separate criteria for the definition of harmful interference. First, a high-quality receiver, say one with an SNR of 63 dB in normal operation, would be considered to be receiving harmful interference from an adjacent-channel signal when the SNR was driven down to 50 dB. The authors showed that this standard was consistent with the FCC's past practice and ITU-R recommendations. They also showed and explained subjective testing results that they felt justified the choice of the 50-dB standard. Second, they defined a criterion for receivers that did not generate a 50-dB SNR audio output when no impairments were present. They recommended that such receivers be considered to be receiving harmful interference when the output SNR is degraded by 5 dB. Thus, a receiver that produces a 45-dB SNR under the best conditions is not to be regarded as suffering from unacceptable adjacent-channel interference

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[30] This conclusion assumes that the OET receiver samples are indexed in the order shown in Table 1 of the OET report. See Table 2 in the OET report.

until the output SNR is driven down to 40 dB. They based the choice of the 5-dB decrement in SNR on subjective test results.[31]

The test criteria recommended by MLJ appear reasonable to us. They match both historical practice and international standards. The criterion of a 5-dB degradation in SNR for the lower-performance receivers is a significant degradation—we expect that most consumers would notice it and that many would find it irritating or annoying. We think that this 5-dB criterion is appropriate but that a good case could have been made for a slightly smaller level of degradation, say 3 dB. We should note, however, that the 50 dB criterion recommended by MLJ reflects consumer preferences of several decades ago. The widespread adoption of audio entertainment systems providing significantly higher SNR levels indicates that many consumers do prefer such higher quality. However, given history, industry practice, and the level of the other protections offered in the FCC's rules, the MLJ choice of the 50-dB criterion is appropriate for analog FM.[32]

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[31] MLJ Report 1 also relied on a study conducted by the Technical Subgroup of the Advisory Committee on Radio Broadcasting and compiled by Larry Middlekamp.

[32] However, the recent development of in-band, on-channel (IBOC) systems using the FM band without extra bandwidth assignment is intended to provide CD-quality audio output with much better quality than 50 dB analog using very sophisticated music audio encoding and digital channel coding and modulation to combat fading and dropouts. It is well known that such digital signals produce an "all or nothing" effect. A system that is receiving and decoding perfectly near the edge of coverage can experience an abrupt and devastating degradation with only a fraction of a dB additional interference. Thus, we believe that a separate measurement with IBOC receivers be done or the nation might lose the ability to obtain full coverage for this new kind of superior service on the FM band.

### 5.2.2 Carl T. Jones Corporation Report

The CTJ report describes the test procedure and the results of the tests on 28 FM receivers. Several elements of the testing procedure deserve comment.

The CTJ tests included two elements that improve consistency and accuracy—as well as making it easier to replicate the tests. The tests took into account impedance mismatches between the test signal generator and the receiver under test. Specifically, they measured the reflected power from the unit under test and adjusted the test equipment until the power delivered to the unit under test reached the desired value. They verified the accuracy of manual tuning by measuring the frequency of the local oscillator radiation from the receiver under test.
CTJ tested "personal receivers" (Walkman-like units) by coupling the test signals to the speaker lead. We believe that this is reasonable and appropriate. The speaker leads normally act as the system antenna, so coupling to the receiver would be essentially unchanged.

The CTJ test results were presented clearly, primarily using graphs. They reported only the key measurements defined by MLJ. Thus, like the case for the OET report, but unlike case for the NLG and NPR et al. reports, it would be hard to use the NAB test data to examine the implications of other criteria.

### 5.2.3 MLJ Report 2

MLJ chose to test 28 receivers in five different categories: clock, personal portables, portables, component systems, and automobile receivers. They tested 5 radios in each category, except car radios in which category 8 radios were tested. In much of the narrative discussion, they used the median receiver in each category to represent the performance of the category.

The use of the characteristics of the median receiver is appropriate. But, Table 1 in the MLJ second report is better than any summary statistic. We have reproduced the MLJ Table 1 in Table 4. In our version, we used shaded cells to indicate the receivers for which the measured 2nd-adjacent D/U ratio was less than the FCC's current 40-dB standard. That is, the vast bulk (22 of 28) of the receivers tested did not perform at the 40-dB standard for 2nd-adjacent interference. Two of the automobile units tested only slightly better than the 40-dB standard (2-dB and 5-dB better). As we discuss below, car radios operate in a more challenging environment than do other receivers and should be expected to perform better than other receivers on tests of adjacent channel interference rejection. Automobile receivers accounted for 5/6, or 85%, of the units that exceeded the FCC standard. The analysis report noted that automobile receivers perform best by some criteria (see pp. 26, 28).

**TABLE 4—Measured 2nd-Adjacent D/U Ratio (dB) for 28 Receivers**

| Receiver type | Measured 2nd adjacent D/U (dB)<br>Desired signal at –55 dB | | | | |
|---|---|---|---|---|---|
| Clock | –12.4 | –15.1 | –16.7 | –17.6 | –32.6 |
| Walkman | –5.5 | –15.3 | –25.6 | –27.4 | –30.8 |
| Portable | –4.2 | –9.0 | –16.6 | –20.7 | –21.7 |
| Component | –15.5 | –25.6 | –31.4 | –31.8 | –45.8 |
| Auto aftermarket | –15.5 | –17.2 | –27.7 | –61.0 | –64.7 |
| Auto OEM | | –41.9 | –45.1 | –61.5 | |

*Source:* MLJ report 2, Table 1.
*Note:* Shaded entries represent receivers that do not meet the FCC's ratio. The report considered 28 receivers but a 5 column by 6 row table has 30 entries; diagonal stripes indicate the two null entries.

## 5.3 NLG Study

Broadcast Signal Lab, LLP, performed the NLG study. The NLG used distortion as their measure of receiver performance degradation, not SNR. The measure of distortion used was THD+N (as was used by the OET).[33] However, unlike the OET, the NLG test used a quantity they called the "transition zone" as an objective measure of unacceptable receiver degradation due to interference.[34] The NLG use of transition zone as a measure of unacceptable interference differs substantially from common engineering practice. It is well known that FM receivers display a phenomenon known as *threshold*.[35] Basically, as the noise or interference on the radio channel increases, the receiver performance degrades in proportion to the increase in noise or interference until threshold is reached—thereafter receiver performance degrades faster. Many authorities regard the point of FM threshold as the point at which the FM receiver quits working acceptably. Based upon the description in the NLG report and the accompanying technical data, we believe that the NLG's transition zone corresponds to the onset of the FM threshold effect. That is, the transition zone is where the radio signal becomes unusable— long after it started sounding terrible. The NLG definition of harmful interference means not just impaired but really unsatisfactory.

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[33] In fact, like the OET, the NLG test also used Audio Precision test equipment to measure THD+N.

[34] NLG report, p. 8.

[35] See, p. 479**,** *Information Transmission, Modulation and Noise*, *Second Edition,* Mischa Schwartz, McGraw-Hill, 1970. Schwartz refers to studies of this phenomenon done as early as 1937.

Even with this significantly flawed measure of the harmful effects of adjacent-channel interference, the NLG reported that some consumer receivers suffered from harmful interference from interfering signals at the FCC limit.[36]

The fundamental flaw in the NLG study is their criterion for harmful interference. However, we have several other concerns about their approach.

They report using alligator clips or tack soldering to connect signal leads to receivers lacking antenna terminals. Who knows what this did to the performance of the receivers under test—especially the smaller personal receivers where the presence of an alligator clip may modify various couplings throughout the receiver. In contrast, the OET chose not to test the personal receivers and the NAB and NPR et al. tests used coupling to the speaker leads that serve as the antenna for such receivers.

The NLG tests displayed several anomalous results. For example, on several receivers a greater adjacency created more interference than a smaller adjacency. See the discussion at page 12 of the NLG report regarding the Marantz component receiver and the Sony Walkman. They also commented on this in the last line of their executive summary. Finding that a receiver is more susceptible to interference at a greater adjacency goes against physical intuition, experience, and other tests (e.g., the OET and NAB studies). Although it is possible that these measurements

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[36] See NLG report, pp. 9-11, "Walkman in transition zone at the FCC interference ratio…" "The Aiwa boom box also did not meet the FCC ratio reference level for second adjacent channel signals." "Most of the lower priced radios that were tested succumbed to lower levels of undesired signal, at or below the FCC ratio reference level."

reflect the behavior of the receivers in question, they may also reflect flaws in the test procedure and call into question any conclusions that are based upon them.

Other examples of anomalous results include cases in which increasing interference improves output SNR. For example,

- Receiver 2, 2nd-adjacent, 27-dB SNR at –20 dB interference level, but 29.5-dB SNR when the interfering signal is increased by 10 dB.
- Receiver 10, 2nd adjacent, stereo tone noise, 63-dB SNR with interference at –20 dB, but 67.4-dB SNR with interference at +10 dB.

The NLG report offers information to show how misleading a focus on THD+N can be. Table 1 in the NLG report displays both SNR and THD+N for the Marantz receiver under increasing interference on the 2nd-adjacent channel. SNR went from 57 dB to 38 dB—a drop of 19 dB. For the same change in interference, NLG reported that THD+N only went from 0.67% to 0.97%.

Like the other groups, the NLG reported that car radios (as a group) worked quite well.

One nice feature of the NLG report was that they recorded and reported substantial additional information besides that upon which they based their conclusions. Most useful, they reported the SNR measured at various levels of interference. Using these data, we can compare the results of the NLG testing with other tests of SNR. Table 5 below displays the SNR measured in the NLG test when the 2nd-and 3rd-adjacent-channel signals were at the limit under the current FCC rules. We have shaded in those entries where the resultant SNR is below 50 dB.

**TABLE 5—Signal-to-Noise Ratio in NLG Test with 2nd- and 3rd-Adjacent Channel Signals at the Limit under Current FCC Rules**

| Category | Receiver | 2nd adj 0 dB, stereo tone | 3rd adj 0 dB, stereo tone |
|---|---|---|---|
| Car | 3 Toyota | 50 | 50.3 |
| Car | 10 Ford | 64.5 | 58.4 |
| High | 1 Marantz | 54 | 42.8 |
| High | 4 Denon | 45.5 | 47.6 |
| High | 8 Technics | 41 | 54 |
| High | 9 NAD | 41.2 | 48.4 |
| Low | 2 Sony Walkman | 0 | 0 |
| Low | 5 Sony clock | 45.8 | 36.4 |
| Low | 6 Aiwa boom box | 48 | 0 |
| Low | 7 Sony boom box | 20 | 38 |
| Low | 11 Aiwa integrated system | 39.9 | 39.6 |

*Note:* Entries in shaded areas do not deliver 50 dB output SNR when interference is at the FCC ratios.

In our analysis, 16 of the 22 entries, or 73%, showed interference by the 50-dB SNR standard recommended by MLJ in the NAB report. Two-thirds of the entries that did not show interference were for car radios. Although we have concerns about the reliability of the NLG measurements, we note that they are consistent with those of the NAB and of NPR et al. (discussed below).

In their pleading, the NLG stated that "about half performed dramatically better than the FCC ratios would suggest."[37] The claim of "dramatically better" flows from their definition of performance and nothing else. As we showed in Table 5, the NLG measurements (flawed as

[37] NLG Comments, p. 19.

they appear to be) show that the performance most of the receivers they measured are significantly degraded by interfering signals right at the FCC limits.

NLG also made the mistake, as did all the other studies, of reporting the results of tests of car radios together with the results for other radios. See the discussion in Section 6 below on car radios.

This study is the worst of the lot—in *Consumer Reports* jargon, "It's a lemon."

### 5.4 NPR et al. Study

RMC Technologies conducted this study under the auspices of National Public Radio (NPR), the Consumer Electronics Manufacturers Association (CEMA), and the Corporation for Public Broadcasting. This study used SNR as its criterion. Although CEMA's comments in this proceeding state that a 45-dB SNR level was used in the testing to define the boundary between acceptable and unacceptable quality, the test results also show the levels of interfering signals required to create an output SNR of either 50 dB ($1^{st}$-, $2^{nd}$-,and $3^{rd}$-adjacent channels) or 30 dB ($1^{st}$-and $2^{nd}$-adjacent channels). The basis for their 45-dB standard was an earlier NPR study that found 45 dB to be the minimal SNR for an acceptable high-quality audio broadcasting service**.** Their tests also provided a wealth of other data on the performance of each receiver. They tested 16 radios and were also undertaking some subjective testing that was to be reported at a later date.

The NPR et al. study confirmed today's receivers do not perform better than the FCC's rules assume. Consider, for example, performance in the presence of interference on the $2^{rd}$-adjacent channel.  Most (11/16) receivers worked acceptably when the interfering signal was 20 dB lower (more favorable) than the FCC rules assume.  Half worked acceptably when the interfering signal was 10 dB lower.  And only a few worked acceptably (3 of 16) when signal was at FCC rule's assumed level.  Only 2 worked okay when the interfering signal was significantly above the level in the current rules.[38]

This study provides good documentation of the test procedure and of the test results for each receiver.  It provides extensive information, but the exposition and organization of the report do not always make the study easy to follow.

The study also examined the effect of the full mix of over-the-air signals (using the local FM environment in Cleveland) had on receiver performance.  One would expect that receiver performance would degrade in this more challenging environment, and that is what they found.[39]

Like the NAB, the NPR et al. study used the conventional SNR measure of service degradation. They chose a slightly less-demanding criterion than did the NAB, and they made no adjustment in their test procedures for receivers that did not perform that well to begin with.  They reported many different measurements.  Their measured results for 2nd-adjacent-channel interference (measured with a –50-dBm desired signal and a D/U of –40 dB) are shown below in Table 6. The shaded entries, all of the entries, show receiver performance that does not meet the 50-dB

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[38] See the table in Appendix B, p. 3.  We counted receiver 7's 44.7-dB performance at the –40 dB D/U level as if that receiver met the 45-dB threshold.  If we had not rounded off, the results would have been more pessimistic.

[39] NPR et al., Appendix F.

SNR criterion. Notice that the first three receivers, all of them car radios, did meet the 45-dB criterion used by NPR et al.

**TABLE 6—Receiver Performance Stereo Output SNR for D/U at FCC Ratios**

| Manufacturer | Upper $2^{nd}$-Adjacent | Lower $2^{nd}$-Adjacent |
|---|---|---|
| | *Automotive* | |
| Delco 1 | 48.3 | 48.3 |
| Ford 5 | 47.5 | 47.3 |
| Audiovox 7 | 45.6 | 44.7 |
| Koss 13 | 40 | 37 |
| Ford 15 | 42.8 | 42.2 |
| | *Portable* | |
| Panasonic 3 | 0.0 | 1.0 |
| Sony Walkman 9 | 1.9 | 2.4 |
| Sanyo 11 | 0.0 | 0.0 |
| SonyTR 12 | 19.5 | 18.5 |
| Mangavox 14 | 31.2 | 31.0 |
| Radio Shack 16 | 0.0 | 0.0 |
| | *Home HiFi* | |
| Den380 2 | 42.5 | 40.5 |
| Pioneer 4 | 22.5 | 21.5 |
| Den680 6 | 38.0 | 33.0 |
| SonyHIFI 8 | 34.5 | 36.7 |
| TechHiFI 10 | 42.5 | 41.5 |

*Source:* NPR et al. study, Table B3.4 in Appendix B, p. 3.

## 5.5 Summary of Study Results

Table 7 below, summarizes our evaluation of the studies and ranks the studies in a consumer-friendly fashion.

**TABLE 7— Condensed Ratings**

| Study | Rating | Receivers tested | Interference criterion | Comments |
|---|---|---|---|---|
| NAB | ***** | 28 | SNR | • Well documented.<br>• Tied test criteria to subjective tests, standards.<br>• Explained basis for criteria.<br>• Misspelled Larry Middlekamp's name in a footnote. |
| NPR et al. | ***** | 16 | SNR | • Lots of data, but confusing organization at times. |
| OET | ** | 21 | Distortion (THD+N) | • Weak documentation of procedures.<br>• Used 1% and 3% increases in THD+N as criterion.<br>• No testing of a significant class of receivers.<br>• Some results are difficult to understand, e.g., Table 3, Receiver 18 (1.1-dB increase in interfering signal pushes THD+N from 1% to 3% (a 10 dB decrease in SNR).<br>• Table 2, receiver 11, data problem. |
| NLG | * | 11 | Distortion (THD+N) | • Use of distortion (similar to OET, but without concern for starting point).<br>• The NLG "transition zone" an ill-defined and misleading criterion.<br>• Some strange results—greatly hamper one's ability to accept results. |

## 6 Car Radios—A Special Case

All studies showed that car radios outperformed other radios. This should be no surprise. Cars operate in a far more hostile radio environment than do home receivers. Car receivers must tolerate rapidly changing multipath (echoes or ghosting of both the desired and undesired radio signals) that can make the strength of each signal change rapidly. One way to improve the car radio's performance against such interference is to improve the radio's adjacent-channel selectivity. In addition, car radios are often used on the highway. Highway travel can take cars into fringe coverage zones where the problems of adjacent signals are more severe than in the average downtown location. In addition, a person listening to a radio in a car may begin listening to a song, news report, or sporting event and may travel a number of miles before the radio segment completes. Loss of the ability to hear such a signal, in which the listener has invested time and attention, can be annoying.

The physics of multipath radio propagation are well studied and well known, as are the problems of communicating to moving platforms in a multipath environment. Each of us has done research on mobile communications in multipath environments. We believe that it is inappropriate and misleading to use the performance of car radios, tested using a test appropriate to a nonmobile environment but not to a mobile environment, as a guide to the performance of consumer receivers under changes to the FCC's rules for 2nd- and 3rd-adjacent channel protection.

Car radios must perform in a hostile environment. The adjacent-channel interference problem for car radios is more severe than for stationary radios. The multipath fading that changes the strength of both the desired and interfering signals makes the problem of rejecting adjacent-channel interference more difficult. There is a good general discussion of this problem in Chapter 4 of Jakes et al., *Microwave Mobile Communications*. Section 4.1.6, "Effects of Rayleigh Fading on Adjacent-Channel Interference" develops analytic tools for studying adjacent-channel interference between two FM signals in the multipath environment—such as is seen by car radios.[40]

A simple calculation shows how severe the effects of multipath fading are. Fading effects are often viewed as multiplicative—the received signal strength varies as if multiplied by a random variable that follows the Rayleigh distribution. The same theory applies to both the desired signal and the undesired interfering signal. Consequently, half the time the fading factor for the desired signal will be greater than the fading factor for the undesired signal.[41] So, if a given level *X* of adjacent-channel interference protection works appropriately for stationary radios, car radios in a multipath environment where the average adjacent channel protection is *X*, must operate in an environment where the adjacent-channel protection is worse than *X* half the time. The distribution of time above and below specific levels of adjacent-channel interference is mathematically messy, and we will not go into it here. The rate of fluctuations around the average depends upon how fast the car is going—but typically the fluctuations occur in seconds or fractions of seconds. Thus, a car radio with adjacent-channel protection *X*, just good enough

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40 *Microwave Mobile Communications*, William C. Jakes, Jr., ed., John Wiley & Sons, 1974, p. 199. Rayleigh fading is a common mathematical model of the effects of multipath on radio signal strength.

41 If you spin a roulette wheel twice, the first number will be smaller than the second number half the time (ignoring ties). More mathematically, if two uncorrelated random variables are drawn from the same continuous distribution, the first will be smaller than the second half the time, and vice versa.

for the average signal levels, will be passing in and out of regions of objectionable interference almost constantly. Listeners find this irritating and prefer radios with better adjacent-channel protection.

Figure 2 below shows the fraction of time a car receiver will deliver an unacceptable audio signal if the car radio has more or less IF selectivity relative to a stationary receiver. The stationary receiver is assumed to be operating just at the limit of acceptability of adjacent-channel interference. The car radio is assumed to be operating with desired and undesired signals at the same average level as the stationary radio but is subject to independent Rayleigh fading on both signal paths.[42]

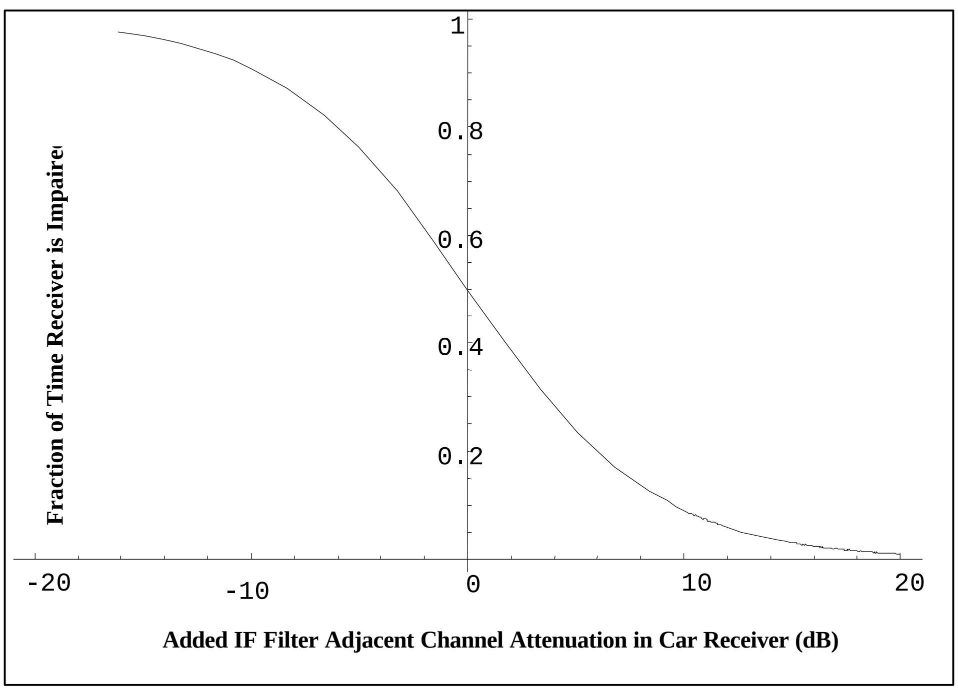


**Figure 2. Fraction of time a car radio would be impaired by adjacent-channel interference as a function of changes in the IF filter adjacent channel selectivity.**

Note that about 10 to 20 dB of extra rejection of adjacent-channel interference is needed to make the adjacent-channel effects on the car radio about the same as the adjacent-channel effects on the stationary radio. With respect to performance in the presence of adjacent-channel interference, car radios clearly benefit from an extra 10 dB of resistance to adjacent-channel interference. Adding 10 dB of adjacent channel protection reduces interference from 50% of the time to 9% of the time. Adding a second 10 dB of adjacent channel protection (20 dB total) pushes interference below 1% of the time. If we assume that the market is working reasonably well, that stationary radios perform at the levels consumers expect in the current interference environment, and that it is not too expensive or difficult (relative to the overall cost and size of a car radio) to improve performance in the presence of adjacent-channel interference, then it should be no surprise that car radios perform significantly better than other radios on tests of adjacent-channel interference.

All four studies suffered from the fault of testing car radios and not sufficiently explaining why the performance of car radios should be expected to differ from other radios. Car radio performance should be considered separately, and it would be appropriate to use different standards or different test procedures for car radios. All of the studies reported the results for car radios together with the results for other classes of radios—an act that is highly likely to be misleading.

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[42] A derivation of the relationship shown in this curve is given in the discussion in Jakes, op. cit., at pp. 59-61, specifically section 1.5.5 Ratio of Signal Envelopes at Two Frequencies.

## 7 Conclusions and Recommendations

Despite the fact that the sponsors of these studies used them to argue for different policy outcomes, there are large areas of agreement among the studies. All groups used similar methods to test receivers; some groups took less-than-diligent care in assuring that the measurement process itself did not introduce extraneous effects. In some cases, even the same equipment was used to perform the tests.[43] All of the studies found that car radios outperform other FM broadcast receivers.[44] Taking the information reported in all of the studies and displaying it in a consistent format (as we have done in the shaded tables above) shows that the measurements were quite consistent. Specifically, the measurements in the OET, NLG, and the NPR et al. studies indicated that the majority of receivers suffered unacceptable interference (with regard to the 50-dB SNR criterion) when subject to undesired signals at the levels in the current FCC rules.

The most important difference among the studies was the criterion used to decide whether the effects of an interfering signal on an adjacent channel caused harm to the desired signal. The four studies put forward three different standards. The NLG study used what they called the transition zone as the measure of unacceptable interference. The transition zone is usually referred to as the FM threshold, and it occurs when the noise is sufficiently strong that slightly more interference will cause the receiver to completely fail to receive the desired signal. We believe that the transition zone would usually be associated with an output SNR of about 30 dB

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[43] For example, the OET, the NLG, and the NPR et al. all used Audio Precision System One equipment for measuring audio signals.

[44] See NPR et al., Appendix A, Table A1 Test Status, NAB's CTJ report, p. 28, NLG Comments, page 19, FCC Table 2 (assuming receivers are numbered as in Table 1).

or lower.[45] The OET also used distortion (actually distortion plus noise) as their measure of receiver performance degradation. They considered two different criteria—that reception was impaired when the measured THD+N increased by either 1% or 3% due to the effects of the unwanted interference. For a receiver with no added distortion of its own, the OET criteria correspond to an SNR of either 40 dB or 30 dB. We examined the implications of the OET 1% criterion for the 16 receivers in the NPR et al. study and showed that the 1% increase in THD+N corresponded to an output SNR in the range of 28 to 39 dB, with an average of 34 dB. Both the NAB and the NPR et al. studies used the output SNR as the criterion to measure receiver performance. NAB chose either a level of 50 dB or, if the receiver was not able to achieve a 50-dB SNR level, a degradation of 5 dB in the SNR of the audio output signal. NPR et al. made measurements at both 30- and 50-dB SNR but indicated that they believed that 45 dB was the appropriate level to define the limit of acceptable service.

If these four studies had measured the height of a child, the difference between them would not be in the heights they reported for the child. Rather it would be what they meant when they said the child was short or tall. Some people think a five-year-old child who is four feet high is tall for a child. Other people think a person must be over six feet to be tall and that all children are short. When someone measures the height of a child and reports the results in inches or centimeters, you know how tall the child is. When someone reports that a child is tall, you must ask what the speaker means by tall.

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[45] For standard FM, with ß=5, the FM improvement factor is 75 (18.8 dB). FM thresholding starts with an input SNR of about 15 to 10 dB, which would be associated with an output audio SNR of 33.8 to 28.8 dB. We used the midpoint of this range, 31.3 dB, rounded off, as an estimate of the output SNR associated with the transition zone or threshold.

In the same way, the difference between these studies lies in the definition of impaired reception. The NLG's definition, although based upon objective measurements, is basically that impaired reception must mean badly broken reception. The OET's definition required substantial interference. The definition used by NPR et al. was not unreasonable and was only slightly different from that used by the NAB. The NAB's definition is that service be degraded to the level many observers would characterize as slightly annoying. The NAB report had the most extensive discussion of the criteria they used to define impaired reception and of the basis for their choice of criteria.

Table 8 below compares the four reports and shows both the fraction of receivers tested that the report claimed did not meet the FCC ratios and the fraction of receivers that we calculated would not meet the FCC ratios if the 50-dB output SNR criterion were used. This table confirms that the differences among the studies flow from the definition of impairment and not the measurement process or the characteristics of the radios tested.

**TABLE 8—Percentage of Receivers Not Meeting FCC Ratios in the Four Reports and Using 50-dB Output SNR Criterion**

| Report | Criterion in SNR terms | Tested radios failing under authors' criterion | Tested radios failing under 50-dB SNR criterion |
|---|---|---|---|
| NPR et al. | 45 dB | 81% (13/16) | 100% (16/16) |
| NLG | 20–30 dB | 27% (3/11) | 73% (16/22) |
| OET | 25–30 dB | 10% (2/21) | 79% (16.5/21) |
| NAB | 50-dB or 5-dB degradation if receiver cannot reach 50 dB | 79% (22/28) | 79% (22/28) |

*Note:* SNR = signal-to-noise ratio.

Consumer tastes are changing—consumers appear to desire audio equipment with a higher SNR than they did in the past. The criteria used in the NAB and NPR studies probably understate losses to consumers associated with use of the current FCC protection ratios. The NAB criterion is appropriate in light of its historical use, but it might not reflect the preferences of the current generation of consumers. Thus, the NAB study may overestimate the amount of interference that modern consumers are willing to tolerate.

One needs to keep in mind that radios operate in a more complex environment than simply the desired signal and an undesired signal on an adjacent channel. The tests using the over-the-air signals in addition to the two test signals were nice touches in the NLG and NPR et al. studies. Tests using only two signals probably underpredict the extent of interference problems in the real world.

The results of these tests were about what one would have expected in advance.[46] In radio engineering, as in most other engineering activities, there is always a tradeoff between cost and performance. It makes little economic sense to build radios that are capable of rejecting more adjacent-channel interference than those radios will actually experience in use. Consequently, we would expect to see radios engineered to perform reasonably well in the radio environment created under the FCC's rules but not any better.

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[46] Of course, it is always hard to know afterwards what one would have expected in advance.

Looking in more detail at the structure of FM receivers supports this general view. The subsection of an FM receiver that contributes most to rejection of interference from signals on the adjacent channel is the IF filter. Several manufacturers sell ceramic IF filters for use in consumer FM receivers.[47] A rule of thumb in electronics manufacturing is that the retail price of competitive products is three or four times the cost to the manufacturer of the materials. That is, a design that uses two $1 ceramic filters instead of one would raise the retail price of an FM receiver by $3 or $4. Such a price increase would be quite significant for a receiver selling for under $50. In contrast, such a price increase would be much less important in a receiver selling for $400. The NPR et al. study showed the number of IF filter stages for 7 of the 16 receivers they tested. The average ability to reject adjacent-channel interference was a full 10 dB higher for those radios with more than one filter stage. The radios that had multiple filter stages were either automotive radios or home HiFi systems; no portables were shown as having multiple filter stages.

Decision makers should understand the tradeoff between added adjacent-channel interference and reduced performance of broadcast receivers. Listen to music at SNRs of 70, 60, 50, 40, and 30 dB. Consider the literature on subjective testing of audio systems and consider consumer preferences. (Why did CD designers choose the level of quality that they did? They faced tradeoffs too. They could have lowered the quality and put more music on the disk or made playback equipment less expensive or made the disks smaller and more convenient.) Finally, decide what quality of FM broadcast service the FCC's rules should protect.

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[47] We spoke to one major manufacturer of such filters who told us that the cost of such filters lies in the range of $0.50 to $6.00, depending upon the characteristics of the filter.

To conclude, we reviewed four reports and found that all four support the view that relaxing the FCC's adjacent channel protection ratios would create increased interference in vast majority of existing FM receiver when interference is measured by consumer preferences. There are real tradeoffs involved with the decisions in this docket.