STRATUS CONSULTING

Review of Urban Visibility Public Preference Studies

Final Report
Under U.S. EPA Contract No. EP-D08-100
with Abt Associates Inc.
Work Assignment #0-11

Prepared for:

Vicki Sandiford
Office of Air Quality Planning and Standards
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

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Prepared by:

Stratus Consulting Inc.
1920 L St. NW, Ste. 420
Washington, DC 20036
202-466-3731

PO Box 4059
Boulder, CO 80306-4059

Contact:

Leland Deck

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1. Introduction

The Clean Air Act ∫302(h) defines public welfare to include the effects of air pollution on "…visibility, … and personal comfort and wellbeing." Visibly poor air quality causes people to be concerned about health risks, but degraded visual air quality (VAQ) adversely affects people in additional ways. These include the aesthetic benefits of better visibility, improved road and air safety, and enhanced recreation in activities like hiking and bicycling. The term "urban visibility" is used to refer to VAQ throughout a city or metropolitan area. Urban visibility includes the VAQ conditions in all locations that people experience in their daily lives, including scenes such as residential streets and neighborhood parks, commercial and industrial areas, highway and commuting corridors, central downtown areas, and views from elevated locations providing a broad overlook of the metropolitan area. Thus, urban visibility encompasses not only visibility conditions at an individual's specific place of residence, but all the VAQ they see on a regular basis. Urban visibility includes not only major cities, but VAQ conditions in smaller towns and cities. The term urban visibility is not used to refer to VAQ conditions at remote natural locations such as National Parks, wilderness areas, and seashores.

The purpose of this paper is to review and reanalyze the methods and results of existing studies of preferences for urban visibility in order to help inform U.S. Environmental Protection Agency (EPA) assessments being conducted in the current particulate matter (PM) National Ambient Air Quality Standard (NAAQS) review. To date, urban visibility preference studies have examined individuals' desire for good VAQ by investigating the basic question, "What level of visibility degradation is acceptable?" Preference studies have used a similar group interview type of survey to investigate the level of visibility impairment that participants described as "acceptable." The specific definition of acceptable is largely left to each individual survey participant, allowing each to identify their own preferences. There are three completed studies that used this method, and one additional related pair of studies (designed for survey instrument development) reviewed in this paper. The completed studies were conducted in Denver, Colorado; the lower Frazer River Valley near Vancouver, British Columbia (BC), Canada; and Phoenix, Arizona. The related pair of survey instrument development projects were conducted in Washington, DC.

2. Background on Visibility and Methods Used in Urban Visibility Preference Studies

One direct physical measure of VAQ used in many visibility analyses is light extinction. Light extinction is the loss of light per unit of distance, and measures the ability of particles and gases in the atmosphere to scatter and absorb light traveling between an object and a person (or

camera). VAQ is commonly measured as either light extinction (in terms of inverse megameters, Mm^{-1}) or the haziness index measured in deciview (dv) visibility (Pitchford and Malm, 1993), which is a logarithmic function[1] of extinction. Extinction and dv are physical measures of the amount of visibility impairment (e.g., the amount of "haze"), with both extinction and dv increasing as the amount of haze increases.

In all but one[2] of the visibility preference studies reviewed in this paper, participants were shown a series of different VAQ conditions projected on a large screen using a slide projector. In the earliest two studies (the Denver and lower Frazer River Valley studies) a range of VAQ conditions were presented by projecting photographs (slides) of actual VAQ conditions. The photographs used in the Denver and BC studies were taken on different days from the same location, and presented the same scene. Photographs were selected to avoid depicting significant weather events (e.g., rain, snow, or fog), and where measured extinction data were available from the time the photograph was taken.

The Phoenix study, as well as the subsequent Washington, DC survey instrument development projects, used photographic-quality images generated by a computer to present different VAQ conditions. The images were developed from an original photograph using the WinHaze software program, which is based on a technique described in Molenar et al. (1994). The Phoenix study and the 2001 Washington, DC project projected slides of digital images prepared by WinHaze. The 2009 Washington, DC project presented images directly from the desktop version of WinHaze using either a liquid crystal display (LCD) projector or a computer monitor.

WinHaze analysis synthetically superimposes a uniform haze on a digitized, near-pristine actual photograph. The WinHaze computer algorithm calculates how a given extinction level would impair the appearance of each individual portion of the photograph. A major advantage of presenting WinHaze-generated images is that they provide viewers depictions of alternative VAQ levels, with each image containing exactly the same scene, with identical light angle, time of day properties, weather conditions, specific scene content details (e.g., the amount of traffic in a intersection), etc. Additional details about WinHaze, and a discussion of the applicability of WinHaze images for regulatory purposes, is in the 2004 PM Criteria Document (U.S. EPA, 2004). The desktop version of WinHaze is available online (Air Resources Specialists, 2008).

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1. The haziness index (humanly perceived changes in VAQ), defined as Haziness (dv) = $10 \times \ln (b_{ext}/.01)$, where b_{ext} is extinction measured in inverse kilometers.

2. Smith and Howell, 2009, used digital projection technology not available at the time of the other studies to present the series of VAQ conditions. Some of the participants in the Smith and Howell study were shown images using a LCD projector connected to a laptop computer. In other sessions, participants in the Smith and Howell study were shown images on a computer monitor connected to the computer.

The first urban visibility preference study was conducted in Denver, Colorado (Ely et al., 1991), and developed the basic survey method used in all the subsequent studies. Although there are variations in specific details in each study, all the studies use a similar overall approach (key variations are discussed in the section on each study later in this paper).

Visibility preference studies consist of a series of group interview sessions, where the participants are shown a set of photographs or images of alternative VAQ conditions and asked a series of questions. The group interview sessions are conducted multiple times with different participants. Ideally the participants are a representative sample of the residents of the metropolitan area. While all studies agree that this is the preferred approach, due to the high cost of organizing and conducting a series of in-person group interviews with a large, statistically representative sample, only the Phoenix study was able to fully meet this objective.

During a group interview session, the participants were instructed to consider whether the VAQ in each photograph or image would meet an urban visibility standard, according to their own preferences and considering three factors:

1. The standard would be for their own urban area, not a pristine national park area where the standards might be more strict

2. The level of an urban visibility standard violation should be set at a VAQ level considered to be unreasonable, objectionable, and unacceptable visually

3. Judgments of standards violations should be based on visibility only, not on health effects.

The photographs (images) are not shown in order of ascending or descending VAQ conditions; the VAQ conditions are shown in a randomized order (with the same order used in each group interview session). In order to check on the consistency of each individual's answers, the full set of photographs (images) shown during the group interview included duplicates with the identical VAQ conditions.

The participants were initially given a set of "warm up" exercises to familiarize them with how the scene in the photographs or image appears under different VAQ conditions. The participants next were shown between 20 and 25 randomly ordered photographs (images), and asked to rate each one based on a Likert-type preference scale of 1 (poor) to 7 (excellent). They were then shown the same photographs or images again (in the same order), and asked to judge whether each of the photographs (images) would violate what they would consider to be an appropriate urban visibility standard (i.e., whether the level of impairment was "acceptable" or "unacceptable").

3. Denver, Colorado Urban Visibility Preference Study

The Denver urban visibility preference study (Ely et al., 1991) was conducted on behalf of the Colorado Department of Public Health and Environment (CDPHE). The study consisted of a series of group interview sessions conducted in 1989 with participants from 16 civic associations, community groups, and employees of state and local government organizations.[3] The participants were not selected to be a statistically representative sample of the Denver metropolitan population, but were rather selected to take advantage of previously scheduled meetings of diverse organizations to reflect different aspects of the Denver area population.

During the 16 group interview sessions, a total of 214 individuals were asked to rate photographs of varying visibility conditions in Denver. The photographs were taken November 1987 through January 1988 by a camera in Thornton, Colorado. Thornton is a suburb of Denver, located approximately six miles north of downtown Denver. The photographs were taken as part of a CDPHE study of Denver's air quality. The scene in the photographs was toward the south from Thornton, and included a broad view of downtown Denver and the mountains to the south. Each group was shown one of two sets of 20 randomly ordered unique photographs (13 of the sessions included 5 duplicate slides, for a total of 25 photographs, to evaluate consistency of responses). The two sets of different slides were used to investigate whether the responses between the two sets of photographs were different (no differences were found). Approximately 100 participants viewed each photograph. Projected color slides were used to present the photographs to focus group participants, and were projected on a large screen.

The VAQ conditions in each Denver photograph were recorded when the photograph was taken and measured by a transmissometer, which measures hourly average total extinction, b_{ext}. The transmissometer was located in downtown Denver, approximately eight miles from the camera and in the middle of the camera's view path. Ely et al. (1991) provide the time of day and measured extinction level for each photograph. The extinction levels presented in the Denver photographs ranged from 30 to 596 Mm^{-1}. Expressed in deciviews, the Denver photographs presented visibility conditions from 11 to 41 dv, approximating the 10th to 90th percentile of wintertime visibility conditions in Denver in the late 1980s.

The participants first rated the VAQ in each photograph on a 1 to 7 scale, and subsequently were asked if each photograph would violate an urban visibility standard. The individual's rating on the 1 to 7 scale and whether the photograph violated a visibility standard were highly correlated (Pearson correlation coefficient greater than 80%).

3. No preference data were collected at a 17th focus group session due to a slide projector malfunction.

The percent of participants who found a photograph acceptable to them (i.e., would meet an appropriate urban visibility standard) was calculated for each photograph. Results of the Denver participants' responses are shown in Figure 1, with VAQ measured in deciviews.

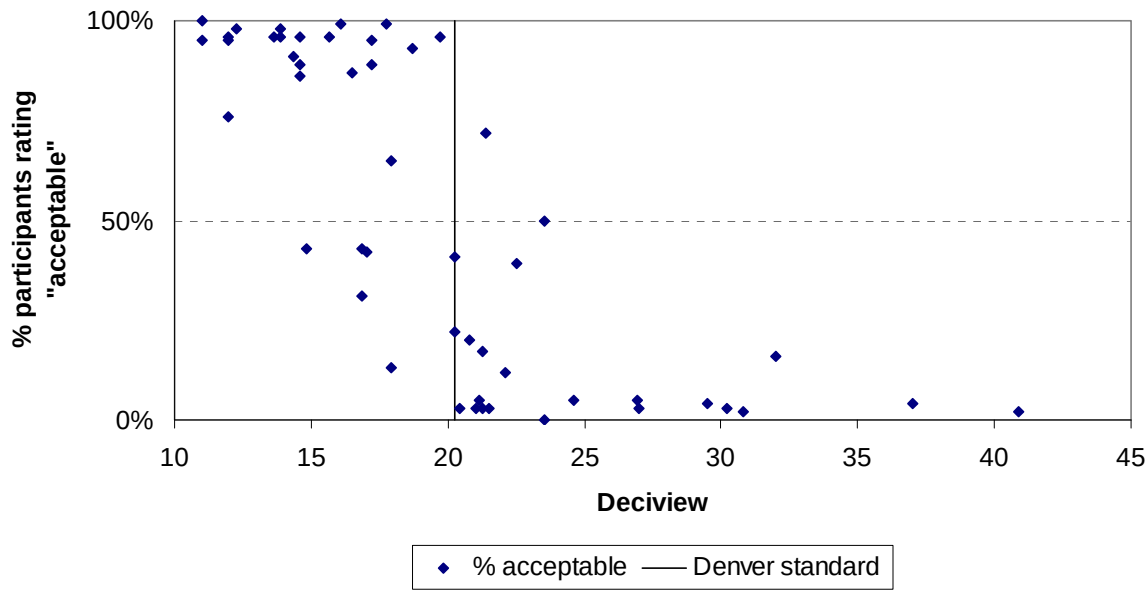

Figure 1. Percent of Denver participants who consider VAQ in each photograph "acceptable."

Ely et al. (1991) introduce a "50% acceptability" criteria analysis of the Denver preference study results. The 50% acceptability criteria is designed to identify the VAQ level that best divides the photographs into two groups; the group of photographs with a VAQ rated as acceptable by the majority of the participants, and the group rated not acceptable by the majority of participants. While no single VAQ level creates a perfect separation between the two groups, the CDPHE identified a VAQ of 20.3 dv as the point that best separates the Denver study responses into "acceptable" and "not acceptable" groups. Based in part on the findings of the Denver visibility preference study, the CDPHE established a Denver visibility standard at b_{ext} = 76 Mm^{-1} (dv = 20.3).

Using 20.3 dv as a 50% acceptability criteria led to six photographs being inconsistently rated by the majority of the viewers. A photograph was inconsistently rated for two possible reasons; the photograph's VAQ was at least 1 dv better than the Denver standard (i.e., dv < 19.3) but was judged to be "unacceptable" by a majority of the participants rating that photograph, or the VAQ was at least 1 dv worse than the standard (dv > 21.3) but found to be acceptable by the majority of the participants. This definition of inconsistent rating helps evaluate the robustness of the

study results to support the selection of the Denver urban visibility standard at 76 Mm^{-1} (20.3 dv) by identifying photographs with VAQ a minimum of 1 dv above or below the standard, and ignoring "near misses" involving photographs within 1 dv of the standard. A change of 1 or 2 dv in uniform haze under many viewing conditions will be seen as a small but noticeable change in the appearance of a scene, regardless of the initial haze condition (U.S. EPA, 2004).

Table 1 presents information about the six photographs that were inconsistently rated.

Table 1. VAQ of Denver photographs inconsistently rated by the majority of participants

Photograph #	VAQ in photograph in extinction (Mm^{-1})	VAQ in photograph (in dv)	% of participants who rated the photo "acceptable"	Time of day of photograph
14	44	13.8	43%	9:00 a.m.
18	54	16.9	43%	9:00 a.m.
19	54	16.9	31%	9:00 a.m.
20	55	17.0	42%	9:00 a.m.
24	60	17.9	13%	9:00 a.m.
36	85	21.4	72%	9:00 a.m.

As shown in Table 1, all six of the inconsistently rated photographs were taken at 9:00 a.m. The five inconsistently rated photographs with a VAQ better than the Denver standard have a VAQ at least 2 dv below the standard. The VAQ in the only inconsistently rated photograph with air quality worse than the standard; Photograph # 36 is 1.1 dv above the standard. The study used 18 photographs from 9:00 a.m., so a third of the 9:00 a.m. photographs were inconsistently rated. Conversely, none of the 32 photographs taken at noon or 3:00 p.m. were inconsistently rated.

Figure 2 shows the same Denver data on the percent of participants who rated each photograph acceptable as in Figure 1, but with the time of day of each photograph indicated by different colors. The time of day colors clearly indicate how inconsistently participants rated some of the 9:00 a.m. photographs.

Eliminating the 9:00 a.m. photographs creates a "hole" in the range of remaining photographs; there are no photographs with a dv between 17.7 dv and 20.3 dv. As seen in Figure 2, this is a critical range in evaluating the responses. All of the photographs with a VAQ equal to or better (i.e., a lower dv value) than 17.7 dv are rated acceptable by the majority of the participants, and all photographs with a VAQ at or above 20.3 dv are rated not acceptable. After eliminating the 9:00 a.m. photographs, any VAQ level between 17.7 and 20.3 dv would completely divide the photographs into two groups with no inconsistent ratings.

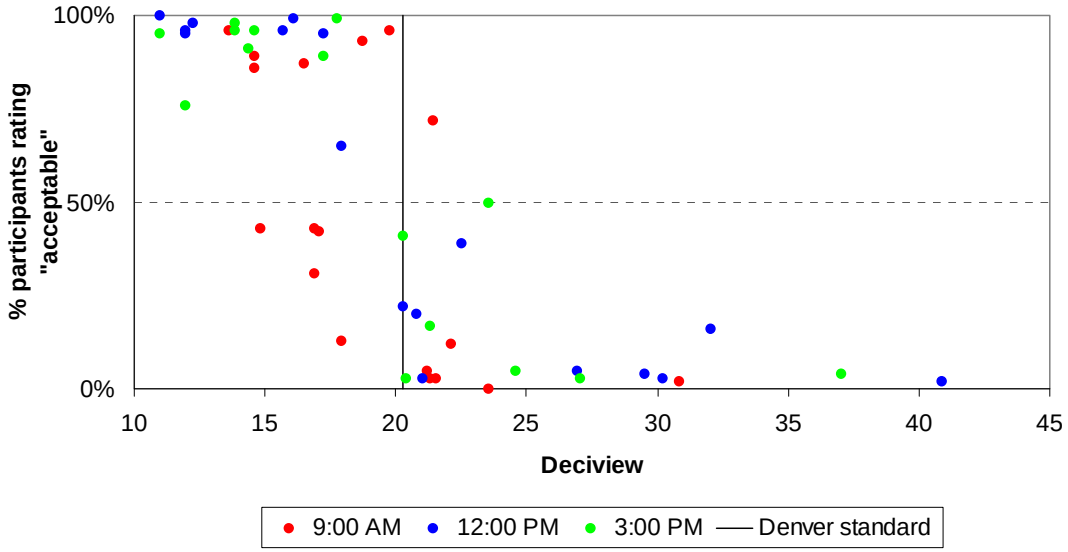

Figure 2. Denver photograph time of day information for the percent of participants who consider VAQ in each photograph "acceptable."

A modestly broader range of VAQ conditions provides an even more unambiguous interpretation of the Denver study results. Every photograph with a VAQ of 17.7 dv or lower was rated acceptable by 89% or more of the participants, and every photograph with a VAQ of 24.6 or higher was rated not acceptable by 84% or more of the participants. The 17.7 dv to 24.6 dv range separating the results is shown in Figure 3 (which also eliminates the 9:00 a.m. results).

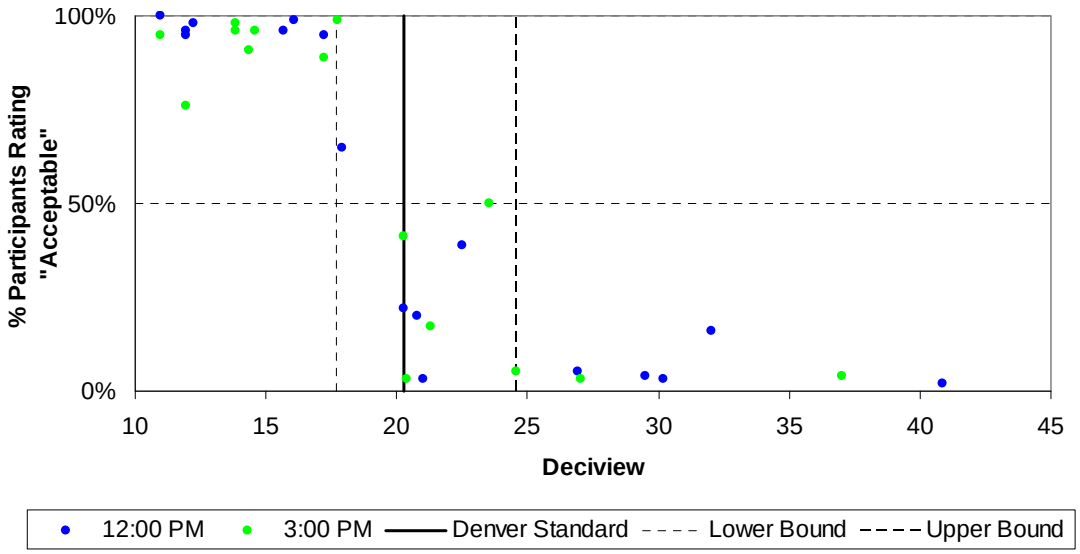

Figure 3. Denver photograph time of day results (9:00 a.m. photographs eliminated), with the broader range (17.7 dv and 24.6 dv) of the 50% acceptability criteria shown.

4. Vancouver, British Columbia, Canada Urban Visibility Preference Study

The BC urban visibility preference study (Pryor, 1996) was conducted on behalf of the BC Ministry of Environment. The BC study conducted focus group sessions that were also developed following the methods used in the Denver study. Participants were students at the University of British Columbia, who were in one of four focus group sessions with between 7 and 95 participants. A total of 180 participants completed the surveys (29 did not complete the survey).

The BC study was conducted using photographs (projected as slides) depicting various VAQ conditions in two cities (Chilliwack and Abbotsford) in the lower Fraser River valley in southwestern BC. Abbotsford is located approximately 75 miles east of Vancouver, with approximately 25% of the labor force working in the Vancouver metropolitan area. Chilliwack is adjacent to Abbotsford to the east. Both cities have experienced rapid population growth, growing faster than the Vancouver metropolitan area, and are considered suburbs (or exurbs) of Vancouver.

The survey was conducted at the University of British Columbia (UBC) in 1994. The participants were 206 undergraduate and graduate students enrolled in classes in UBC's Department of Geography. Information about student demographics and where they lived prior to enrolling at UBC (which potentially influences their knowledge of, and preferences for, Vancouver area visibility) are not available.

The BC survey showed 20 unique photographs to the participants in random order. Ten photographs were from Chilliwack and 10 were from Abbotsford. The Chilliwack photographs were taken at the Chilliwack Hospital, and the scene includes a complex foreground with downtown buildings, with mountains in the background up to 40 miles away. Figure 4 is a composite of two of the Chilliwack photographs used in the preference study, showing the scene with a good visibility day (14.1 dv) in the middle, and a significantly impaired day (34 dv) around the border (Jacques Whitford AXYS, 2007). The Abbotsford photographs were taken at the Abbotsford Airport. The Abbotsford scene includes fewer man-made objects in the foreground, and is primarily a more rural scene with the mountains in the background up to 36 miles away.

Figure 4. Composite Chilliwack, BC photograph showing VAQ of 14.1 dv and 34 dv.

The photographs were taken in July and August 1993 as part of a VAQ and fine particulate monitoring project sponsored by the BC Ministry of Environment, Lands and Parks (REVEAL, the Regional Visibility Experimental Assessment in the Lower Fraser Valley). All of the photographs were taken at either 12:00 p.m. or 3:00 p.m. VAQ data were available for each photograph from visibility monitors near the location of each camera. The type of VAQ measurement data available from the two locations were not identical. The Chilliwack location used both an open-chamber nephelometer and a long path transmissometer, and collected hourly average data on both aerosol light scattering (b_{sp}) and total extinction (b_{ext}), respectively. The visibility monitoring Abbotsford location had only a nephelometer, and collected only b_{sp} data.

Aerosol light scattering is a component of total extinction, but does not measure other components of total extinction. Total light extinction is the sum of scattering by gases (b_{sg}, known as Rayleigh scattering with an assumed constant level of 10 Mm^{-1}) and particles (b_{sp}) plus light absorption by gases (b_{ag}) and particles (b_{ap}). In order to present the preference results from both cities in the BC study in comparable terms, b_{ext} for each Abbotsford photograph is estimated using the average ratio $(b_{ext}-b_{sg})/b_{sp}$ from all 10 Chilliwack photographs to estimate b_{ext} in the Abbotsford photographs. Estimated b_{ext} in each Abbotsford photograph is calculated by

multiplying the average ratio from Chilliwack (average ratio = 1.476) by the measured b_{sp} in each Abbotsford photograph, and adding b_{ag} to estimate $b_{ext.}$ Table 2 presents the data from the photographs used in the BC study, including the estimated b_{ext} for the Abbotsford photographs.

Table 2. Summary of photographs used in British Columbia study

Date	Time	b_{sp}	b_{ext}	Ratio $(b_{ext}-b_{sg})/b_{sp}$	Estimated b_{ext}	Deciview
Chilliwack						
7/26/93	12:00 p.m.	86	128	1.372	NA	25.49
7/26/93	3:00 p.m.	67	112	1.522	NA	24.16
7/27/93	12:00 p.m.	63	105	1.508	NA	23.51
7/27/93	3:00 p.m.	119	185	1.471	NA	29.18
8/2/93	12:00 p.m.	18	37	1.5	NA	13.08
8/2/93	3:00 p.m.	20	36	1.3	NA	12.81
8/5/93	12:00 p.m.	45	70	1.333	NA	19.46
8/5/93	3:00 p.m.	51	96	1.686	NA	22.62
8/19/93	12:00 p.m.	46	81	1.543	NA	20.92
8/19/93	3:00 p.m.	105	170	1.524	NA	28.33
Average		*62*	*102*	*1.476*		*21.96*
Abbotsford						
7/26/93	12:00 p.m.	39	NA	NA	68	19.17
7/26/93	12:00 p.m.	82	NA	NA	131	25.73
7/27/93	12:00 p.m.	104	NA	NA	205	30.20
7/27/93	3:00 p.m.	132	NA	NA	164	27.97
8/2/93	12:00 p.m.	24	NA	NA	45	15.04
8/2/93	3:00 p.m.	25	NA	NA	47	15.48
8/5/93	12:00 p.m.	62	NA	NA	121	24.93
8/5/93	3:00 p.m.	75	NA	NA	102	23.22
8/19/93	12:00 p.m.	67	NA	NA	224	31.09
8/19/93	3:00 p.m.	145	NA	NA	109	23.89
Average		*76*			*122*	*23.67*

There are two caveats to be noted about the extinction data for the photographs reported in Pryor (1996). First, in Table 2 of the original article, two of the Abbotsford photographs are listed with the same date and time (12:00 p.m., 7/26/1993), but different b_{sp}. There is no information provided for a 3:00 p.m., 7/26/1993 Abbotsford photograph, although there is a Chilliwack photograph from that time. The preference and VAQ data for these two Abbotsford photographs are assumed to be correct for both photographs, and one of the two date or time labels is assumed to be a typographical error. The second caveat is that b_{sp} levels from the same date and time can

differ substantially between Abbotsford and Chilliwack, and the relative levels can change rapidly, even though the two cities are only 25 miles apart. For example, at 12:00 p.m. on 8/19/1993, the b_{sp} level in Chilliwack was about one-third of the Abbotsford b_{sp} level. By 3:00 p.m. the situation was reversed, with the Chilliwack b_{sp} level 50% higher than Abbotsford. In those three hours the Chilliwack b_{sp} level had over doubled (from 46 Mm^{-1} to 105 Mm^{-1}), and the Abbotsford level had fallen by over half (from 145 Mm^{-1} to 67 Mm^{-1}). Such substantial changes in measured b_{sp} levels occurring across a relatively short period of time and short distance, may reflect an inherent uncertainty introduced by using a single measure of light extinction from a portion of visual scene (where the nephelometer or transmissometer was operating) to assess visibility conditions throughout an actual photographs of a complex scene. Spatial and temporal non-uniformity of visibility conditions within a scene are an atmospheric condition known to occur on some days, and may contribute to the variability in participant responses in preference studies utilizing actual photographs.

Figure 5 presents the results of the BC study. The division corresponding to the Denver "50% acceptable" criteria occurs between 22.6 and 23.5 dv. All of the photographs with a VAQ lower than 22.6 dv were rated acceptable by the majority of the participants with one exception (47% of the participants judged the 19.0 dv photograph to be acceptable). All photographs with a VAQ above 20.9 dv were rated acceptable by over 90% of the participants. All photographs with a VAQ above 23.5 dv were rated not acceptable the majority of the participants, and all photographs with a VAQ above 28.3 dv were rated not acceptable by over 90% of the participants.

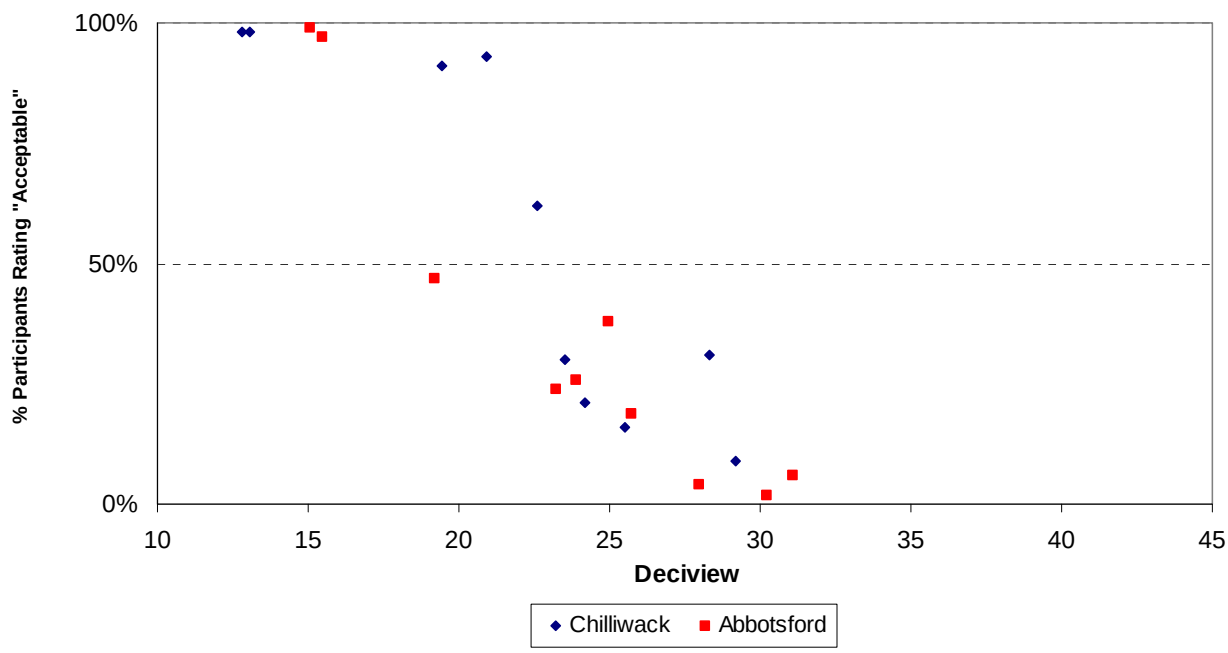

Figure 5. Percent of BC participants who consider VAQ in each photograph "acceptable."

Figure 5 also suggests that there may be some difference between the preferences expressed about the Chilliwack scene than for the Abbotsford scene. All photographs were rated by the same individuals (students at UBC), but the summary of the responses indicate that the participants may have rated as acceptable a worse level of impaired VAQ impairment (e.g., higher dv levels) in photographs showing more of a downtown area (Chilliwack) than in a more rural scene (Abbotsford). The strongest evidence for this hypothesis, however, is the expressed preferences for a single photograph (the 19.0 dv photograph from Abbotsford, rated as acceptable by 47%), previously identified as a possible outlier observation.

The BC urban visibility preference study is being considered by the BC Ministry of the Environment as part of establishing urban and wilderness visibility goals in BC (RWDI AIR, 2008).

5. Phoenix, Arizona Urban Visibility Preference Study

The Phoenix urban visibility preference study (BBC Research & Consulting, 2003) was conducted on behalf of the Arizona Department of Environmental Quality. The Phoenix study used a group interview method based on the Denver study with two notable differences:

1. The focus group participants were selected as a representative sample of the Phoenix area population

2. The pictures presented in the focus groups were computer-generated images to depict specific uniform haze conditions.

The Phoenix study included 385 participants in 27 separate focus group sessions. Participants were recruited using random digit dialing to obtain a sample group designed to be demographically representative of the larger Phoenix population. During July 2002, group interview sessions were held at six neighborhood locations throughout the metropolitan area to improve the participation rate. Participants received $50 as an inducement to participate.

Three sessions were held in Spanish in one region of the city with a large Hispanic population (25%), although the final overall participation of native Spanish speakers (18%) in the study was below the targeted level. The age distribution of the participants corresponded reasonably well to the overall age distribution in the 2000 U.S. Census for the Phoenix area (BBC Research & Consulting, 2003). Participants slightly over-represented the middle-income range ($50,000 to $74,999) compared with 2000 Census data, and slightly under-represented very low-income

ranges (under $24,999). The distribution of participant education levels were fairly consistent with the education distribution in the 2000 Census.

Photographic-quality images were developed from an original Phoenix photograph using the WinHaze software program. The scene used in the Phoenix study images was taken at a water treatment plant. The view is toward the southwest, including downtown Phoenix, with the Sierra Estrella Mountains in the background at a distance of 25 miles. The WinHaze image with the best VAQ (15 dv) is reproduced in Figure 6.

Figure 6. Reproduction of the WinHaze image with the best VAQ (15 dv) used in the Phoenix study.

A total of 21 unique WinHaze images were used in the study. Four of the 21 unique images were randomly selected and used twice to evaluate consistency; participants viewed a total of 25 images. The 25 images were randomly ordered, with all participants viewing the images in the same order. The WinHaze images used in the Phoenix study do not include layered haze, a frequent and widely recognized form of visibility impairment in the Phoenix area.

The VAQ levels in the 21 unique images ranged from 15 to 35 dv (the extinction coefficient b_{ext} range was 45 Mm^{-1} to 330 Mm^{-1}). As in the Denver study, participants first individually rated the randomly shown slides on a VAQ scale of 1 (unacceptable) to 7 (excellent). Participants were instructed to rate the photographs solely on visibility, and to not base their decisions on either health concerns or what it would cost to have better visibility. Next, the participants individually rated the randomly ordered slides as “acceptable” or “not acceptable,” defined as whether the visibility in the slide is unreasonable or objectionable.

Figure 7 presents the percent acceptability results from the Phoenix study. The combination of the use of evenly spaced (the VAQ in the images differed by 1 dv) WinHaze images and the larger number of participants than any other study may account for the "smoother" pattern of preferences found in the study.

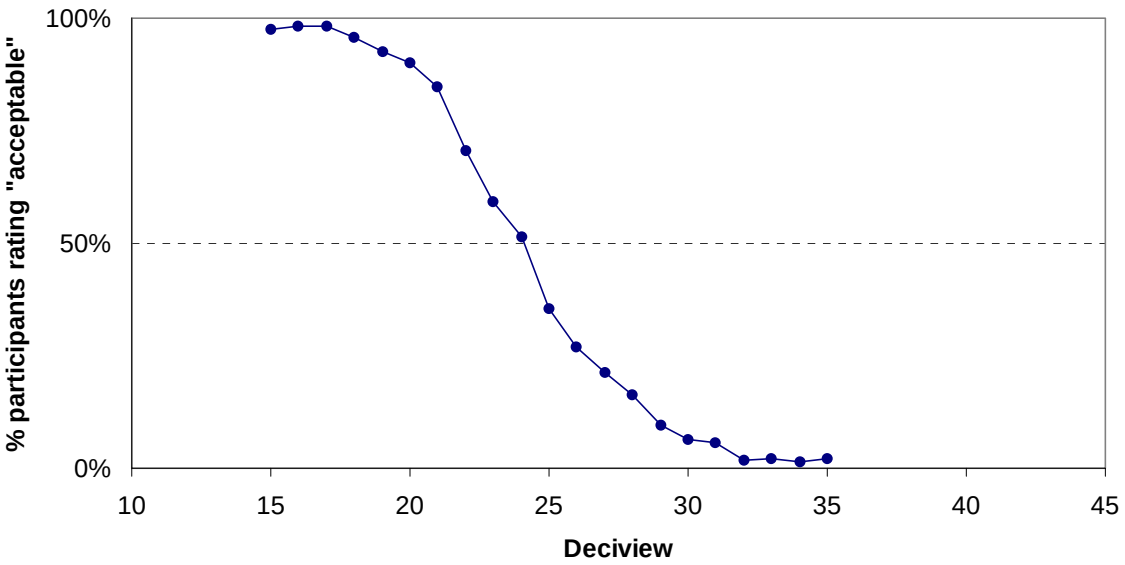

Figure 7. Percent of Phoenix participants who consider VAQ in each image "acceptable."

A VAQ of 20 dv or better was rated acceptable by 90% or more of the participants, and 70% rated a VAQ of 22 dv or better as acceptable. The "50% acceptable criteria" was met at 24 dv (with 51.3% of the participants rating that image as acceptable). The percent acceptability declines rapidly as VAQ worsens; only 27% of the participants rated a 26 dv image as acceptable, and fewer than 10% rated a 29 dv image as acceptable.

The Phoenix urban visibility study formed the basis of the decision of the Phoenix Visibility Index Oversight Committee for a visibility index for the Phoenix metropolitan area (Arizona Department of Environmental Quality, 2003). The Phoenix Visibility Index establishes five categories of visibility conditions, ranging from "Excellent" (14 dv or less, which was a better VAQ than any of the images used in the Phoenix study) to "Very Poor" (29 dv or greater, which less than 10% of the study participants rated as acceptable). The "Good" range is 15 to 20 dv (more than 90% of the participants rated images in this VAQ range as acceptable). The environmental goal of the Phoenix urban visibility program is to achieve continued progress through 2018 by moving the number of days in poorer quality categories into better quality categories.

6. Washington, DC Urban Visibility Pilot Preference Studies

One of the Washington, DC urban visibility pilot studies (Abt Associates, 2001) was conducted on behalf of EPA. It was designed to be a pilot focus group study, an initial developmental trial run of a larger study. The intent of this pilot focus group study was to explore, examine, and refine both the group interview method design and potential survey questions. Due to funding limitations, only a single focus group session was held, consisting of one extended session with nine participants. No further urban visibility focus group sessions were held in Washington, DC on behalf of EPA.

In March 2009, Dr. Anne Smith conducted a separate study of Washington urban visibility, using the same photographs and similar approach as the 2001 study (Smith and Howell, 2009) conducted for the Utility Air Regulatory Group (UARG). Dr. Smith presented comments (Smith, 2009) to the Clean Air Science Advisory Committee (CASAC) at a public meeting held April 2, 2009 to review EPA's plans for conducting further urban visibility studies in support of the PM NAAQS (U.S. EPA, 2009). Dr. Smith submitted the Smith and Howell (2009) report to the CASAC as part of the public comment process. The Smith and Howell study conducted three variations of a Washington, DC preference study, including one experiment involving 26 participants designed to replicate the EPA 2001 preference study.

Both the EPA 2001 study results and the results of the Smith and Howell (2009) study are discussed below.

EPA 2001 Washington, DC urban visibility preference study (Abt Associates, 2001)

EPA's Washington, DC study adopted the general study methods used in the Denver, BC, and Phoenix studies, modifying them appropriately to be applicable in an eastern urban setting. Washington's (and the entire East's) current visibility conditions are often worse than western cities, and have different characteristics. Washington's visibility impairment is primarily a uniform whitish haze dominated by sulfates, and the relative humidity levels are higher. Many residents are not well informed that anthropogenic emissions impair visibility on hazy days. In addition, the relatively low-lying terrain[4] in Washington, DC provides substantially shorter maximum sight distances.

4. The maximum elevation in Washington, DC is 409 feet.

The Washington focus group session included questions on valuation, as well as on preferences. The focus group content dealing with preferences for an urban visibility standard was similar to the focus group sessions in the Denver, BC, and Phoenix studies.

A single scene of a panoramic photograph taken from Arlington National Cemetery in Virginia was used, and included an iconic view of the Potomac River, the Washington Mall, and downtown Washington, DC. All of the distinct buildings in the scene are less than four miles from the camera, and the higher elevations in the background are less than 10 miles from the camera. The original photograph used in the study is presented in Figure 8.

Figure 8. Reproduction of the image with the best VAQ (8.8 dv) used in the Washington, DC study.

The Washington, DC study used 20 unique images generated by WinHaze, each prepared from the same original photograph. Humidity and gaseous light scattering was held constant in preparing the WinHaze images, as was the relative chemical mix of aerosol particulates in the photos (i.e., only the aerosol concentrations were increased to create the images with worse VAQ). Five of the images were randomly selected to be used twice as a consistency check, so participants viewed a total of 25 slides.

The range of VAQ in the images ranged from 8.8 to 38.3 dv, which is approximately the 10th to the 90th percentile of the annual distribution of hourly VAQ conditions in Washington, DC.

Figure 9 presents the percent acceptability results from the 2001 Washington, DC study. Because only nine participants were involved in the study, the possible values of "percent acceptable" are limited to multiples of 1/9. Figure 9 also shows an anomalous result involving one of the five repeated images. Three of the repeat images had the same ranking each time they were presented (i.e., all nine participants rated them acceptable or not acceptable both times they rated that slide). One of the images (the image with 8.8 dv, the best VAQ image used in the study) was rated acceptable by all nine participants the first time it was used, but the repeat of that slide was rated not acceptable by one participant. Another image, however, had a substantially different result. The 30.9 dv image was rated acceptable by five of the nine participants the first time it was presented, but the repeat of the slide was only rated acceptable by one of the nine participants. The responses for all five pairs of repeated images are shown in red on Figure 9, including the images which were identically rated both times they were presented.

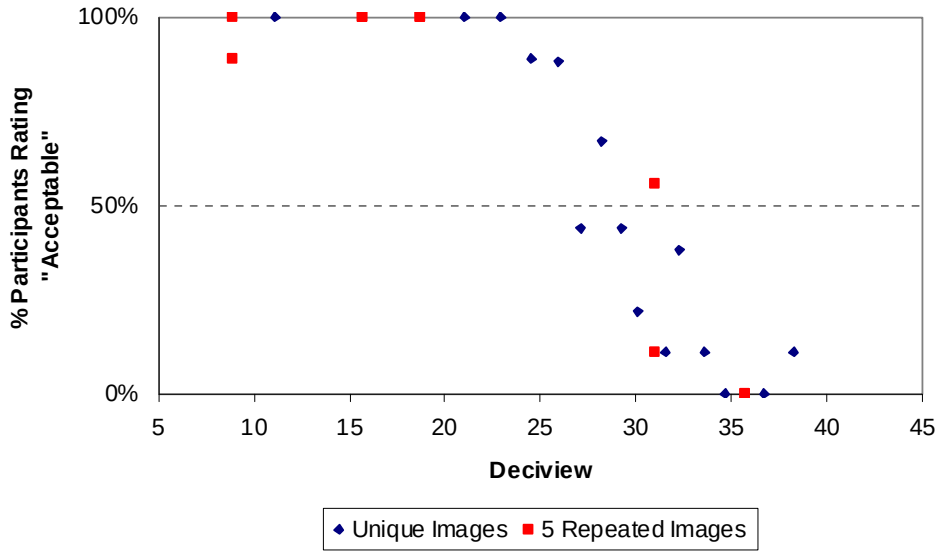

Figure 9. Percent of 2001 Washington, DC participants who consider VAQ acceptable in each image.

In the 2001 Washington, DC study, all images with a VAQ below 25.9 dv were rated acceptable by the majority of the participants, and all images with a VAQ below 29.2 dv were rated acceptable by at least four of the nine (44%) participants. All images with a VAQ above 30.9 dv were rated not acceptable. The "50% acceptability criteria" division occurs in the range of 25.9 dv to 30.9 dv, with the anomalous result of the inconsistent responses to the repeated image with 30.9 dv effectively broadening this range and adding uncertainty to identifying a clear division.

2009 Washington, DC urban visibility preference study (Smith and Howell, 2009)

The Smith and Howell (2009) study conducted additional focus group sessions based on the methods and materials used in the 2001 Washington, DC study. Smith and Howell recreated the WinHaze images used in the 2001 Washington, DC urban visibility preference study, using the description in the report on the 2001 study (Abt Associates, 2001), and created images using currently available desktop computer version of WinHaze (Version 2.9.0). Smith and Howell used a shortened version of the same question protocol as the 2001 study. The WinHaze images were presented to a total of 64 participants who were all employees of CRA International, Inc. (Smith and Howell also are CRA International employees). The CRA employees were based at the firm's Washington, DC and Houston, Texas offices (44 and 20 participants, respectively). The Houston participants were included to explore whether familiarity with Washington, DC VAQ conditions developed from currently living in the Washington region noticeably influenced the responses. As noted by Smith and Howell, the participants were not a representative sample of either metropolitan area's population; all participants were employed and the participant group included a higher proportion of college educated individuals and higher household incomes than the general population.

Eight of the Washington-based participants, and all of the Houston participants, viewed the WinHaze images on a desktop computer monitor. The remaining Washington participants viewed the images projected on a screen using an LCD projector connected to a computer.

The stated purpose of the Smith and Howell study was to explore the robustness of the 2001 results. To investigate this issue, Smith and Howell conducted three different tests concerning urban visibility preferences. Each participant was involved with only one test. Test 1 was designed to replicate the 2001 study. Test 2 reduced the upper end of the range of VAQ by eliminating the 11 images used in Test 1 with a VAQ above 27.1 dv. Test 3 increased the upper end of the range of VAQ by including two new images of worse VAQ; the two new images had a dv of 42 and 45.

Sixteen employees from the Washington, DC office and 10 participants from the Houston office took Test 1 (a total of 26 participants). All the participants were shown the same unique 20 Washington, DC WinHaze images as the 2001 study (plus repeated images for a total of 25 images shown to participants). Images were presented in the same random order as in the 2001 study. Figure 10 presents the results of Test 1. The results for the 16 Washington, DC participants are indicated in blue, and results for the 10 Houston participants in red. Although all images used in the study were of Washington, DC, the results suggest that there is not a significant difference in the preferences of participants based in the two offices. The scene in the images is an immediately recognizable iconic view of the National Mall and downtown Washington, DC, which may influence the similarity of responses by residents of the two cities.

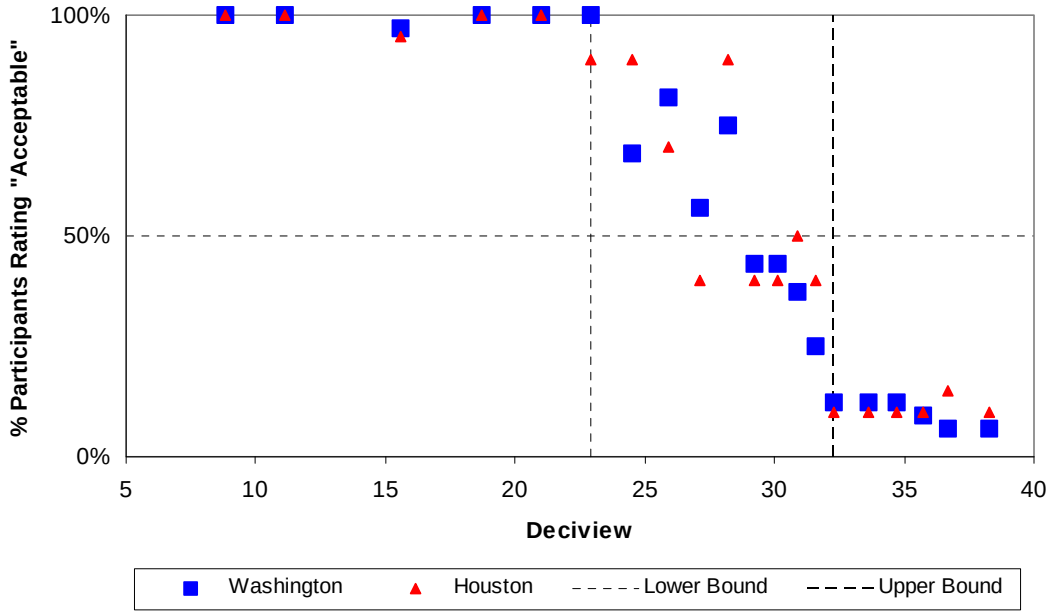

Figure 10. Percent of 2009 Test 1 study participants who consider VAQ acceptable in each image, showing the range of the lower and upper bound of 50% acceptability criteria.

Source: Smith and Howell, 2009. Acceptability response for the two repeated images (15.6 and 35.7 dv) with different responses are depicted as the average of the two responses. Total participants: 26.

Using the combined Test 1 results from the two CRA offices (26 total participants), the majority of participants in the 2009 study rated all VAQ images with 25.9 dv or less as acceptable, and all VAQ images with 29.2 dv or greater as not acceptable. The image of 27.1 dv was rated as acceptable by 50% of the total participants (56% of the Washington-based and 40% of the Houston-based participants). All images with a VAQ less than 22.9 dv were rated acceptable by at least 90% of the participants, and all images with a VAQ greater than 32.3 dv were rated not acceptable by 88% of the participants.

Figure 11 presents the 2001 and 2009 study (Test 1) results on a single graph, representing the results of 35 total participants of preferences for urban visibility in Washington, DC. The results from the 2009 study on Figure 10 combine the Test 1 responses from the two CRA offices. Figure 11 also shows the 50% acceptability criteria range (22.9 dv to 32.3 dv) from the 2009 study, Test 1. In comparison, the 2001 study 50% acceptability range was 25.9 dv to 30.9 dv. The results in Figure 10 indicate that the results from the 2009 study (Test 1) are not appreciably different than the results of the 2001 Washington study.

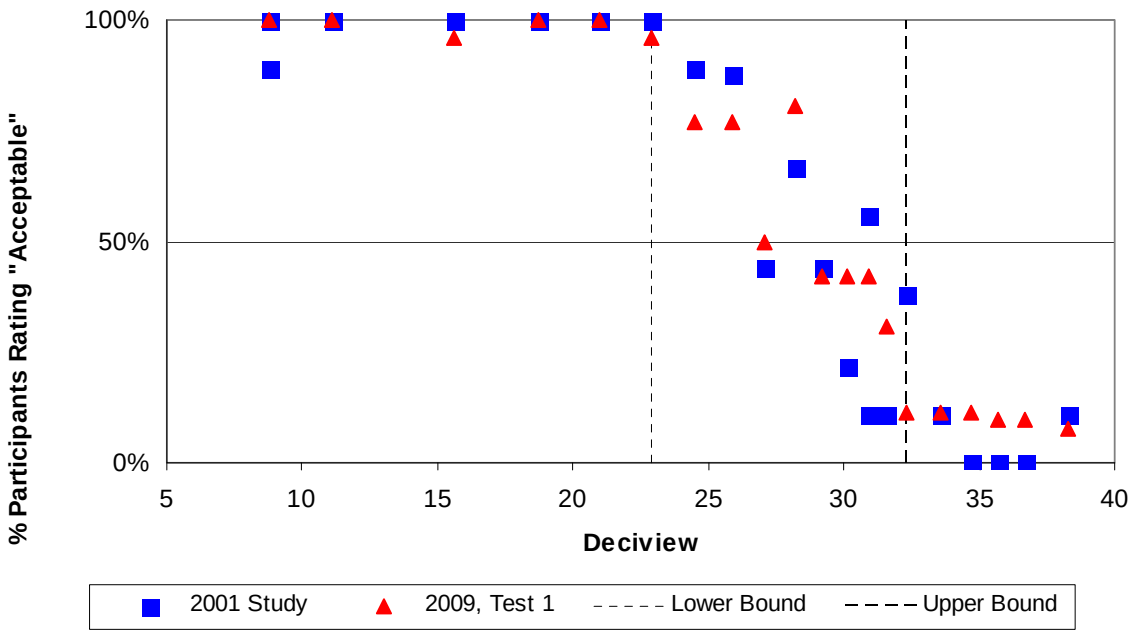

Figure 11. Combined results of two comparable Washington, DC preference studies (showing 50% acceptability criteria from 2009, Test 1).

In Test 2, Smith and Howell reduced the range of VAQ images presented to 26 participants to images with a VAQ of 27.1 dv or less. The 26 participants were different people than the Test 1 participants. Test 2 presented only the nine unique clearest WinHaze images from the full Test 1 set of 20 images. This constricted the VAQ levels presented to the range that the majority of participants in the 2001 study rated as acceptable, and reduced the upper end of the VAQ range by 11.2 dv. Nine unique WinHaze images were used in Test 2, with three duplicates included, so Test 2 participants were shown 12 images. Figure 12 presents the Test 1 and Test 2 results. Test 2 found a substantial shift in the responses about which VAQ level is considered acceptable. The smaller number of images used in Test 2 makes identifying the range of the 50% acceptability criteria more difficult than in Test 1. The lower bound of the range occurs between 15.6 and 18.7 dv, and the upper bound occurs between 24.5 and 27.1 dv. Smith and Howell conclude that the shift in the acceptability responses between Test 1 and Test 2 suggests that the acceptable responses in an urban visibility preference study conducted using the general approach used in the all the studies may be susceptible to the range of VAQ images presented.

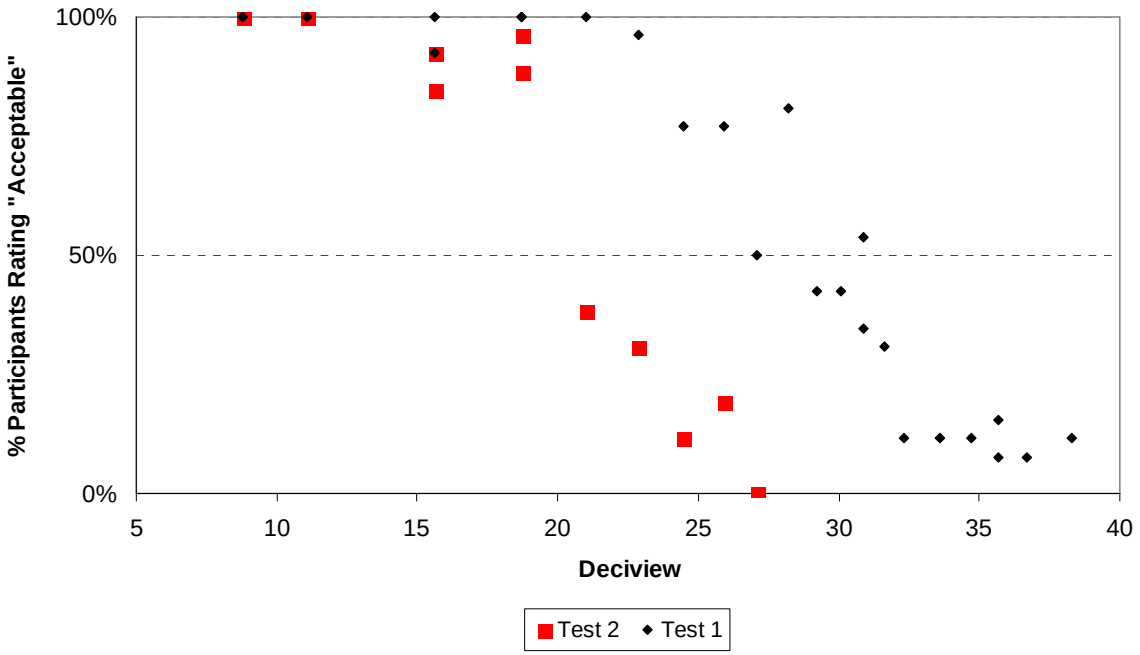

Figure 12. Comparison of results from the Washington, DC 2009 study, Test 1 and Test 2.

One hypothesis (not raised by Smith and Howell) suggested by the Test 2 results is that the 50% acceptability criteria occurs near the middle of the range of images shown to participants. This might be the result of the participants consciously or subconsciously identifying approximately the middle of the VAQ range presented to them. Participants become familiar with the VAQ range during the "warm up exercises," and consciously or subconsciously calibrate their subsequent responses to the VAQ range they were presented.

In Test 3, Smith and Howell expanded the VAQ range of WinHaze images shown to the participants, including two new images with a worse VAQ. The new images had a VAQ of 42 dv and 45 dv, raising the upper end of the VAQ range by 6.7 dv. Test 3 reduced the total number of images shown to participants to 19 images by eliminating the use of the five repeat images in Test 1, and also eliminated three additional images in order to reduce the participants' time burden. The three deleted images had a VAQ of 11.1, 15.6, and 24.5 dv, respectively. The best VAQ image shown to Test 3 participants was 8.8 dv (same as the best VAQ image in Tests 1 and 2). However, in Test 3 there were no images with VAQ between 8.8 dv and 18.7 dv, creating a significant "hole" in the distribution of VAQ conditions presented to the Test 3 participants.

Test 3 was conducted with 12 participants from the CRA Washington office (none of whom participated in Test 1 or Test 2). No Houston participants were involved with Test 3. The results of Test 3 are shown in Figure 13, along with the results of Test 1.

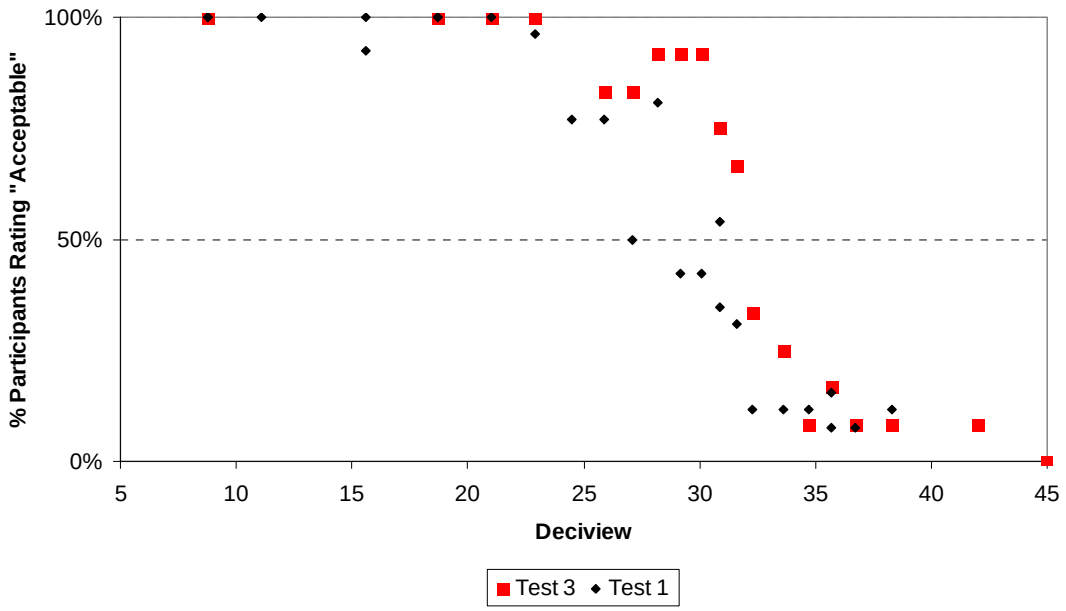

Figure 13. Comparison of results from the Washington, DC (2009) Test 1 and Test 3.

Increasing the upper end of the VAQ range in Test 3 resulted in an overall increase in the percent of respondents rating as acceptable the VAQ images used in both tests. In Test 3 all images with a VAQ below 22.9 dv were rated acceptable by 100% of the participants (to the same as the Test 1 results), implying there was no general change in the acceptability of the images with good VAQ. However, for all VAQ images (that were used in both studies) between 25.9 dv and 33.6 dv, a noticeably larger percentage of the participants in Test 3 rated the image as acceptable than in Test 1. At VAQ levels worse than 33.6 dv, the majority of the participants found the VAQ level not acceptable in both tests.

While not as dramatic as the impact in Test 2 (which substantially reduced the VAQ range), the impact of increasing the VAQ range in Test 3 supports Smith and Howell's conclusion that changing the range of VAQ presented to the participants affects the responses about whether a particular VAQ is acceptable. Test 3 also supports the hypothesis that the "dividing line" for the 50% criteria occurs near the middle of the range of VAQ presented, and that changing the range of VAQ images changes the 50% criteria "dividing line," with the "dividing line" remaining in roughly the middle of the VAQ range.

The VAQ ranges that Smith and Howell used in Tests 2 and 3 did not span the range of actual VAQ conditions that occur in Washington, DC, and Smith and Howell provided no information about the range of actual conditions in Washington in any of their tests. The images used in the 2001 Washington, DC study (and Test 1) were deliberately selected to present the range of VAQ conditions in Washington, DC. In the 2001 study, participants were shown an image of annual average VAQ in Washington at the time, as well as an image of conditions on a hazy day (the 20th percentile day in the annual distribution). The Denver, Phoenix, and BC studies also provided participants with information that the range of VAQ conditions they would be seeing included the actual annual range of VAQ conditions in their city. It is not known whether the participants in the Smith and Howell Tests 2 and 3 recognized (based on their own knowledge and experience) that the range of VAQ images presented did not represent the actual annual range, or if they believed the range did depict the annual distribution.

7. Summary of Preference Studies in Four Cities

Each of the studies reviewed in this report investigate the common question, "What level of visibility degradation is acceptable?" The approach used in the four studies is similar, and are all developed from the method first developed for the Denver urban visibility study. The specific materials and methods used in each study vary, however, making direct comparison of the study results challenging. Key differences between the studies include:

1. The use actual photographs or WinHaze images

2. The number of participants in each study

3. How well the participants portray a representative sample of the general population of the relevant metropolitan area

4. The specific wording used to frame the questions used in the group interview process.

Although the differences between the methods used in the urban visibility preference studies are significant, it is possible to examine the results of the studies to identify overall trends in the study findings. Figure 14 present a graphical summary of the results of the studies in the four cities. Figure 14 draws on results previously presented in Figures 2, 4, 6, and 9. For clarity in Figure 14, the Denver results omit the 9:00 a.m. photograph results, the Chilliwack and Abbotsford photographs are presented as a single set of data for the BC study, and the results from 2001 and 2009 (Test 1) studies of VAQ preferences in Washington, DC are presented as a single combined set of data. The results from the 2009 Washington, DC study Tests 2 and 3 are not included on Figure 14; those tests are not comparable studies because they did not present the actual range of VAQ conditions in the study city.

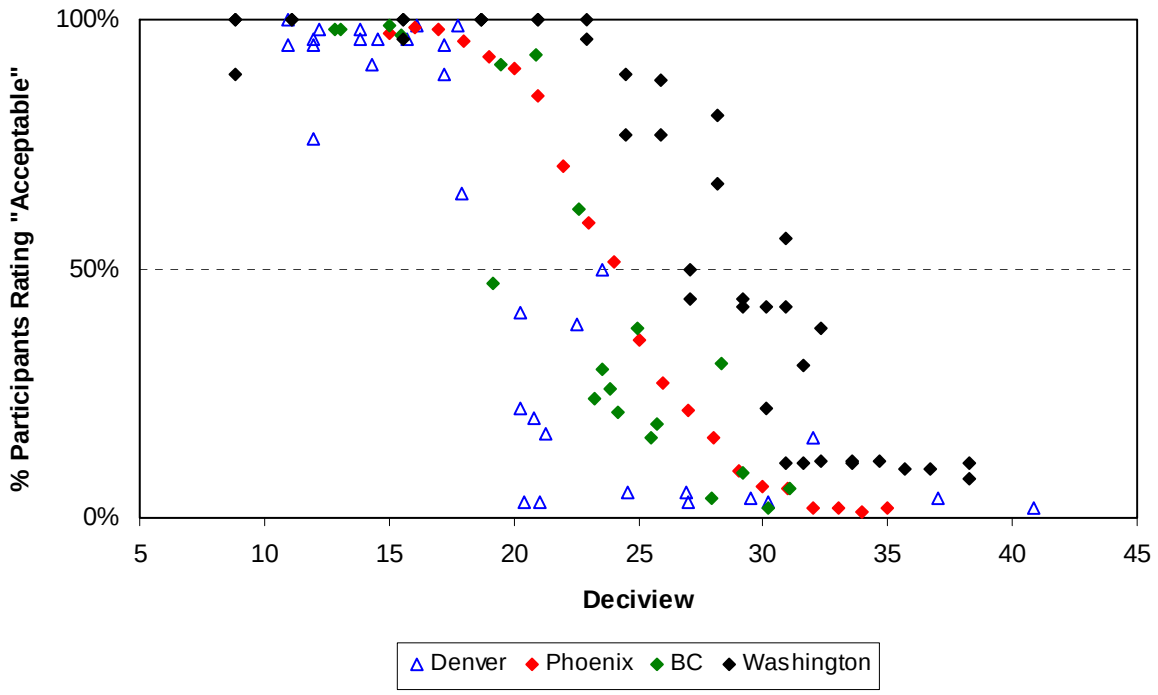

Figure 14. Summary of results of urban visibility studies in four North American cities.

Discussion

Figure 14 shows that while there is a considerable amount of similarity between the preferences found in each study, the figure suggests that there may be important differences in VAQ preferences in the four cities as well. For example, the Denver study identified preferences for a relatively good level of VAQ; the 50% criteria separating the preferences for acceptable and not acceptable occurs between 17.7 and 20.3 dv. In Washington, DC, however, the 50% criteria separation occurs at a substantially worse level of VAQ, between 27 and 31 dv.

Drawing conclusions about the similarity and differences in the results of the studies is difficult, largely due to the substantial differences in specific methods and materials used in each study. The use of actual photographs or WinHaze-generated images is a substantive difference in the materials used in the different studies. There are substantial differences in the number of participants, ranging from 35 in the combined Washington, DC studies to 385 in the Phoenix study, as well as important issues with how well the participants in each study are a representative sample of the general population of the city.

Figure 15 includes vertical lines drawn at 20 to 30 dv, which effectively and pragmatically identifies a range where the 50% acceptance criteria occurs. Out of the 114 data points shown in Figure 14, only one photograph (or image) with a VAQ below 20 dv was rated as acceptable by less than 50% of the participants who rated that photograph.[5] Similarly, only one image with a VAQ above 30 dv was rated acceptable by more than 50% of the participants who viewed it.[6]

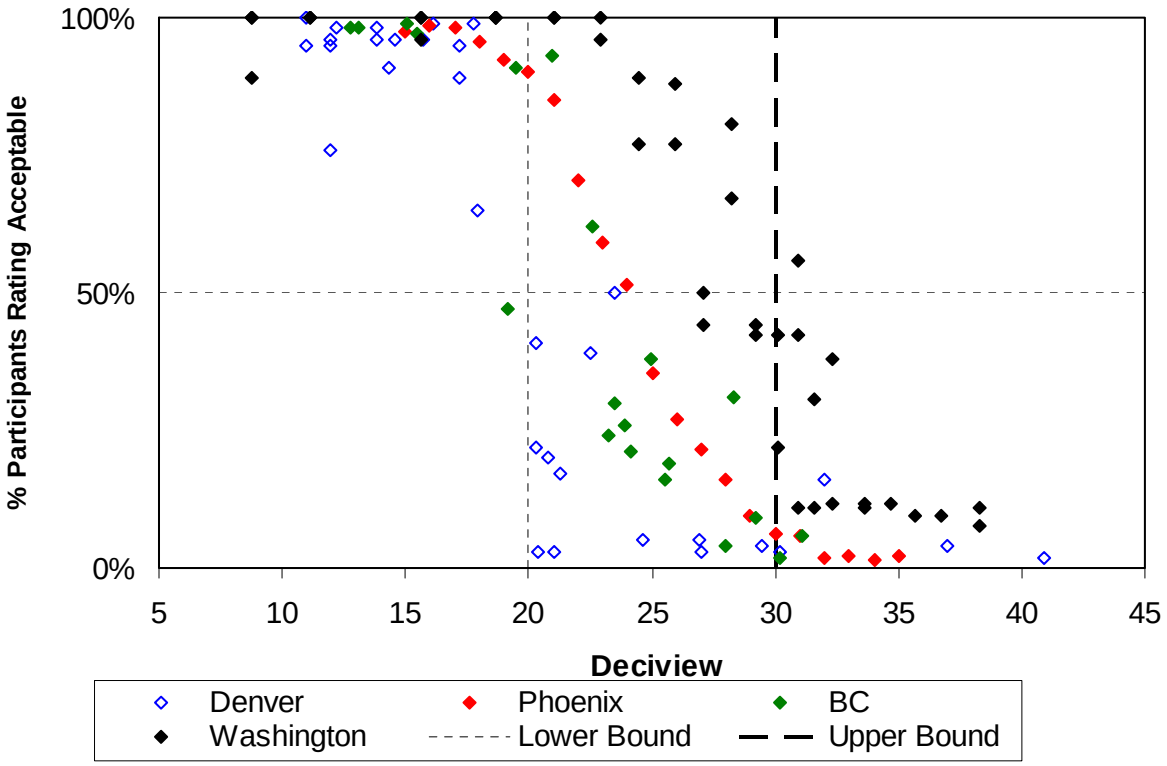

Figure 15. Summary of results of urban visibility studies in four North American cities, showing the identified range of the 50% acceptance criteria.

5. Only 47% of the BC participants rated a 19.2 dv photograph as acceptable.

6. In the 2001 Washington, DC study, a 30.9 dv image was used as a repeated slide. The first time it was shown 56% of the participants rated it as acceptable, and 11% rated it as acceptable the second time it was shown. The same VAQ level was rated as acceptable by 42% of the participants in the 2009 study (Test 1).

There are several major hypotheses about why the results of the existing studies suggest that there may be potentially important differences between the preferences for VAQ in different cities as measured in these studies. The first hypothesis arises from the potential from a type of measurement error. As mentioned, the use of photographs versus WinHaze-generated images may play a significant role in preference studies, perhaps introducing bias (such as suggested by the responses to the 9:00 a.m. Denver photographs) as well as variability. Using actual photographs from different days and times of day (as was done in the Denver and BC studies) and ambient measurements of average hourly light extinction from one portion of the scene introduces two types of uncertainty. First, the intrinsic appearance of a scene can change due to the changing shadow pattern and cloud conditions. Therefore photographs from different dates and times are not depicting scenes that differ only by their measured VAQ. In addition, due to temporal and spatial variations in air quality, the measured hourly average ambient light extinction measurements taken across one specific portion of a scene is not necessarily representative of the VAQ conditions throughout the entire scene depicted in a photograph taken at a single moment in time. WinHaze avoids these two sources of uncertainty because the same base photograph is used (i.e., no intrinsic change in scene appearance), and the modeled haze that is displayed in the WinHaze generated image is determined based on uniform light extinction throughout the scene. The challenges arising from using photographs in a preference study, in combination with the availability of WinHaze, a peer-reviewed technique now used by EPA in various regulatory contexts to depict alternative VAQ levels, combine to make WinHaze the preferred method for future preference studies.

A second hypothesis is that the use of iconic (e.g., picture postcard-like) images, or images with limited sight differences, may elicit different responses than the use of scenes with a more typical view of the metropolitan area and background. For example, the scene used in the Washington, DC studies is dominated by famous landmark buildings along the National Mall, such as the Lincoln Memorial, the Washington Monument, and the U.S. Capital. All of the prominent buildings in the Washington, DC scene are between 1 and 4 miles from the camera. Presenting scenes of a more typical downtown Washington vista with a broader range of sight distances (similar to the urban scenes presented in the Denver, Phoenix, and BC studies) would present a more varied and commonplace urban vista which study participants may rate substantially different. Including multiple scenes in a study, such as presenting both a downtown scene and a suburban residential street or park scene, may improve participant's understanding of the impacts of visibility impairment in their city.

A third major hypothesis is that urban visibility preferences may differ by location, and the differences may arise from inherent differences in the cityscape scene in each difference. The key evidence to suggest this hypothesis is that the apparent differences between the Denver results (which found the 50% acceptance criteria occurred in the best VAQ levels among the four cities) and the Washington, DC results (which found the 50% acceptance criteria occurred at the worst VAQ levels among the four cities). This hypothesis suggests that these results may occur

because the cityscape of Denver includes clearly visible snow-covered mountains in the distance, while the prominent features of the Washington, DC cityscape are buildings relatively nearby with only modest changes in elevation. Without additional studies in a variety of cities, it is impossible to know the extent to which this hypothesis may be valid.

A fourth hypothesis arising from Smith and Howell (2009) is that the range of VAQ images presented in the survey may influence the results.

A final hypothesis is the nature of the basic urban setting in each city may have an important influence on peoples' preferences about what is an acceptable amount of VAQ degradation in an individual city. For example, the cityscape in some cities can include prominent mountains as an important and integral feature of the cityscape. The cityscape in some other cities include a famous urban skyline of tall buildings (such as New York City), or a combination of waterfront and urban skyline (e.g., Chicago). This hypothesis suggests that there may not be a single VAQ level that would meet a 50% acceptability criteria in all locations because of inherent differences in the nature of cityscape scenes between cities.

While additional quantitative analysis of the results of these existing studies may be able to further refine the interpretation of the existing study results, properly interpreting any comparative statistical results would be difficult due to the critical differences in the studies. A more thorough understanding of what people consider to be an acceptable VAQ level in urban areas, and whether an acceptable VAQ level is the same in all cities, will require more data than is available from the existing studies. Additional preference studies, ideally conducted in diverse cities and using similar methods and materials, are necessary to better understand preferences for urban visibility.

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STRATUS CONSULTING

1881 Ninth Street, Suite 201 Boulder, Colorado 80302 phone 303.381.8000 fax 303.381.8200 (headquarters)

1920 L Street, N.W., Suite 420 Washington, D.C. 20036 phone 202.466.3731 fax 202.466.3732

www.stratusconsulting.com