

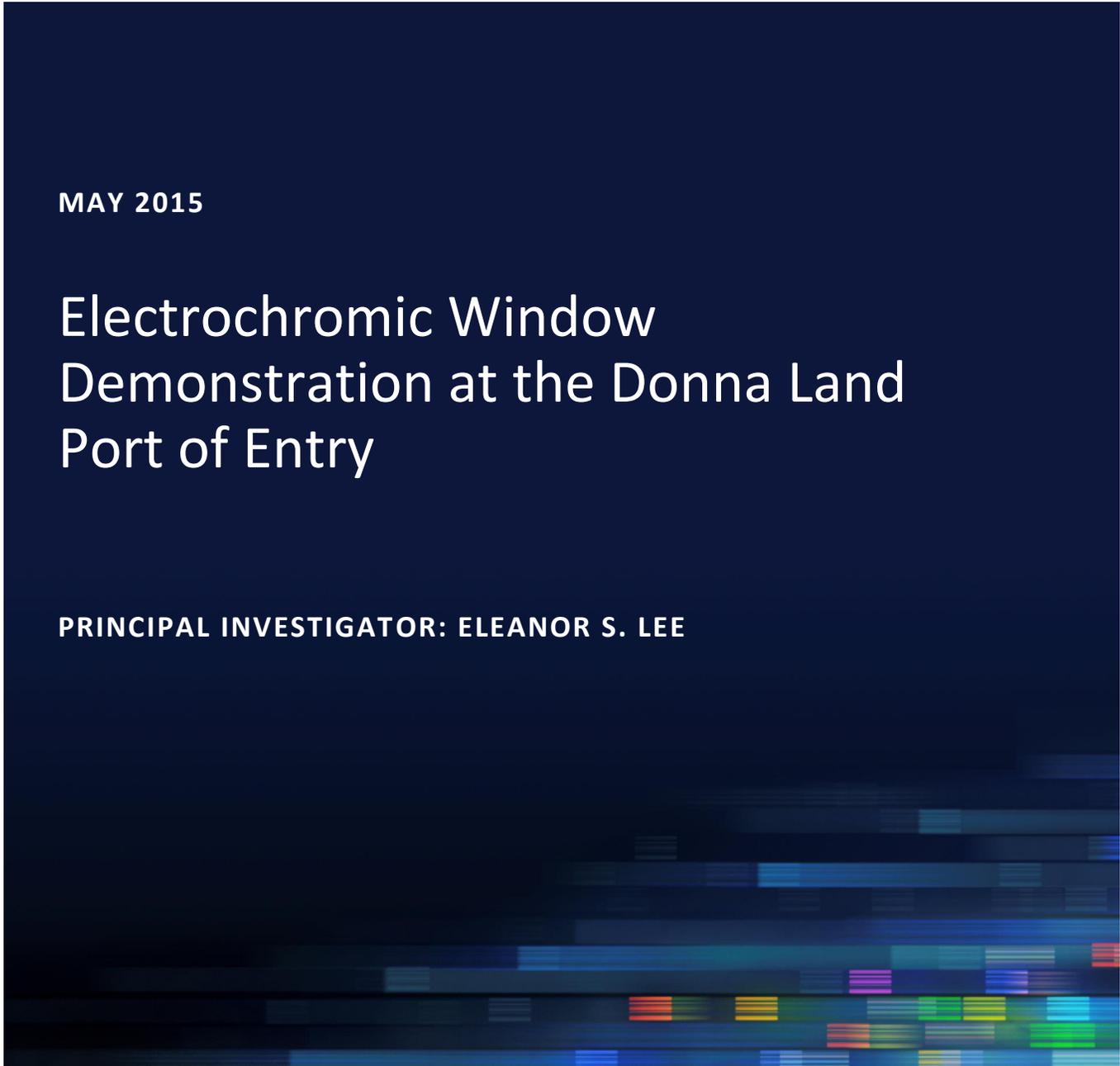


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Electrochromic Window Demonstration at the Donna Land Port of Entry

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The Green Proving Ground program leverages GSA's real estate portfolio to evaluate innovative sustainable building technologies and practices. Findings are used to support the development of GSA performance specifications and inform decision-making within GSA, other federal agencies and the real estate industry. The program aims to drive innovation in environmental performance in federal buildings and help lead market transformation through deployment of new technologies.

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I. Executive Summary

The U.S. General Services Administration (GSA) Public Buildings Service (PBS) has jurisdiction, custody or control over 105 land ports of entry throughout the United States, 35 of which are located along the southern border. At these facilities, one of the critical functions of windows is to provide border control personnel with direct visual contact with the surrounding environment. This also can be done through surveillance cameras, but the high value that U.S. Customs and Border Protection (CPB) officers place on direct visual contact can be encapsulated in the following statement by a senior officer regarding this project: “nothing replaces line of sight.” In sunny conditions, however, outdoor visibility can be severely compromised by glare, especially when the orb of the sun is in the field of view. This often leads to the deployment of operable shading devices, such as Venetian blinds. While these devices address the glare, they obstruct the view of the surroundings, negating the visual security benefits of the windows.

Electrochromic (EC) windows have the ability to adjust their tint dynamically in response to environmental conditions. This provides the potential to control glare by going to a dark tint at times when extreme glare is likely. In previous studies, these windows have shown that this ability to control glare has the potential to increase the amount of time during which view is unobstructed. This technology is available in the U.S. as a commercial product from two vendors with high-capacity manufacturing facilities, and could be deployed on a nationwide scale if successful in a pilot test.

In this project, EC windows were installed at a land port of entry near Donna, Texas. The technical objectives of the study were to determine whether the installation of the EC windows resulted in the following:

- Reduction in visual discomfort caused by glare from daylight and direct solar orb visibility
- Reduction or elimination of need for operable shading deployment
- Improved tenant satisfaction with visibility to the outside
- No significant negative impact on visibility of the exterior due to the decrease in window transmittance.

To avoid inordinate installation costs and voiding the warranty of existing bulletproof building components, the original windows were kept in place and the EC windows were installed by adding a custom-built, hinged, framed EC window to the existing windows.

While EC windows can also provide energy savings, the facility selected for this study is not optimally suited to demonstrate these benefits. The energy impact of ECs is the focus of other completed (Denver Federal Center) and ongoing (Moss Federal Building in Sacramento, California, and the 911 Federal Building in Portland, Oregon) Green Proving Ground (GPG) program demonstrations.

Verification of the attainment of technical objectives was accomplished primarily through surveys of CBP officers’ perceptions of comfort and visibility through the EC windows. To aid in the understanding of survey results, physical measurements were conducted to help quantify daytime visual and thermal comfort, as well as nighttime visibility through windows.

Results from the surveys showed that CBP officers experienced a significant improvement in visual and thermal comfort after EC windows were installed without a significant degradation in daytime

or nighttime visibility. Officers overwhelmingly stated they would prefer switchable EC windows to conventional windows (Table ES-1).

Measurements confirmed significant improvements in visual (Figure ES-1) and thermal comfort, although the improvements in thermal comfort were probably largely due to factors other than the EC properties of the windows. They also showed that nighttime visibility might be impaired, especially when interior lights are on, although survey results indicate that CBP officers generally did not perceive this to be an issue at this facility. During a post-installation site visit, bright reflections on the interior surface of the EC booth windows were visible (in sunny conditions and with windows at full tint) when looking into the booth from the outside through the open door. Survey results, however, generally indicated no perceived degradation in daytime visibility.

Table ES-1. Responses to two-alternative forced preference between original and EC windows.

Question

Overall, if given the option, would you prefer switchable windows or conventional windows at the command center/processing area?

Options

Number of responses

| Options | Number of responses | |
|--------------------------------------|---------------------|--------|
| | Command center | Booths |
| Switchable windows | 28 | 24 |
| Conventional, non-switchable windows | 0 | 0 |

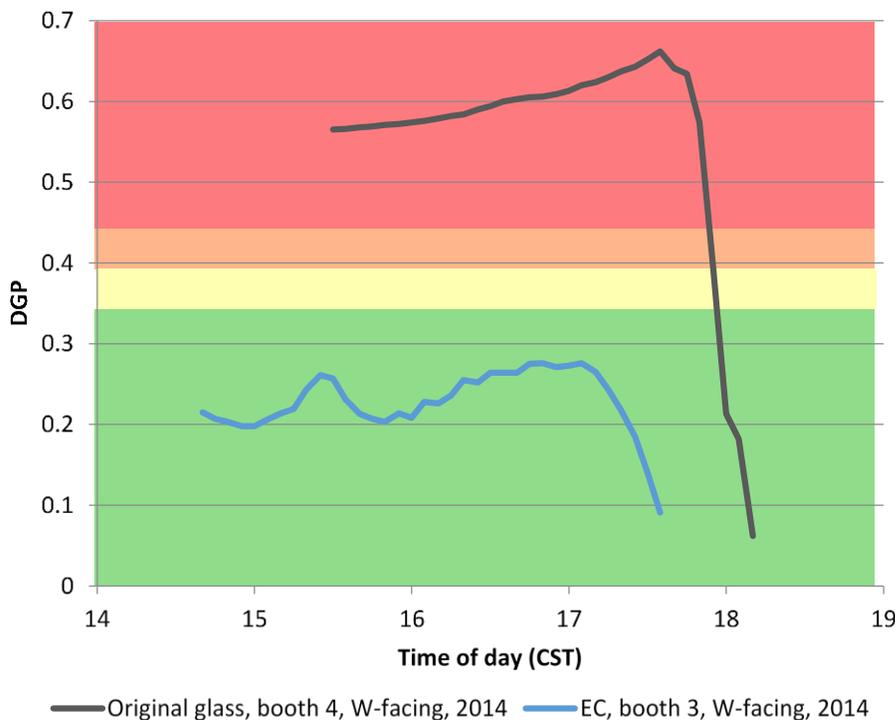


Figure ES-1. Measured Daylight Glare Probability (DGP) in vehicle inspection booths with conventional (gray curve) and EC (blue curve) windows, facing west on the afternoon of October 15, 2014, under sunny conditions (i.e., with the sun in the field of view). The booth with EC windows had much lower DGP throughout the afternoon. Note: DGP is a number between 0 and 1 representing the percentage of people that would experience disturbing glare.

The results of this study indicate that it is likely that an EC retrofit of this type would have similar performance if deployed at comparable facilities. This includes other border control facilities, as well as military, law-enforcement or any other type of governmental or private security facility in which it is valuable to maintain visual contact with the exterior surroundings in glary, sunny conditions.

Care should be taken in attempting to extrapolate the results of this study to situations in which the original glazing is replaced by an EC insulated glazing unit (IGU) or if the facility does not have a canopy or deep overhang. In such cases glare control is likely to be less effective due to the higher visible transmittance of the window and the number of hours when the orb of the sun is in the field of view. For these situations, the installation of electrochromic windows may not be sufficient to completely eliminate the need for view-obstructing interior shading. When replacing the original glazing with an EC IGU, one possible solution would be to lower the visible transmittance of the bullet-/blast-resistant EC double-pane IGU to the transmittance of the whole assembly studied here (based on the best available information, this transmittance could be as low as 0.21 in the clear state, and 0.0035 when fully tinted).

Care should also be taken when applying any of these configurations (EC IGU add-on to existing windows or transmittance-matched EC bullet-/blast-resistant IGU) in facilities with particularly stringent requirements for nighttime visibility of dark exterior surroundings. Further testing is recommended in such situations or, at a bare minimum, an analysis comparing the interior surface reflectance of the EC IGU (including the original window, in the case of an add-on retrofit like the one studied here) to that of the original IGU.

II. Introduction

A. PROBLEM STATEMENT

At land ports of entry, one of the critical functions of windows is to provide border control personnel with direct visual contact with the surrounding environment, allowing them to monitor constantly the exterior environment for possible suspicious activity. This also can be done through surveillance cameras, but U.S. Customs and Border Protection (CPB) officers place very high value on direct visual contact; this can be encapsulated in the following statement by a senior officer regarding this project: “nothing replaces line of sight.” In sunny conditions, however, outdoor visibility can be severely compromised by glare, especially when the orb of the sun is in the field of view. This often leads to the deployment of operable shading devices, such as Venetian blinds. While these shading devices address the glare, they partially or totally obstruct the view of the surroundings, thereby negating the visual security benefits of the windows.

Electrochromic (EC) windows have the ability to adjust their tint dynamically in response to environmental conditions. This capability can result in cooling and lighting energy savings [Lee et al., 2006]. It also provides the potential to control glare by going to a dark tint at times when extreme glare is likely. Previous studies have shown that this ability to control glare can significantly increase the amount of time during which the view is unobstructed by shading devices [Fernandes et al., 2013]. This technology is commercially available in the U.S. from two vendors with high-capacity manufacturing facilities, and could be deployed on a nationwide scale if successful in a pilot test.

B. OPPORTUNITY

This Green Proving Ground (GPG) program study examines whether EC window retrofits can reduce or eliminate the need for view-obstructing blinds in a very specific setting: border crossing stations. While EC windows can also provide energy savings, the facility selected for this study is not optimally suited to demonstrate these benefits. The energy impact of ECs is the focus of other completed (Denver Federal Center [Lee et al., 2014]) and ongoing (Moss Federal Building in Sacramento, California, and the 911 Federal Building in Portland, Oregon) GPG program demonstrations.

The U.S. General Services Administration (GSA) Public Building Service (PBS) has jurisdiction, custody or control over 105 facilities of this type throughout the United States, 35 of which are located along the southern border. These facilities approximately range in size from 300,000 rentable ft² (Otay Mesa, CA) to rentable 1,000 ft² (Poker Creek, AK). These land ports of entry have a combination of pedestrian, bicycle, private vehicles, commercial trucks, and freight train traffic. The findings of this study also can potentially be relevant to similar facilities oriented towards security and surveillance operated by other government, military or private entities.

There are potential risks associated with mass deployment of this technology throughout land ports of entry in the United States. Retrofitting EC windows onto these buildings needs to be done while maintaining compliance with stringent requirements for bullet or blast resistance and, in some areas, due to frequent hurricanes, wind load resistance. Because of the tint of the EC windows, visibility through windows could be decreased in low outdoor light conditions, especially at nighttime, if indoor light levels and surface brightness are maintained equal.

III. Methodology

A. TECHNOLOGY DESCRIPTION

Electrochromic (EC) windows have the ability to change their visible light transmittance dynamically. They achieve this through thin-film coatings applied to glass that can be actively controlled to change appearance reversibly from a clear to a dark blue tint when a small direct current voltage is applied by a manual switch or an automated building control system. EC windows preserve the outward view while modulating transmitted light, glare and solar heat gains.

The EC coating itself is a one-micron-thick (1×10^{-6} m, 4×10^{-5} in), multi-layer film or stack deposited on glass, usually on the inward-facing surface of the outboard pane of an insulated glazing unit (IGU). Transparent conductors form the outer layers of the stack (Figure 1). Active EC and counter-electrode layers are located adjacent to each of the two transparent conducting layers, facing the center of the stack. Finally, an ion-conducting electrolyte layer forms the center portion of the stack. An electric potential is applied to the outer transparent conductors, which causes lithium ions to migrate across the ion-conducting layer from the counter-electrode layer to the EC layer. A reversible electrochemical reaction takes place causing a tinted Prussian blue appearance. Reversing the potential causes the ions to migrate back, causing a bleached clear appearance.

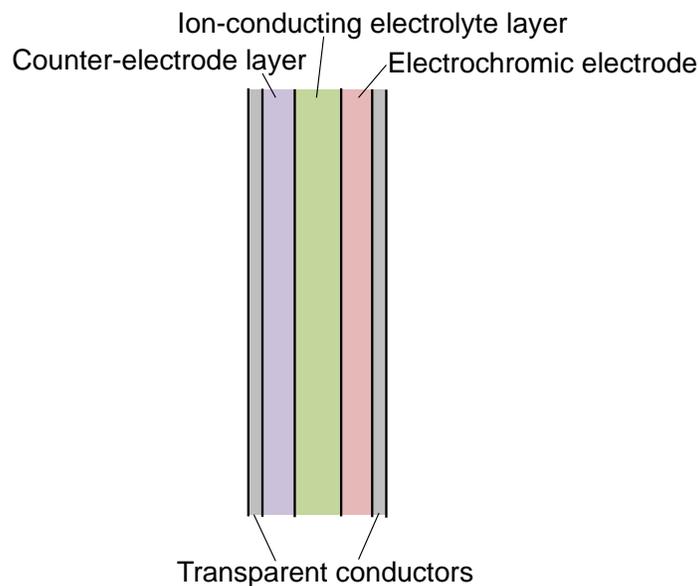


Figure 1. Component layers of an electrochromic film. Layer thickness not to scale.

How fast EC windows transition between states is dependent on temperature and size of the window. Transition speed decreases with window size and increases with temperature. For example, a 4x5 ft window on a hot day can take 2-3 minutes to switch from clear to fully tinted. A 5x8 ft window on a cold day can take 40-60 minutes to switch from clear to its fully tinted state. Most of the transition happens within a relatively short time (*e.g.*, the 5x8 ft window in the example above would only take 5-10 minutes to reach 80% of full tint), with the latter part of the transition taking longer.

The material and physical composition of the EC window can vary and this dictates the unique properties of the EC window: its switching range, speed versus temperature characteristics, power consumption when being switched, durability, and color. EC windows, at this time, are

fundamentally the same from the two known U.S. manufacturers that currently offer this technology: the EC materials exhibit approximately the same solar-optical properties when switched. For both manufacturers, the technology readiness level is in the “late R&D” stage (cost reduction and performance improvement stage).

As a commercial product, EC windows are deployed as part of a system that includes other components. Light and solar radiation sensors provide information on exterior and interior light levels, allowing windows to be controlled accordingly. The automated control system usually comprises a central controller, installed in a utility closet, in addition to vendor-specific control and communications hardware such as cables and networking hubs. Wall switches allow building occupants to control the tint of the windows manually. The main controller also can be connected to a building automation system (BAS) to be able to respond to specific inputs from the BAS, a control option that was not implemented in this study because of the focus on visual comfort and visibility rather than energy performance¹.

PREVIOUS CASE STUDIES

Several monitored demonstrations of EC windows have been undertaken, studying energy and occupant comfort impacts in conventional office settings to differing degrees. No studies have been conducted to evaluate performance related to viewing outdoor conditions as the primary tasks. In these prior demonstrations, EC windows were either installed anew or replaced the original glass. A full-scale field test in an office mockup provided rigorous analysis of the window heat gain and lighting impacts of an integrated EC window and lighting system, with occupant satisfaction evaluated over a short period (4-6 hour exposure per subject) [Clear et al., 2006]. Average daily energy savings were 10±15% for lighting and 0±3% for cooling [Lee et al., 2006]. A two-year monitored installation of EC windows in a large office building demonstrated end user acceptance of this technology, but the windows were shaded by a 10-foot deep overhang and conventional skylights confounded the analysis of energy and occupant impacts [NREL]. An 18-month installation of EC windows and dimmable lighting in a conference room also demonstrated feasibility of the technology, but end user acceptance was inferred by manual override switch activity, not direct subjective survey data [Lee et al., 2012]. A prior GPG demonstration at the Denver Federal Center showed a decrease in glare, although at the expense of perceived daylight levels in the space [Lee et al., 2014]. A recent field study of EC windows in a U.S. Department of Defense office building showed increased occupant satisfaction due to increased access to view [Tinianov, 2014]. Other GPG EC demonstrations are underway in office buildings in Sacramento, California, and Portland, Oregon.

Besides visual comfort, EC windows can significantly impact energy consumption in buildings, reducing cooling loads (*e.g.*, the GPG demonstration in Denver predicted a 22% reduction relative to a base case with single-pane clear glass windows [Lee et al., 2014]) and, depending on how they are controlled and how shading is used, increasing or decreasing lighting energy consumption. While these are important effects, it would be impractical to include them in this study due to several factors specific to the test site - see Section III.C below for more detail.

¹ The window control system was actually connected to the BAS, but only for the purpose of logging window operation data.

B. TECHNICAL OBJECTIVES

The technical objectives of the study were to determine, from occupant surveys and supporting measurements, whether the installation of the EC windows resulted in the following:

- Reduction in visual discomfort caused by glare from daylight and direct solar orb visibility
- Reduction or elimination of need for operable interior shading deployment
- Improved tenant satisfaction with visibility to the outside
- No significant negative impact on visibility of the exterior due to the decrease in window transmittance.

Strong evidence for all of these would suggest that ECs are suitable for further deployment in other similar land ports of entry or any facilities in which (1) it is important to maintain continuous direct visual contact through windows and (2) severe glare conditions, such as direct visibility of the solar disk, are expected.

C. DEMONSTRATION PROJECT LOCATION

The Donna Land Port of Entry (LPOE) (Figure 2) is a border inspection station located at the border between the United States and Mexico near Donna, Texas, and situated about 50 miles from the Gulf of Mexico coast (latitude 26°N, longitude 98°W). The port of entry is in operation on every day of the year, between 6 AM and 10 PM. The study took place in two areas of the facility: the command center and one of the inspection booths for privately-owned vehicular traffic into the United States (Figure 3).

The command center, located in the secondary inspection building (Figure 4), is the room from which U.S. Customs and Border Protection (CBP) operations in the Donna LPOE are overseen. Command center windows face east, west and south, with vehicular traffic coming from the south past the inspection booths and into an outdoor inspection area. Inspection booths and the outdoor inspection area are shaded by a large canopy (Figure 5). At nighttime, the inspection area is lighted by luminaires mounted on the underside of the canopy. Horizontal illuminance at night is in the 300-400 lx range. The facility grounds, as well as other buildings in the facility, are visible towards the west and east. In sunny conditions, command center occupants can view the solar disk directly during the morning and afternoon, resulting in the need to lower Venetian blinds (Figure 6), thereby blocking the view. During the middle of the day, the sun is blocked by the canopy.

The four inspection booths are located to the south of the inspection area and the secondary inspection building. Booth doors face east. Booths have windows on all four elevations. The south elevation faces the road that accesses the LPOE from Mexico. In sunny conditions, the solar disk is visible during a substantial part of the day. During normal booth operations, the occupants of the inspection booths spend a substantial amount of time inspecting incoming vehicles. As a result, booth doors are usually open.

Due to multiple factors, this facility is not well-suited for the study of energy impacts of EC windows. The heating, ventilating, and air conditioning (HVAC) system is not zoned in a way that allows separate monitoring of the areas of the facility under study. These areas represent a small part of the facility and impacts on overall HVAC energy use would probably be very hard to discern. The inspection booths have dedicated HVAC units, but are frequently operated with their doors open in patterns that are hard to reproduce. During a preliminary visit, it was noted that the command

center was operated with lights turned off, both during the day and at night. In these conditions, it appeared highly unlikely that useful lighting energy impacts would be measureable.

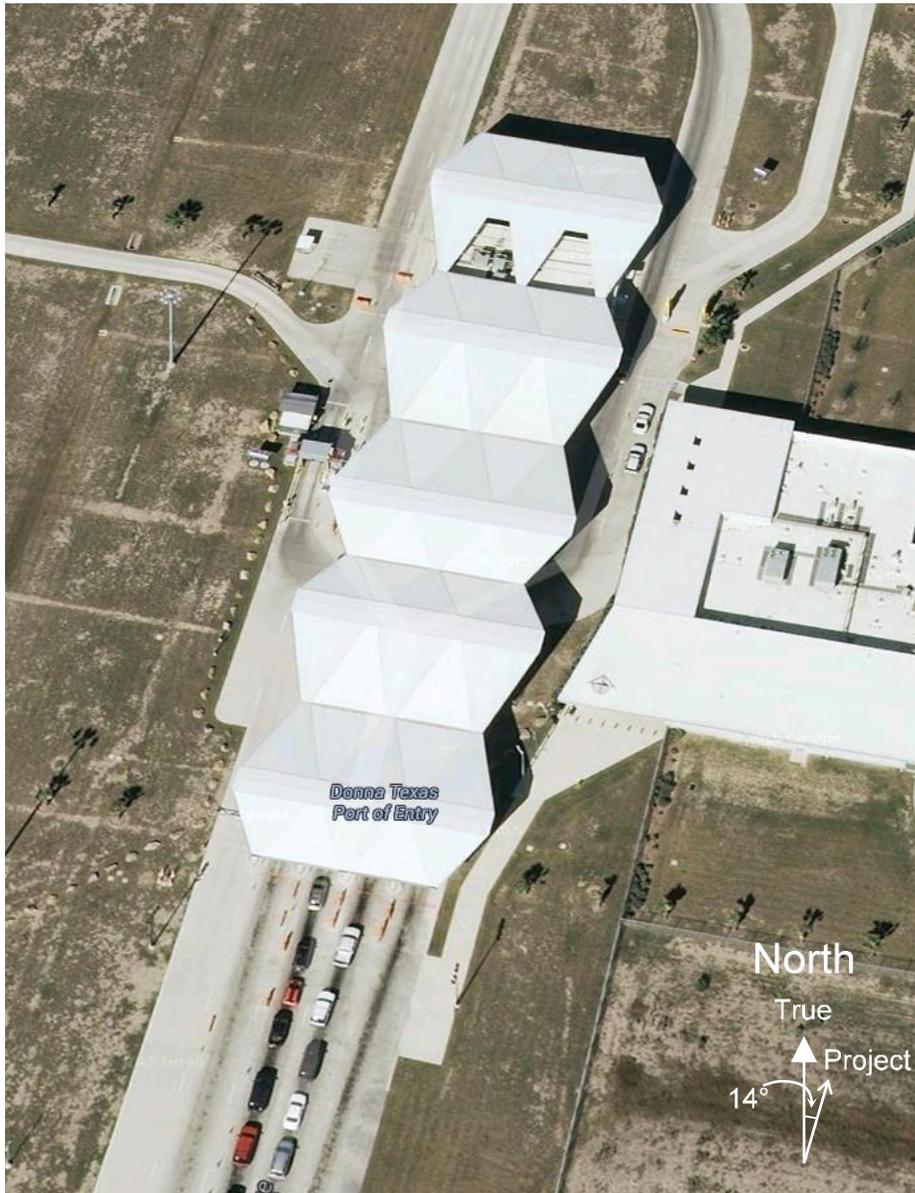


Figure 2. Satellite view of the Donna LPOE. U.S.-bound vehicles enter from the bottom. The main inspection area of the port, including the inspection booths and secondary inspection building, are covered by a canopy. Source: Google Maps.

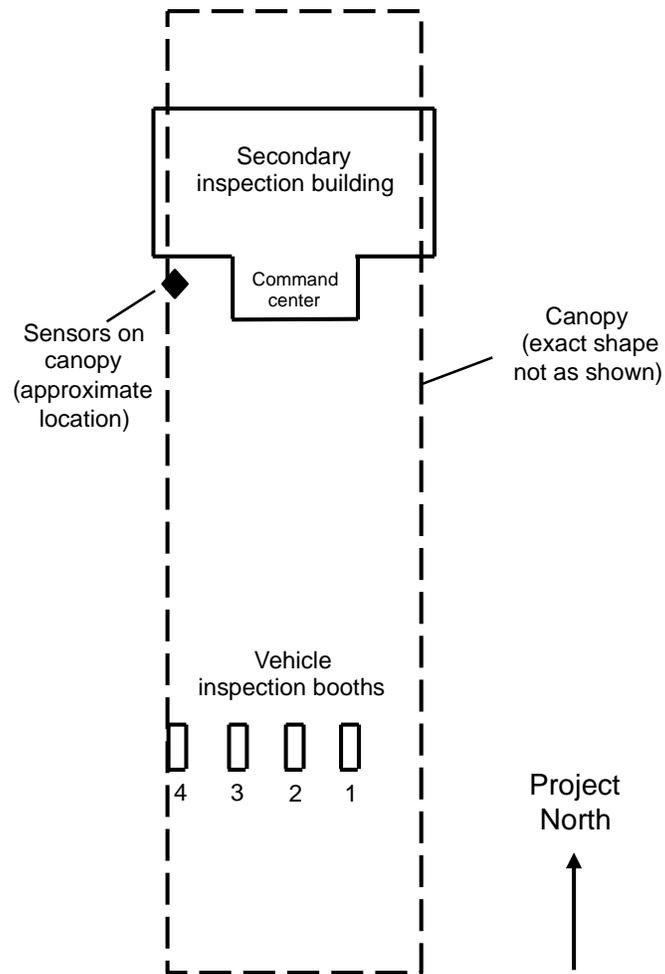


Figure 3. Schematic diagram of the layout of the site, showing approximate relative location of secondary inspection building and vehicle inspection booths. Diagram not to scale. Exact shape of canopy is not as shown here – see Figure 2; the overhangs project past the dotted line.



Figure 4. Secondary inspection building, viewed from the east, with command center to the left.



Figure 5. View towards south from outside the command center, with four inspection booths at the far end of the inspection area. Booth numbering used in this report is also shown.

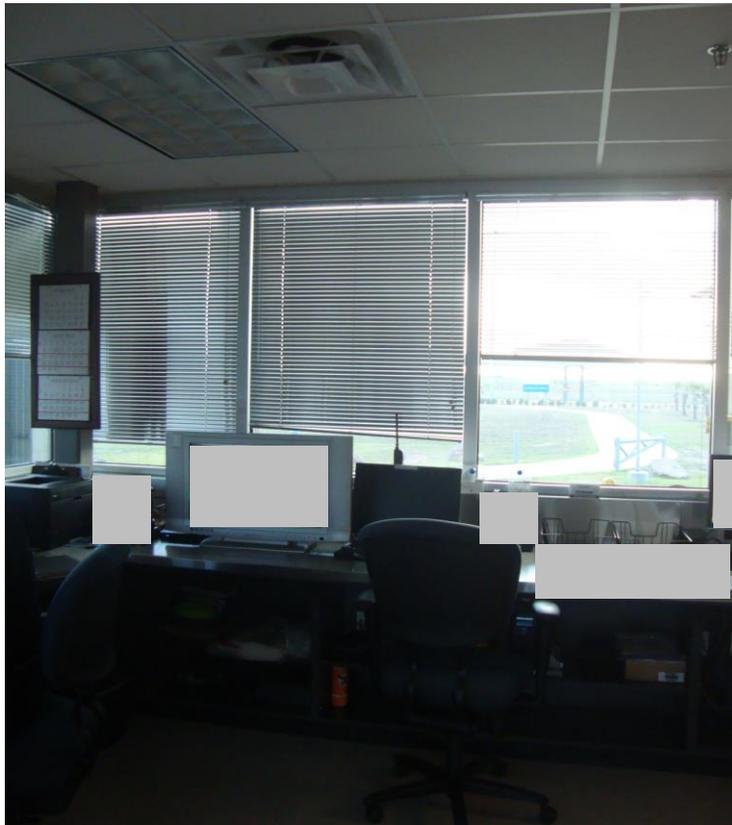


Figure 6. Venetian blinds blocking the view to the west from the command center on a sunny afternoon, prior to the installation of electrochromic windows.

IV. M&V Evaluation Plan

A. FACILITY DESCRIPTION

Electrochromic (EC) windows were installed in two areas of the Donna Land Port of Entry: (a) command center and adjacent processing area and (b) vehicle inspection booth no. 3 (see Figure 5 for booth numbering). The original windows in the command center are shown in Figure 7. Table 1 shows the specifications for the original, dual-pane command center windows. A schematic floor plan of that area is shown in Figure 8. The original vehicle inspection booth windows are shown in Figure 9. Booth windows were single-pane bullet-resistant glass and polycarbonate laminate, 31-mm (1.22-in.) thick². The floor plan of a booth is shown in Figure 10. The total area of EC glass installed was 268 ft² (236 ft² in the command center/processing area and 33 ft² in the vehicle inspection booth). The EC windows were installed by adding a custom built frame to the interior (command center/processing area) or exterior (vehicle inspection booth) of the existing windows. Images and diagrams of the installed EC windows are in Figures 11 to 14.



Figure 7. Original windows in the command center.

² Exact visible transmittance or window composition data were not available for the booth windows. A very approximate estimate can be obtained by using the visible transmittance we estimated for the bullet-resistant laminate of the command center windows. This value is 0.72, but could vary significantly depending on the actual layer composition of the laminate.

Table 1. Specifications for original windows in command center/processing area.

| Component/Measurement | Specification |
|-------------------------------------|---|
| Layers (outboard to inboard) | 6 mm gray tinted, heat strengthened glass layer with low-emittance (low-e) coating (pyrolitic) on inward-facing (no. 2) surface 13 mm air gap 36* mm bullet-resistant laminate (3 mm clear w/ low-e coating (sputtered) on outward-facing (no. 3) surface + polycarbonate + 3 mm clear with spall resistant film) |
| Visible transmittance | ≥ 0.35 |
| Winter nighttime U-factor | ≤ 1.65 W/m ² -K (0.29 Btu/h-ft ² -°F) |
| Summer daytime U-factor | ≤ 1.53 W/m ² -K (0.27 Btu/h-ft ² -°F) |
| Solar Heat Gain Coefficient | ≤ 0.24 |
| Shading coefficient | 0.28 |

* laminate thickness estimated based on best available information

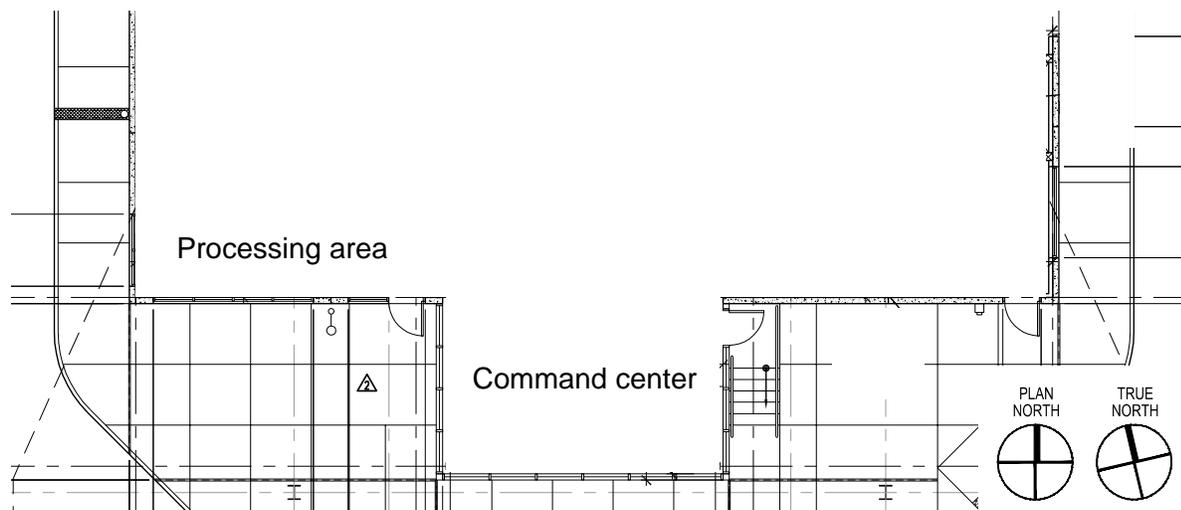


Figure 8. Floor plan of the command center/processing area.



Figure 9. Original windows in vehicle inspection booth no. 4.

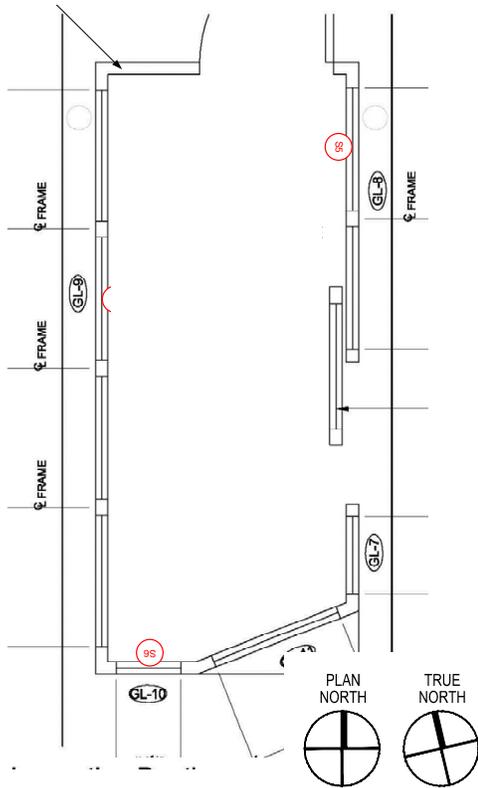


Figure 10. Floor plan of vehicle inspection booth.



Figure 11. EC windows installed in command center. Hinged frame allows the EC window to be opened from the interior for cleaning and maintenance.

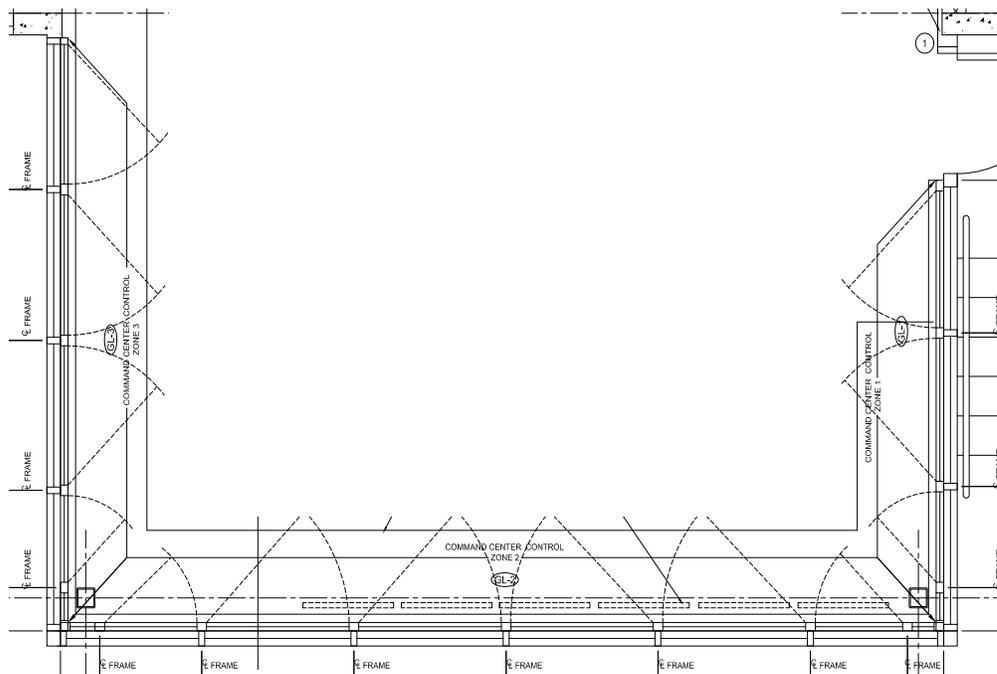


Figure 12. Floor plan of the command center with interior EC window retrofit.



Figure 13. EC windows installed in vehicle inspection booth no. 3.

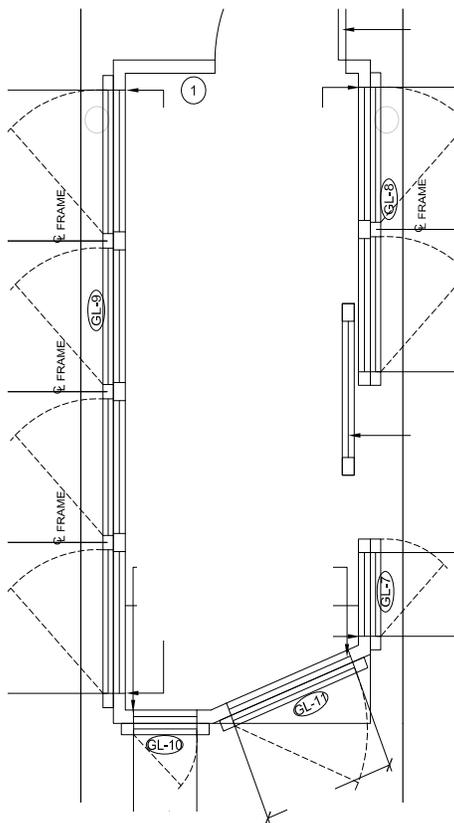


Figure 14. Floor plan of vehicle inspection booth with exterior EC window retrofit.

B. TECHNOLOGY SPECIFICATION

WINDOWS

The physical composition of the EC windows is given in Table 2. The EC IGU could be set to one of four visible transmittance (T_{vis}) levels: approximately 60%, 20%, 6% and 1% (not including the existing window). These levels also are referred to throughout the text as “clear,” “light tint,” “medium tint,” and “full tint,” respectively. Based on the best available information, the visible transmittance of the existing command center window could be as low as 0.35, which would result in a transmittance range of the 4-pane window of approximately 0.21-0.0035.

Table 2. Physical composition of electrochromic windows.

| Framing | Layers (inboard to outboard) |
|--|---|
| Aluminum frame, thermally broken, 11.5 mm stainless steel spacer | 5.7 mm clear, heat strengthened 11.5 mm air space 7.1 mm EC pane, heat strengthened |

SENSORS

The system used three vertical illuminance sensors mounted above the canopy (see Figure 3 for approximate location), facing east, south and west. These were used in the control of the east-, south- and west-facing window zones, respectively.

CONTROL ALGORITHM

The EC windows were zoned as shown in Figures 15 and 16, with every window within a zone always controlled to the same tint. Control modes are summarized in Table 3 and explained in more detail below.

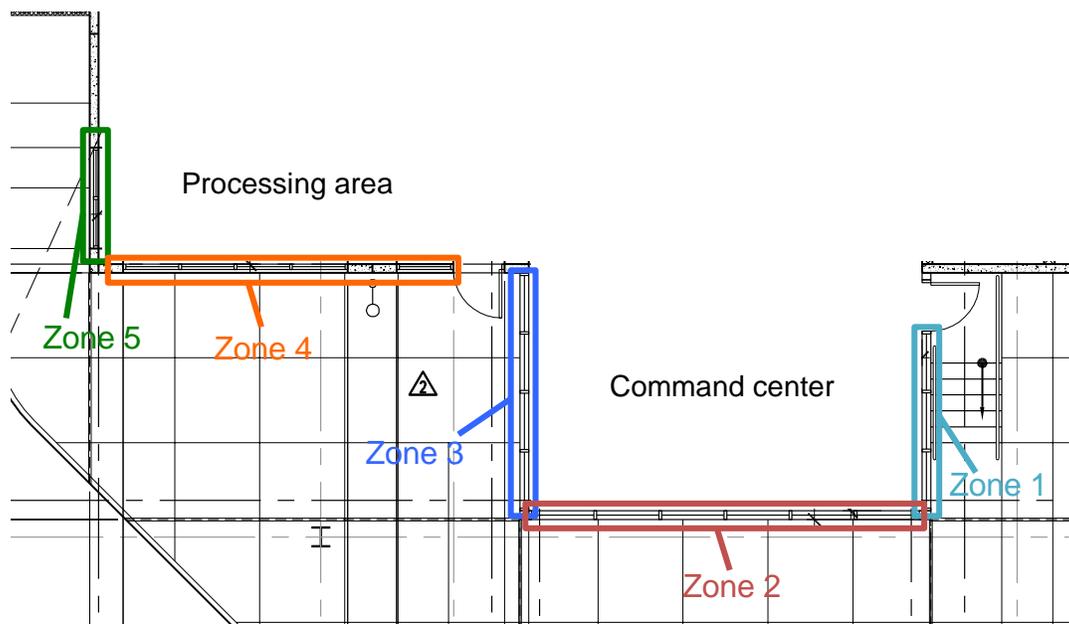


Figure 15. Zoning of the EC windows in the command center/processing area (project north is up).

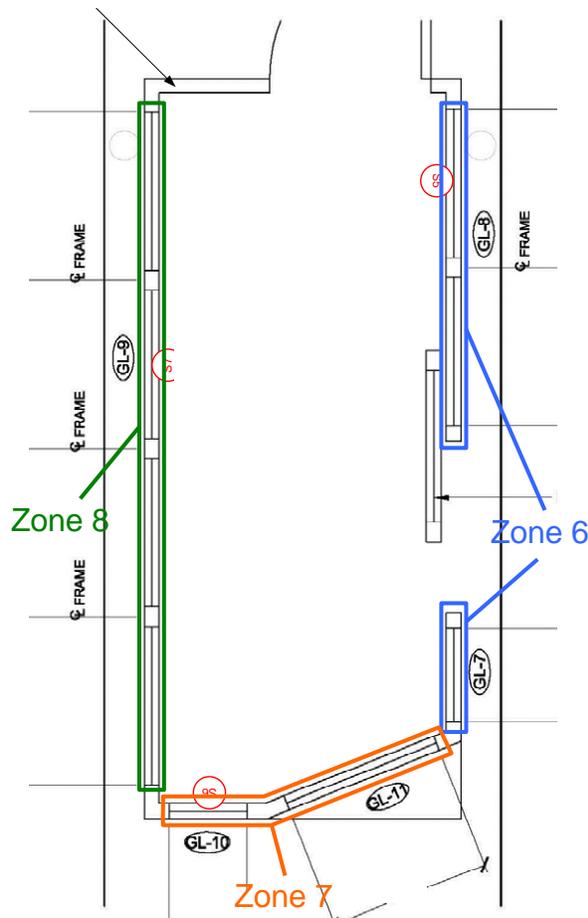


Figure 16. Zoning of the EC windows in vehicle inspection booth no. 3 (project north is up).

Table 3. Summary of window control modes

| Control mode | Summary description | Priority |
|-----------------|---|--|
| Daylight mode | Window automatically tints/untints according to exterior vertical illuminance normal to window | This mode has the lowest priority |
| Glare override | Window set to full tint when direct sun is on window (i.e., within altitude and azimuth parameters and exterior vertical illuminance above threshold) | This mode is able to override daylight mode only |
| Manual override | Window set to the tint as selected by occupant using wall switch | This mode is able to override all other modes |

a Daylight mode

In daylight mode, a zone is automatically set to one of the four tint levels according to the signal from the exterior vertical illuminance sensor that has the same orientation as the window zone. This adjustment occurs continuously from sunrise to sunset. The control loop is open, *i.e.*, there is no feedback to the control system regarding the effect that tint level changes may have on interior light levels. The sensitivity of each zone to exterior light levels is determined by a control setpoint. This setpoint was set to 5000 lux for all zones.

b Glare override

During glare override mode, the control system sets the zone’s windows to full tint. A zone is set to glare override mode when two conditions are satisfied: (1) the sun is within pre-set azimuth and altitude angles³ and (2) exterior vertical illuminance exceeds a pre-set threshold⁴. The control system will send the zone back into daylight mode when either of the following two conditions are satisfied: (1) the sun is no longer within the pre-set azimuth and altitude angles or (2) exterior vertical illuminance goes below a pre-set threshold⁵ (which is lower than the one for entering glare override mode). Solar position is calculated by the control system based on astronomical formulas, date, time of day, geographical location of the building, and orientation of the window zone. The pre-set thresholds are set by the manufacturer prior to or during commissioning, based on knowledge gained from past installations and feedback from the building occupants during commissioning. See Table 4 for parameter values used at the Donna site.

Table 4. Glare mode parameters. Shading indicates glare mode does not operate during that period. Azimuth and altitude angles are given as degrees from north and are positive in clockwise direction.

| Zone | Morning (local time) | | | | | | Afternoon (local time) | | | | | |
|------|----------------------|----------|---------|----------|-----------------|------|------------------------|----------|---------|----------|-----------------|------|
| | Start | | Stop | | Threshold (klx) | | Start | | Stop | | Threshold (klx) | |
| | Azimuth | Altitude | Azimuth | Altitude | Start | Stop | Azimuth | Altitude | Azimuth | Altitude | Start | Stop |
| 1 | 45 | 0 | 135 | 45 | 19 | 14 | | | | | | |
| 2 | 180 | 0 | 253 | 35 | 21 | 15 | 180 | 35 | 253 | 0 | 19 | 10 |
| 3 | | | | | | | 210 | 45 | 315 | 0 | 18 | 4 |
| 4 | 180 | 0 | 253 | 60 | 21 | 15 | 180 | 60 | 253 | 0 | 19 | 10 |
| 5 | | | | | | | 210 | 45 | 315 | 0 | 18 | 4 |
| 6 | 45 | 0 | 135 | 45 | 19 | 14 | | | | | | |
| 7 | 135 | 0 | 225 | 50 | 21 | 15 | 135 | 50 | 253 | 0 | 19 | 10 |
| 8 | | | | | | | 210 | 45 | 315 | 0 | 18 | 4 |

c Manual override

Building occupants can override any of the other two modes using wall switches (Figures 17 and 18). The switches also display the currently selected tint. When overridden, a zone will stay for two hours at the set tint level, and then return to automatic control.

³ /i.e. between the “start” and “stop” values indicated in Table 4.

⁴ In Table 4, this is shown in the “start” column under “threshold.”

⁵ In Table 4, this is shown in the “stop” column under “threshold.”



Figure 17. Wall switches for the command center and processing area. These are located in the hallway in between the two areas. Note: zone labeling on switches was found to be not entirely consistent with the numbering in Figure 15.



Figure 18. Wall switches in the vehicle inspection booth no. 3.

C. TECHNOLOGY DEPLOYMENT

In the command center/processing area, the expense of removing the original bullet-resistant glass and replacing it with EC glass was not an option for this project. It was decided to install the ECs on the indoor side of the existing windows in hinged frames that could be opened manually by occupants (Figure 11). This solution maintained the aesthetic integrity of the building and also allowed easy access to the cavity between the original and EC windows for cleaning and maintenance (the command center windows were too high to be easily accessed from the outside without a ladder). To mitigate possible heat or moisture build-up, the design included holes that allowed air in the cavity between the original and EC windows to mix with that in the ceiling plenum.

In the vehicle inspection booth, EC windows were installed on the outside, also using hinged frames that allowed for cleaning and maintenance access (Figure 19). In this case, although replacing the existing glass would have been feasible, it would have caused the undesirable outcome of voiding the manufacturer's warranty for the bulletproof booths.

The difference in window performance between exterior and interior retrofits was not expected to impact significantly the evaluation of visual comfort and exterior visibility⁶. In terms of thermal comfort, the effect of adding two additional panes of glass, which, in effect, upgrades these windows to be triple- (in the booths) or quadruple-pane, probably predominates over the effect of adding EC capability. However, it is conceivable that an interior retrofit with the EC glass pane installed on the interior side in the command center might cause, when compared to the original windows, a decrease in thermal comfort when the windows were tinted due to radiant heat gains towards the interior.

⁶ To ascertain the exact impact on exterior visibility, it would be necessary to have data on the interior-facing reflectance of the existing windows. Such information was not available.



Figure 19. Operable EC window frame vehicle inspection booth no. 3.

The EC glass was fully installed and commissioned by the end of March 2014. The window frames, control hardware and control wiring had been installed prior to delivery of the EC glass. Most of the glass was in place and commissioned by the end of January 2014. Two panes that had been sized improperly were delivered and installed by the end of March 2014. These and other relevant project dates are shown in Table 5.

At the time of commissioning, as windows began their automatic operation, CBP personnel noticed that the south-facing windows in the command center were too dark (Zone 2 in Figure 15). The EC window vendor adjusted the control algorithm so that these windows, when in daylight mode, would never go below 20% visible transmittance (they could still go to full tint when in glare mode or manual override). This was the only modification from the default control algorithm the vendor had pre-determined for this installation.

Table 5. Project timeline.

| Activity | Completed by |
|--------------------------------|---------------------|
| Pre-installation survey | Aug. 31, 2013 |
| Pre-installation measurements | Nov. 18, 2013 |
| Installation and commissioning | Mar. 30, 2014 |
| Post-installation measurements | Oct. 16, 2014 |
| Post-installation survey | Dec. 2, 2014 |

D. TEST PLAN

Performance of EC windows at this site was evaluated primarily through surveys of the occupants' perceptions of comfort and visibility through windows. To aid in the understanding of survey results, we also conducted physical measurements. These quantified daytime visual and thermal comfort, as well as nighttime visibility through windows. Finally, data from the window control system was used to illustrate how building occupants operated the windows.

SURVEYS

We issued two surveys to the officers that operate at the facility, one prior to installation of EC windows, another after they had been in operation for at least six months – see Appendix A for full text. Initially, both surveys were to be online questionnaires. After the response rate to the pre-installation survey turned out to be poor (8 responses out of a population of approximately 20-30 officers), it was decided to undertake the post-installation survey using a procedure that the local U.S. General Services Administration (GSA) office typically follows when issuing tenant satisfaction surveys: GSA personnel travel to the site and issue the survey on paper. This increased the number of responses to 28.

The pre-installation survey was aimed at quantifying occupant experiences with the original windows regarding visual comfort and visibility through the windows. The post-installation survey was designed to quantify the perceived differences in visual comfort and visibility between the post- and pre-installation conditions. A question about thermal comfort was added when anecdotal reports emerged that the officers felt less heat from the sun while indoors after the EC windows were installed.

Answers to the pre-installation survey were analyzed using descriptive statistics, with 95% confidence intervals determined by a one-sample t-test. In the post-installation survey, survey answers regarding pre-/post-installation differences in comfort and visibility were analyzed using the same statistical techniques. Answers to two-choice questions on preference between original and EC windows were analyzed using binomial statistics, with 95% confidence intervals for maximum likelihood estimators determined using the Clopper-Pearson method [Clopper, 1934].

VISUAL COMFORT MEASUREMENTS

To document pre- and post-installation visual comfort conditions, measurements were performed in the command center and vehicle inspection booths using high-dynamic-range (HDR) photography. This technique involves taking several digital photographs of the same scene, each with a different exposure.

Two types of cameras were used for these measurements. For the pre-installation measurements (November 2013), we used Canon A570IS point-and-shoot cameras, fitted with Opteka fisheye lenses (Opteka Super Wide Fisheye Lens 0.20X). The original camera firmware was modified using publicly available software [CHDK, 2014] to automate image capture. Figure 20 shows this type of camera in operation at the command center. This was, at the time, a convenient portable solution for automated HDR image capture. When the post-installation measurements were taken (October 2014), more accurate portable equipment was available: Canon EOS 60D SLR cameras with Sigma EX 4.5 mm f/1.8 fisheye lenses, controlled by a computer running Mac OS X custom software, and fitted

with light sensors for continuous calibration (Figure 21). In all cases, cameras were operated while mounted on lightweight tripods.



Figure 20. Canon A570IS HDR camera setup in operation at the command center.



Figure 21. Canon EOS 60D HDR camera setup in operation at a vehicle inspection booth. Light sensor can be seen mounted on top of camera.

The data from multiple camera images were combined, using software, to produce a luminance map of the scene, effectively using each pixel of the camera’s sensor as if it were a luminance meter (Figure 22). Each luminance map, like the one shown in Figure 22, was then further condensed into a single number representing Daylight Glare Probability (DGP), a metric for visual comfort [Wienold, 2006]. DGP values range from 0 to 1 and represents the percentage of people who would experience disturbing glare when viewing the scene captured in a luminance map. Table 6 shows the correspondence between DGP levels and qualitative perceptions of glare [Reinhart, 2011].

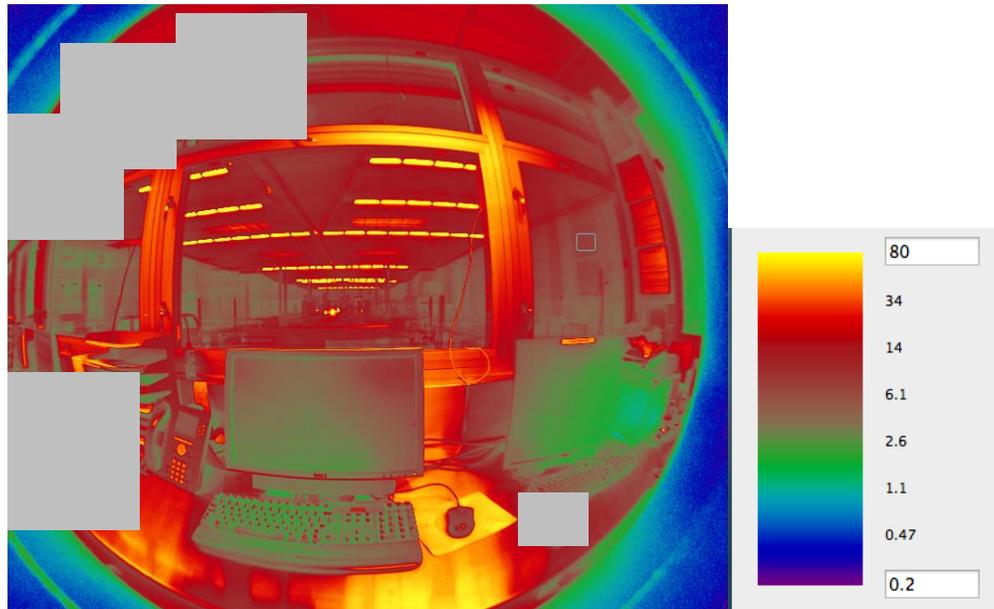


Figure 22. Luminance map taken from command center at nighttime. The false color scale to the right is in units of cd/m^2 . Note: the maximum luminance shown in yellow represents $\geq 80 \text{ cd/m}^2$.

Table 6. DGP classification.

| DGP | Qualitative interpretation |
|--------------|----------------------------|
| < 0.35 | Imperceptible glare |
| 0.35 to 0.40 | Perceptible glare |
| 0.40 to 0.45 | Disturbing glare |
| > 0.45 | Intolerable glare |

NIGHTTIME VISIBILITY MEASUREMENTS

At night, the interior of an occupied building is often more brightly lit than its surroundings. A reflection of the brightly lit interior can usually be seen on windows when looking out through them. This reflection can obscure the view and, if the surroundings are dark enough relative to the interior, completely prevent building occupants from observing those surroundings. In the case of the Donna command center, this issue is mitigated by relatively high nighttime light levels outside while the port is in operation. However, adding additional panes of glass can decrease nighttime visibility. To quantify this decrease, nighttime luminance measurements using HDR photography were taken from inside the command center. Measurements were performed with the original glass, and then with the added ECs, in both cases with and without the indoor lights turned on.

A simple metric was used to assess nighttime visibility, based on the principle that reflections from bright indoor objects reduce the contrast between areas of the outdoor view that have different brightness. Two areas of differing brightness were selected, and the luminance (a physical quantity that can be taken as a proxy for brightness) of the two areas was obtained from the HDR-generated luminance maps. We then analyzed how the luminance ratio between the two areas was affected by the addition of ECs.

GLASS SURFACE TEMPERATURE MEASUREMENTS

After installation of the EC windows, anecdotal reports emerged that building occupants noticed a significant improvement in thermal comfort. The ideal way to support that finding with measurements would involve using infrared imaging. However, transporting the required equipment to the Donna site proved impractical. As a practical alternative, we performed spot measurements of glass surface and frame temperature using a thermistor connected to a multimeter (B&K Precision Took Kit 2706A). The thermistor was manually held in place, using a piece of insulating polymer, for two to five minutes, for the temperature to stabilize. The stability criterion used was no more than 0.1°C variation in approximately 5 seconds. The thermistor was unshielded from solar radiation, which meant that measurements taken facing the sun could overestimate actual glass temperature, but that effect would probably be small (approximately on the order of 2°C; the purpose of the measurement was to determine if the difference between interior glass surface temperature and the air temperature was roughly on the order of 10°C or greater).

WINDOW CONTROL SYSTEM DATA

Data from the EC window control system was logged by the building automation system on a one-minute interval. Data included window tint, control mode and sensor levels. This data was used to verify that windows were operating as intended prior to site visits, as well as to characterize the frequency of manual overrides.

V. Results

A. OCCUPANT EXPERIENCE

PRE-INSTALLATION SURVEY

The first online survey gathered information on occupants' perceptions of the original condition prior to installation of the electrochromic (EC) windows. U.S. Customs and Border Protection (CBP) requested that the survey be relatively short to minimize disruption to port operations. There were 8 responses out of a pool of approximately 20-30 occupants. Survey takers were asked to rate statements on a scale from 1 (disagree) to 9 (agree). Results are summarized in Table 7 and shown graphically in Figure 23. See Appendix A for full text of survey.

Table 7. Baseline (pre-installation) survey results summary. Scale is from 1 (disagree with statement) to 9 (agree with statement). Ninety-five percent confidence intervals were obtained by a one-sample t-test.

| Questions | Number of responses | Average | Standard Deviation | 95% confidence interval | | Qualitative interpretation |
|--|---------------------|---------|--------------------|-------------------------|-------------|----------------------------|
| | | | | Lower bound | Upper bound | |
| <i>Command Center</i> | | | | | | |
| Because of glare from the sun, it is often very uncomfortable to look at the outside | 8 | 8.38 | 1.06 | 7.49 | 9.26 | Agree |
| Because of glare from the sun, I often need some of the blinds down in order to work comfortably | 8 | 7.38 | 2.77 | 5.06 | 9.69 | Agree |
| At night, it is hard to see the outside because of reflections from bright objects inside | 8 | 7.00 | 1.77 | 5.52 | 8.48 | Agree |
| Overall, outdoor visibility through the windows meets the needs of my mission | 8 | 5.00 | 2.39 | 3.00 | 7.00 | Neutral |
| <i>Inspection Booth</i> | | | | | | |
| Because of glare from the sun, it is often very uncomfortable to look at the outside | 8 | 7.25 | 1.83 | 5.72 | 8.78 | Agree |
| Overall, outdoor visibility through the windows meets the needs of my mission | 8 | 5.88 | 2.47 | 3.81 | 7.94 | Marginally agree |

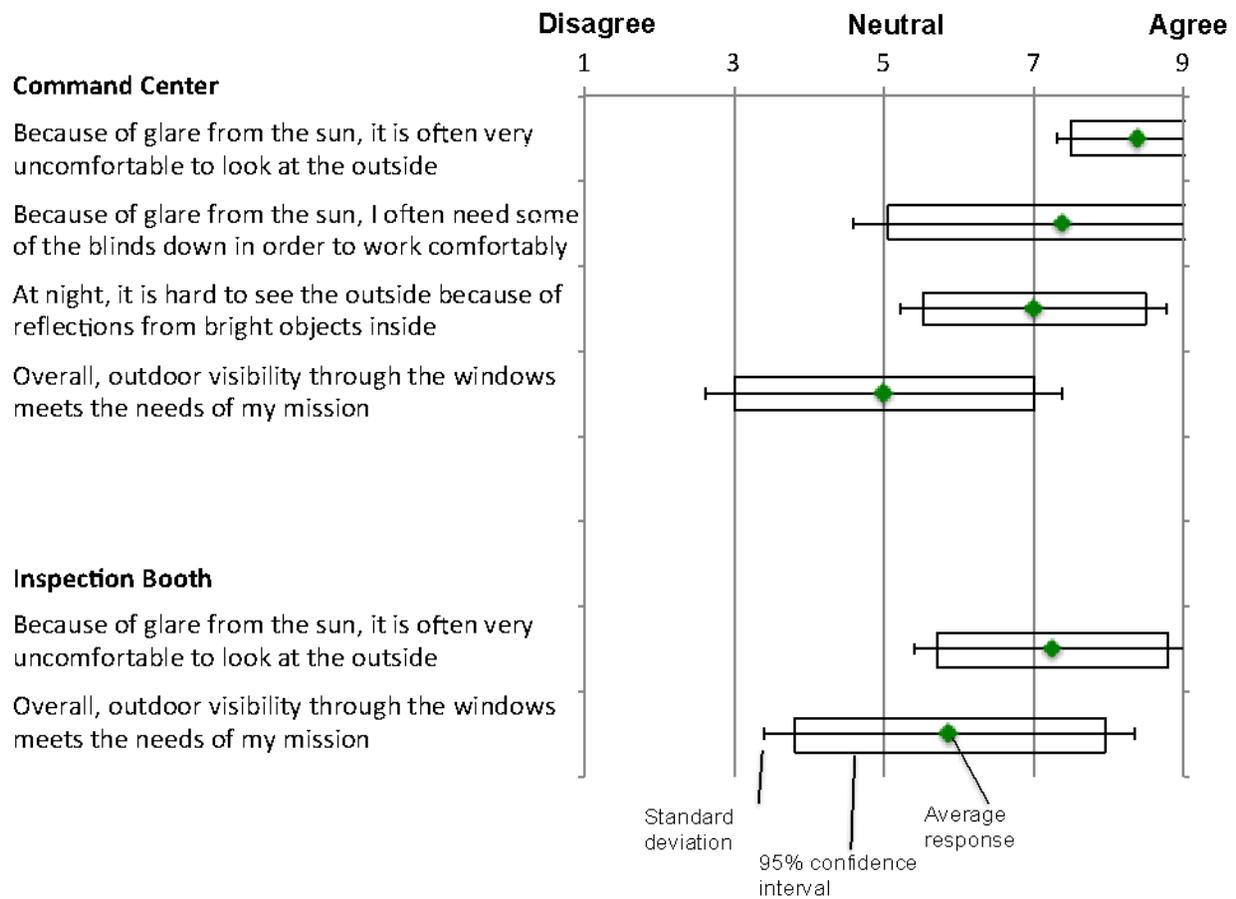


Figure 23. Baseline (pre-installation) survey results: 95% confidence intervals obtained by a one-sample t-test.

Results show a clear agreement regarding the frequent occurrence of glare and need for some kind of protection from it. There is also agreement that nighttime reflections can make it hard to see things outside the windows. Overall, occupants do not appear to feel wholeheartedly that the existing windows with Venetian blinds fully meet the needs of their mission.

These results are generally in line with what was expected. It seems fair to conclude that there is a serious glare problem at the Donna site and that it has a noticeable, but not completely debilitating, effect on the mission of the CBP officers who work there. Furthermore, results suggest a reasonable likelihood that similar effects will be present in other, comparable facilities with similar population.

Participants were also asked to submit written comments on how the windows affected their view through the window and their ability to conduct their mission. Two (25%) of the respondents submitted comments. Comments focused on tradeoffs between visibility and using blinds to control glare. One respondent noted that “the blinds do help a lot to keep the glare out but they also do hinder complete visibility.”

POST-INSTALLATION SURVEY

The second survey was administered on paper, and took place after the windows were in operation for at least eight months. There were a total of 28 responses, comprising the majority of the officers operating in that facility. Survey takers were asked to rate statements on a scale from 1 (disagree) to 9 (agree) and to state their preference between the original and the EC windows. Results for these

questions are shown in Tables 8 to 10 and Figures 24 and 25. See Appendix A for full text and additional results.

Table 8. Post-installation survey results summary (command center/processing area). Scale is from 1 (disagree with statement) to 9 (agree with statement). Ninety-five percent confidence intervals were obtained by a one-sample t-test.

| Questions | Number of responses | Average | Standard deviation | 95% confidence interval | | Qualitative interpretation |
|---|---------------------|---------|--------------------|-------------------------|-------------|----------------------------|
| | | | | Lower bound | Upper bound | |
| <i>Command Center</i> | | | | | | |
| With the new switchable windows, I experience less glare from the sun than with the original conventional windows | 28 | 8.64 | 0.68 | 8.39 | 8.89 | Agree |
| With the new switchable windows, I feel the need for blinds less often than with the original conventional windows | 28 | 8.50 | 0.69 | 8.24 | 8.76 | Agree |
| During daytime, it is easy to observe outside activity through the new switchable windows, even when they are at their darkest tint | 28 | 8.25 | 1.17 | 7.81 | 8.69 | Agree |
| During nighttime, indoor reflections on the new switchable windows don't make it harder to see outside activity than with the original conventional windows | 25 | 7.76 | 1.59 | 7.14 | 8.38 | Agree |
| With the new switchable windows, I experience less heat from the sun while indoors than with the original conventional windows | 27 | 8.44 | 0.97 | 8.08 | 8.81 | Agree |
| Overall, the new switchable windows meet the outdoor visibility needs of my mission better than the original conventional windows | 28 | 8.57 | 0.88 | 8.25 | 8.90 | Agree |

Table 9. Post-installation survey results summary (booth). Scale is from 1 (disagree with statement) to 9 (agree with statement). Ninety-five percent confidence intervals were obtained by a one-sample t-test.

| Questions | Number of responses | Average | Standard deviation | 95% confidence interval | | Qualitative interpretation |
|---|---------------------|---------|--------------------|-------------------------|-------------|----------------------------|
| | | | | Lower bound | Upper bound | |
| <i>Inspection Booths</i> | | | | | | |
| With the new switchable windows, I experience less glare from the sun than with the original conventional windows | 26 | 8.77 | 0.51 | 8.57 | 8.97 | Agree |
| With the new switchable windows, I feel the need for blinds less often than with the original conventional windows | 26 | 8.35 | 1.62 | 7.72 | 8.97 | Agree |
| During daytime, it is easy to observe outside activity through the new switchable windows, even when they are at their darkest tint | 26 | 8.42 | 0.86 | 8.09 | 8.75 | Agree |
| During nighttime, indoor reflections on the new switchable windows don't make it harder to see outside activity than with the original conventional windows | 25 | 8.28 | 1.06 | 7.86 | 8.70 | Agree |
| With the new switchable windows, I experience less heat from the sun while indoors than with the original conventional windows | 26 | 8.65 | 0.56 | 8.44 | 8.87 | Agree |
| Overall, the new switchable windows meet the outdoor visibility needs of my mission better than the original conventional windows | 26 | 8.77 | 0.51 | 8.57 | 8.97 | Agree |

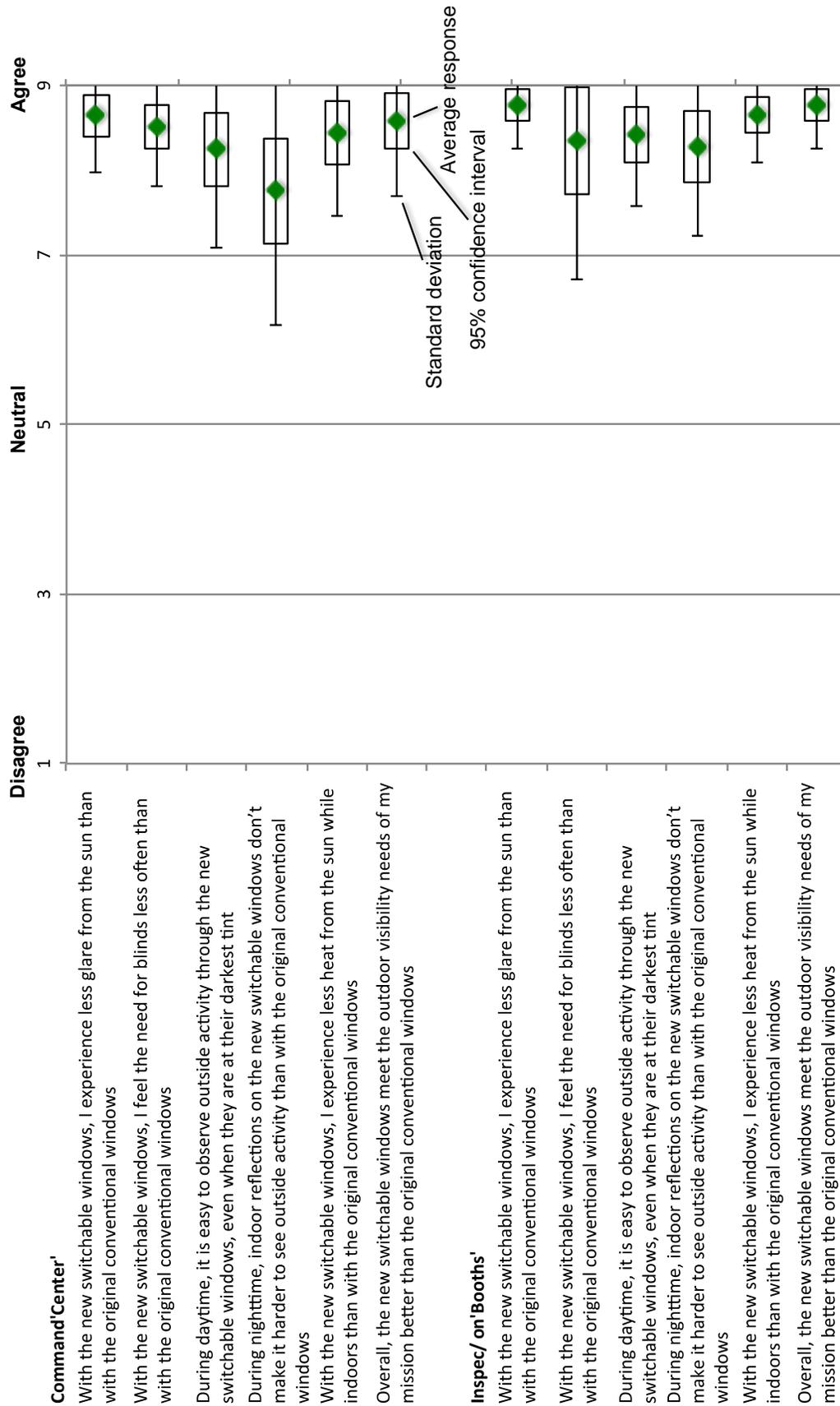


Figure 24. Post-installation survey results: 95% confidence intervals obtained by a one-sample t-test.

Table 10. Responses to two-alternative forced preference between original and EC windows.

Question

Overall, if given the option, would you prefer switchable windows or conventional windows at the command center/processing area?

Options

Number of responses

| | Number of responses | |
|--------------------------------------|---------------------|--------|
| | Command center | Booths |
| Switchable windows | 28 | 24 |
| Conventional, non-switchable windows | 0 | 0 |

Probability that a person will prefer switchable windows

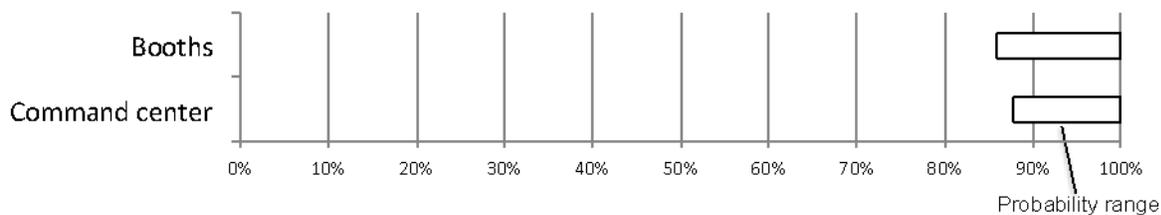


Figure 25. Probability that a person will prefer switchable windows, derived from responses to two-alternative forced preference between original and EC windows.

These results indicate that subjects strongly consider the ECs to be better performing than the original windows in terms of glare control and thermal comfort. They also consider that the ECs do not significantly degrade outside visibility during the daytime or nighttime. Overall, they strongly perceive an improvement in the ability to perform their mission. The probability is high that CBP officers operating in other, similar facilities also will prefer ECs (in a similar retrofit configuration) to conventional windows.

Participants also were asked for written comments on the EC windows. Comments submitted (eight regarding the command center and six regarding the booths) were generally enthusiastic (“very pleased with outcome,” “great concept,” “less glare – less heat,” “the ability to tint/untint is priceless,” “we are now more able to work in computer area without heat or glare issues”). Two participants commented on the dark windows at the command center (“very dark,” “may tint to an unsuitable level during mid-day”). One participant mentioned not being sure of how to control the windows manually (“I would like to be informed on how to control the switches”).

MANUAL OVERRIDES

Figures 26 to 28 show the results of analyzing the frequency of manual overrides to each window zone for an extended period of operation (May 22 to Oct 12, 2014). This frequency can be interpreted as the percentage of that period for which the windows were in override at a particular time of the day. For example, at noon, the south-facing booth windows were in override on 33% of

the days between May 22 to Oct 12, 2014 (Figure 28), whereas the south-facing command center windows were in override on only 3% of the days (Figure 26).

Override frequency varied significantly between the several areas of the port. Overrides were relatively infrequent in the command center, never surpassing a frequency of 6% for any time of the day. Frequency was somewhat higher in the processing area, especially in the afternoon between approximately 3 and 6 PM, but never going over 10%. In the vehicle inspection booth, however, windows were in override during a significant fraction of the operating hours. For example, when considering the period from 8 AM to 8 PM, windows were in override from 16% to 48% of the time, depending on orientation and time of day.

The much higher frequency of overrides in the booth is noteworthy. Visual comfort conditions in booth no. 3 are not obviously worse than in the command center/processing area. As mentioned below in the section on daylight visual comfort measurements (Section V.B), measured DGP was lower in the command center than in the booths but it was not possible to perform worst-case visual comfort measurements in the command center, so the available DGP data is probably not suited to a direct comparison of this kind. Furthermore, the canopy protects booth no. 3 throughout the day from direct solar exposure in a manner not vastly different than the command center or the processing area - the west-facing windows of the processing area are, during the afternoon, actually more exposed than any of the booth windows. This suggests that the differences in override frequency between the booth and the command center/processing area may be mainly due to factors other than visual comfort.

To further investigate this issue, we can turn to the results from the post-installation survey, specifically the question, "Do you use the wall switches to tint or untint the windows?" There were 35% and 42% of "Yes" responses for the command center/processing area and booth, respectively. While more officers used the switches in the booth, the difference between 42% and 35% is not nearly large enough to explain completely the differences in override frequency shown in Figures 26-28 between the booth and other areas. What this could indicate is that, while roughly the same number of officers use the switches in both areas, they use the switches more frequently or for longer periods of time, or both, in the booth. This could be due to one or more of several factors:

- (1) booth no. 3 is in operation during longer periods than other areas of the center (probably not true for the command center, but could be true for the processing area);
- (2) when booths are in operation, they are occupied more intensively, *i.e.*, an officer at a booth is performing relatively repetitive tasks in a relatively small area for what may be an extended period of time, whereas in the command center and processing areas officers may have more variety in tasks and in their physical location, possibly increasing their tolerance of glare;
- (3) in a booth, an officer is freer to operate the switches with fewer concerns about social or hierarchical pressure to operate (or not) the ECs a certain way;
- (4) switches in the booth are physically closer to the officer(s) than in the command center/processing area.

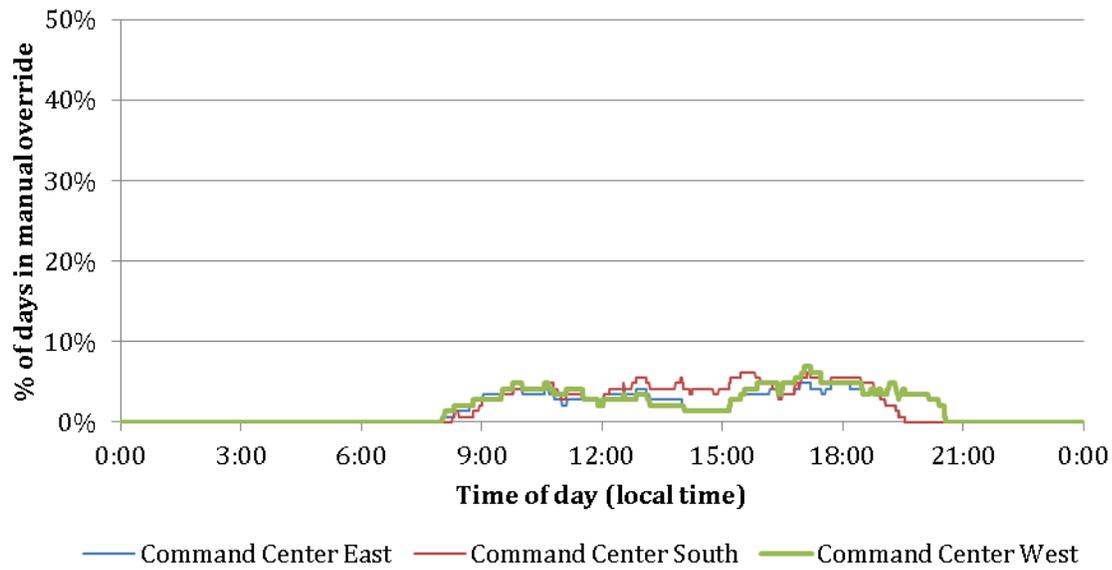


Figure 26. Override frequency throughout day in the command center, May 22 to October 12, 2014.

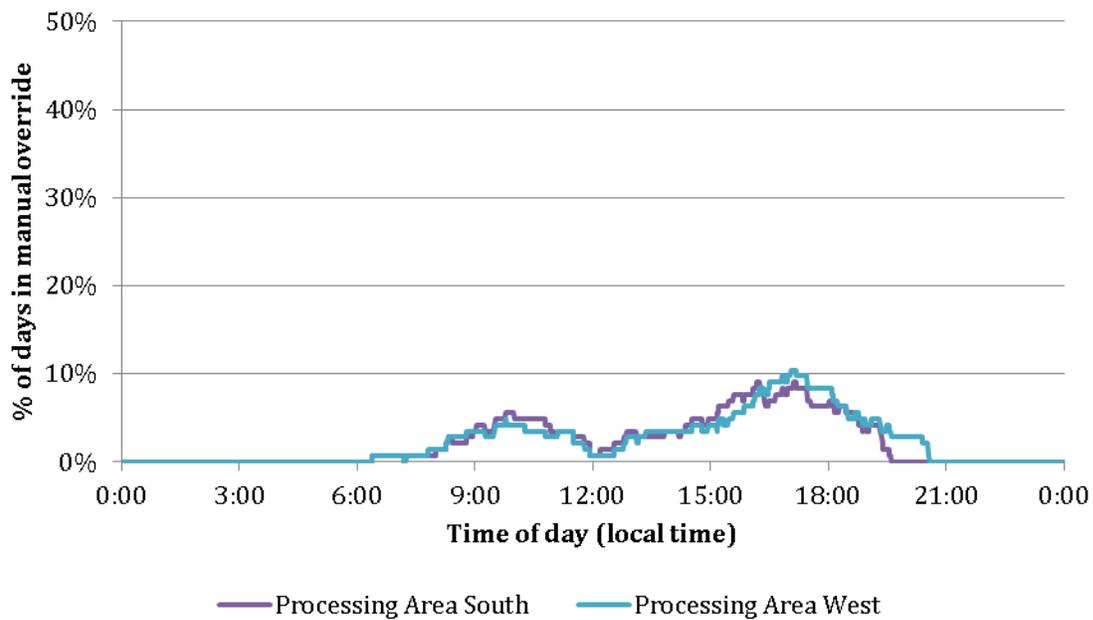


Figure 27. Override frequency throughout day in the processing area, May 22 to October 12, 2014.

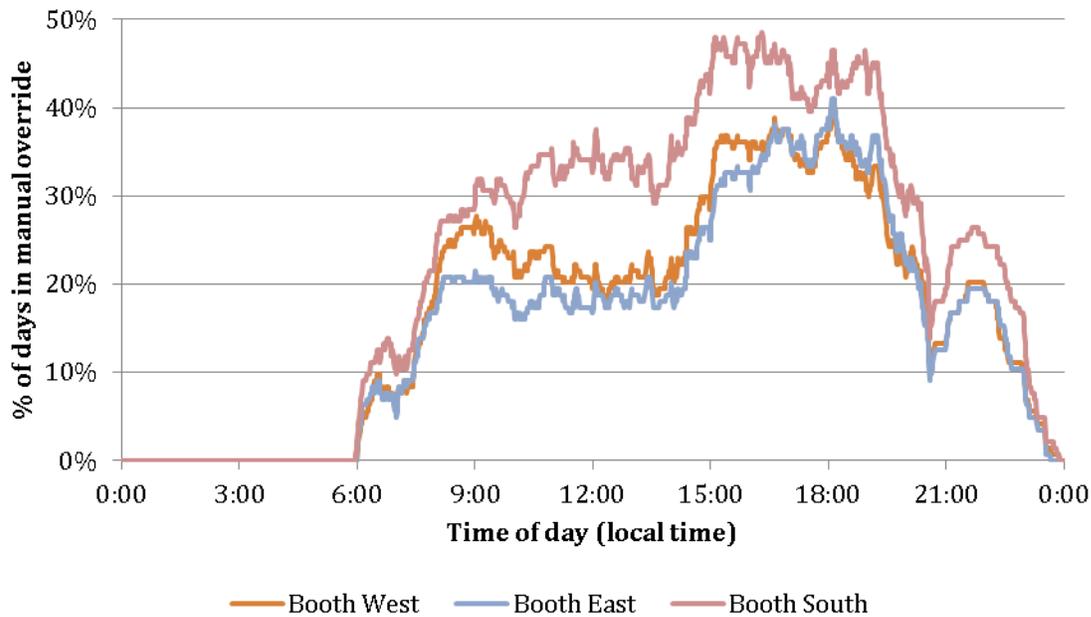


Figure 28. Override frequency throughout day in booth no. 3, May 22 to October 12, 2014.

B. DAYTIME VISUAL COMFORT

VEHICLE INSPECTION BOOTHS

Daylight Glare Probability (DGP) indices calculated for measurements taken in vehicle inspection booths in the afternoon of October 15, 2014, are shown in Figure 29. These measurements were taken facing west, simultaneously in booths 3 and 4, which have EC and original windows (without Venetian blinds), respectively. The results support the pre-installation survey results that indicate prevalence of severe glare in the booths with the original glass. When the orb of the sun is visible through the window, DGP is well above 0.4 (the threshold for disturbing glare). On the other hand, with the EC windows, DGP stays under 0.35 (the threshold for perceptible glare) throughout the afternoon. Booth 3 receives more shading from the canopy than booth 4, and is shaded by booth 4 itself (see Figures 30 and 31 for the views and solar paths from the two measurement positions). This means that these measurements probably somewhat overestimate the difference in DGP between the original and EC windows. However, the additional shading on booth no. 3 is probably not nearly enough to account for the magnitude of the measured difference in DGP.

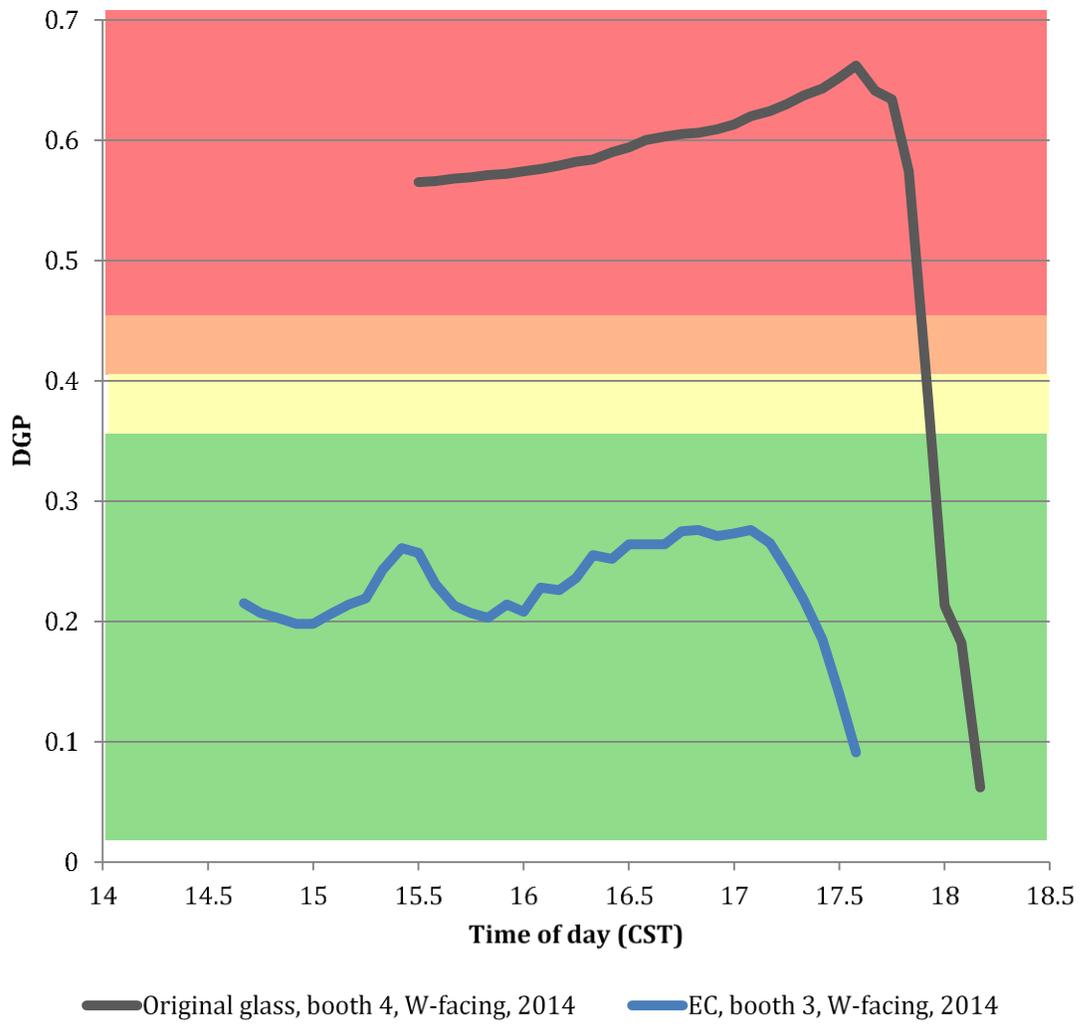


Figure 29. Measured DGP in vehicle inspection booths. These measurements were taken facing west simultaneously in two booths (3 and 4), on October 15, 2014.

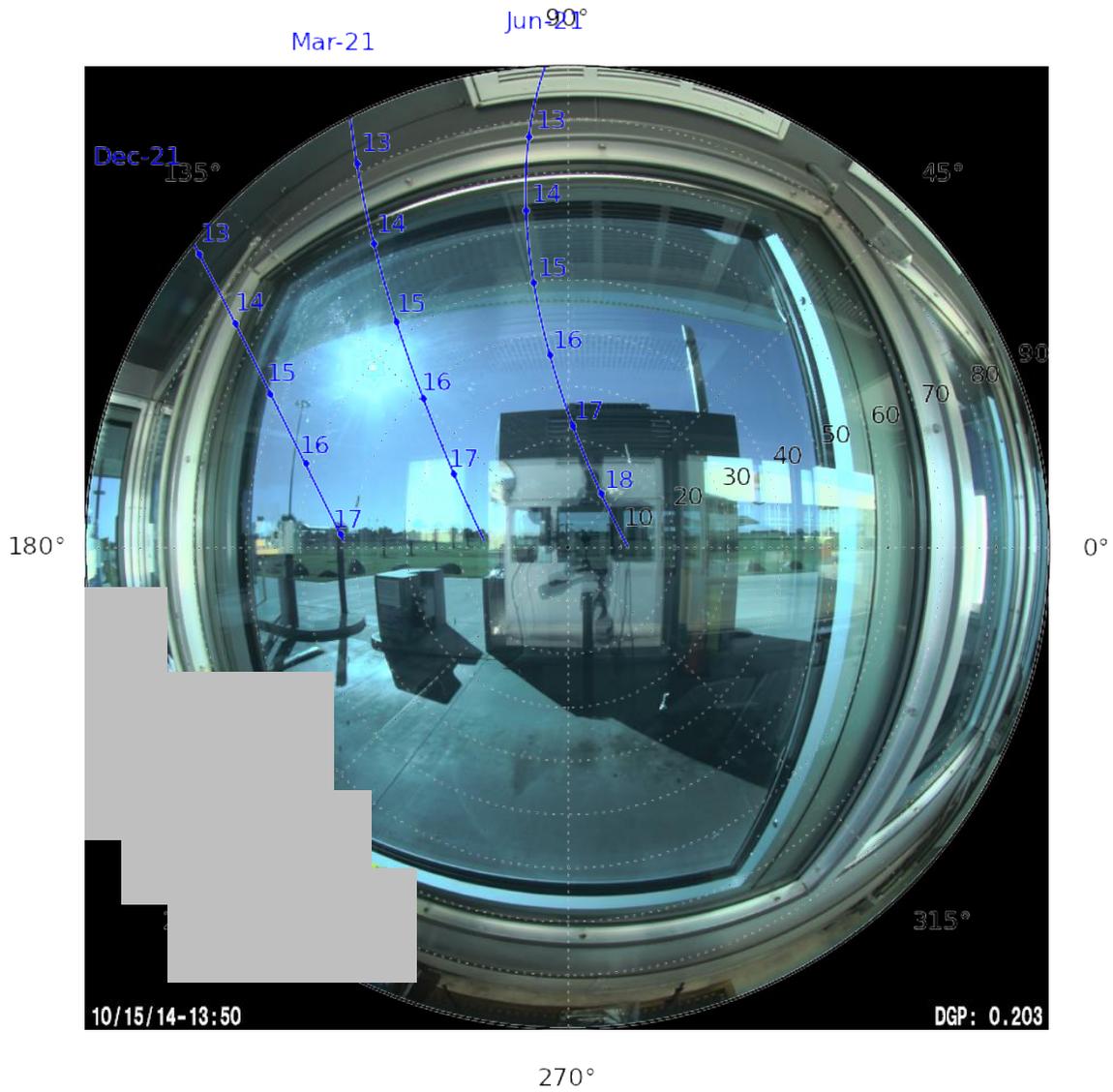


Figure 30. Fisheye view facing west from booth 3, with sun path superimposed. Timestamp on lower left-hand corner of image is in Pacific Standard Time. Hour of day indicated on the sunpaths is local solar time (approximately Central Standard Time).

further complicated, besides the less-than-ideal weather, by the presence of a tinted film on the windows in the areas where the worst glare conditions were likely to be experienced. This film had been installed on the windows due to CBP complaints of intolerable glare after the blinds were removed in anticipation of the upcoming installation of EC windows, which turned out to be delayed more than expected. The film was removed after installation of the EC windows. The pre-installation measurements were performed from an alternative position that, while allowing the original glazing to be measured, was a sub-optimal position from the point of view of capturing the worst glare conditions (see Figures 34 and 35 for the views and solar paths from the two measurement positions). Finally, it should be noted that post-installation measurements were performed with more accurate and reliable equipment than the pre-installation measurements. Nevertheless, the magnitude of the difference points to a significant reduction in glare due to the addition of EC windows.

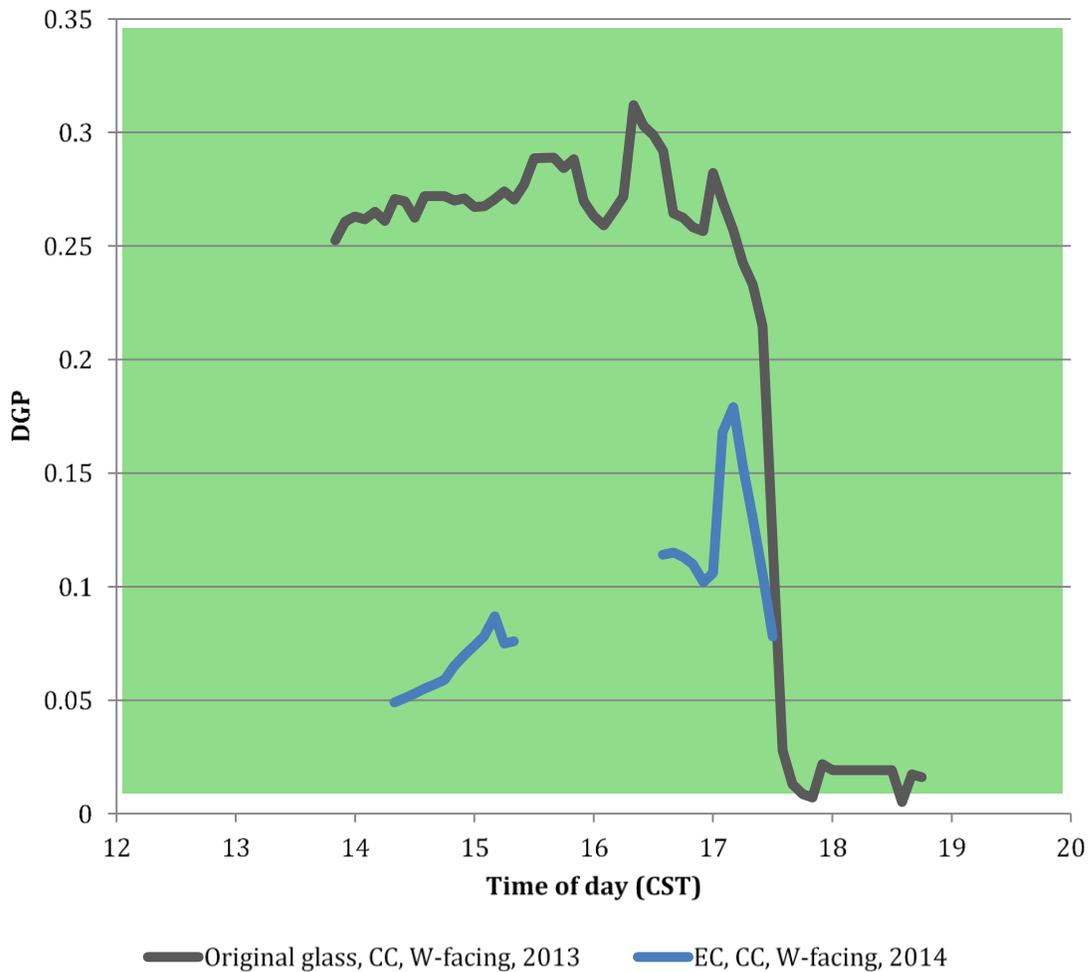


Figure 32. Measured DGP in command center. These measurements were taken facing West, on November 18, 2013, and October 15, 2014. The gap in the EC window curve is due to the fact that light levels were too low for the HDR imaging equipment to make an automated capture.

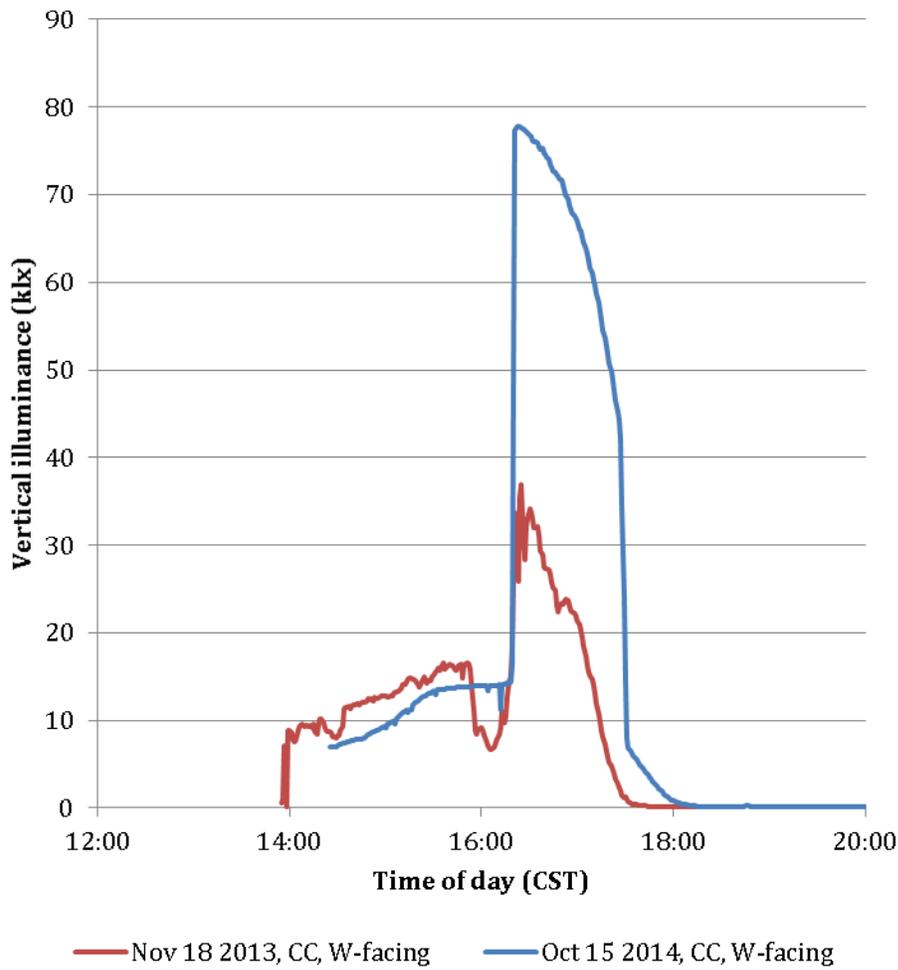


Figure 33. Measured west-facing vertical illuminance on the façade of the command center.

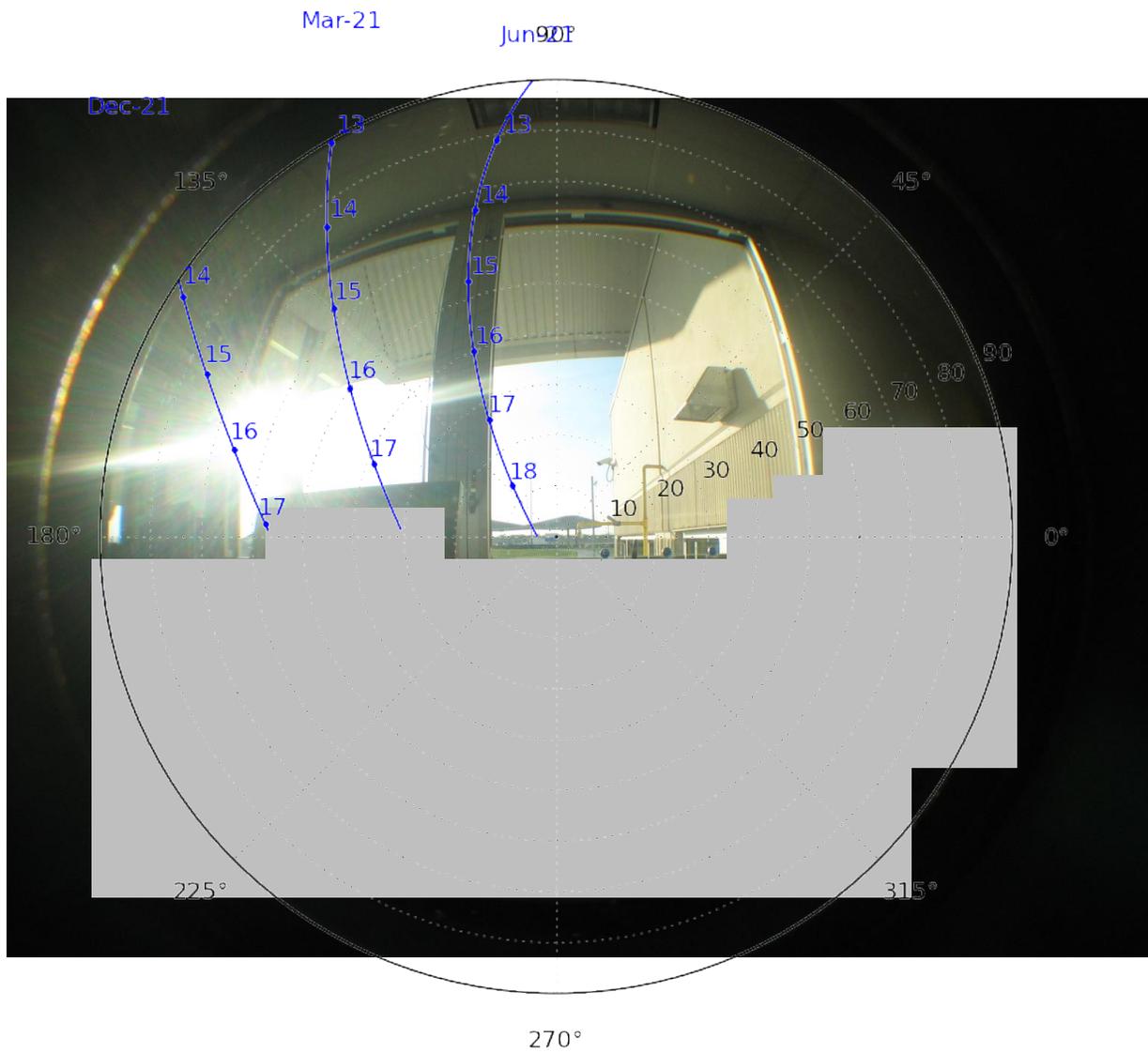


Figure 34. Fisheye view of pre-installation measurements (November 18, 2013) facing west from command center, with sun path superimposed.

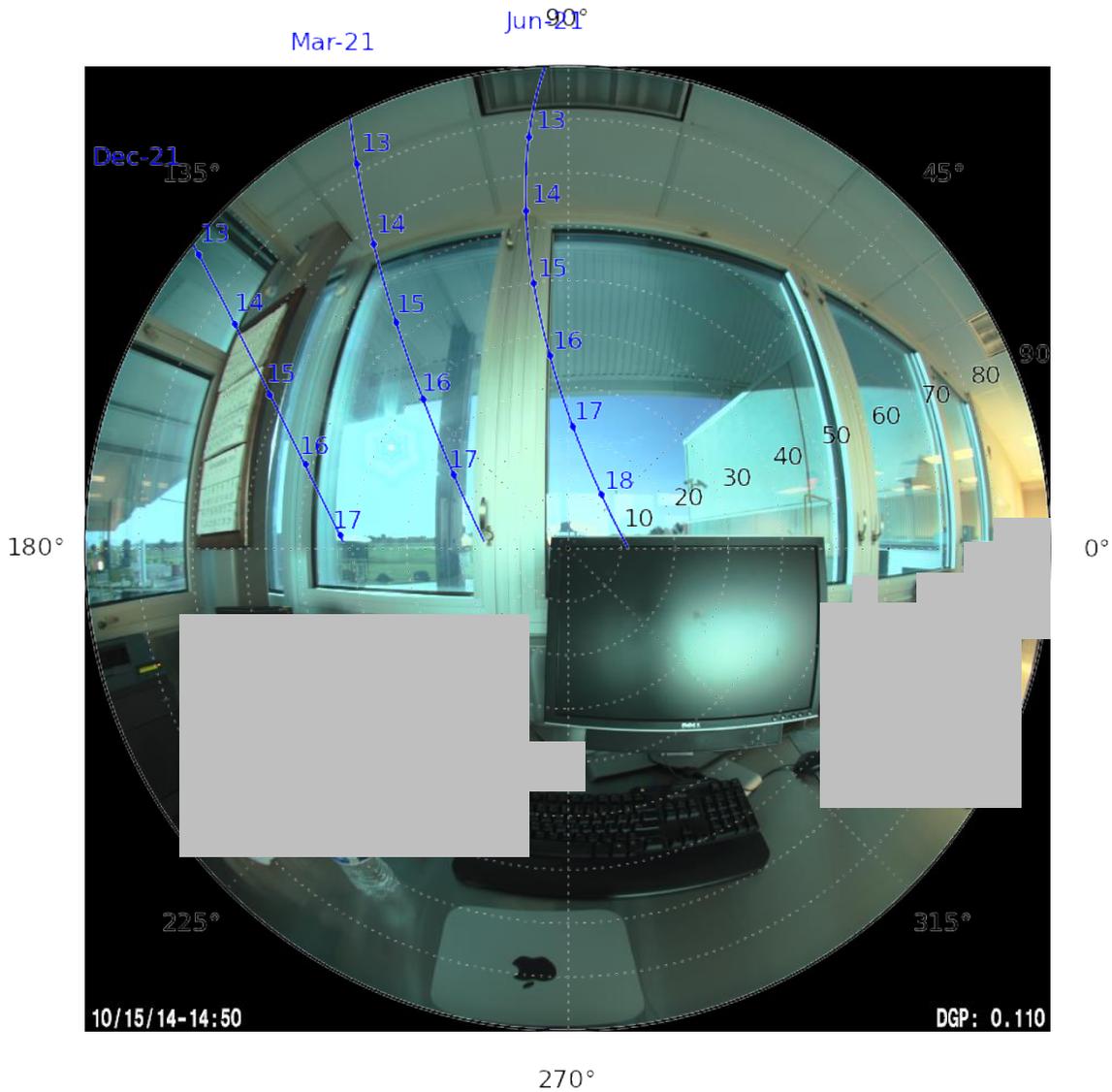


Figure 35. Fisheye view of post-installation measurements (October 15, 2013) facing west from command center, with sun path superimposed.

C. NIGHTTIME VISIBILITY

Using HDR-generated luminance maps, we assessed nighttime visibility using the contrast between two exterior areas of differing brightness. The two areas used are shown in Figure 36. They were chosen because (1) there was at least a 2-to-1 ratio (approximately) in the measured luminance between the areas, (2) they were bright enough that noise in the luminance data did not appear significant, and (3) they were affected visibly and consistently by reflections of the interior when the lights were turned on. Figure 37 shows the four conditions under which measurements were performed: original glass and original glass plus EC retrofit, in both cases with the indoor lights on and off. Average area luminance and calculated contrast ratios are shown in Table 11 and plotted in Figure 38.



Figure 36. Areas used for contrast ratio calculation. Image shows the view out through the existing windows when the indoor lights are off.

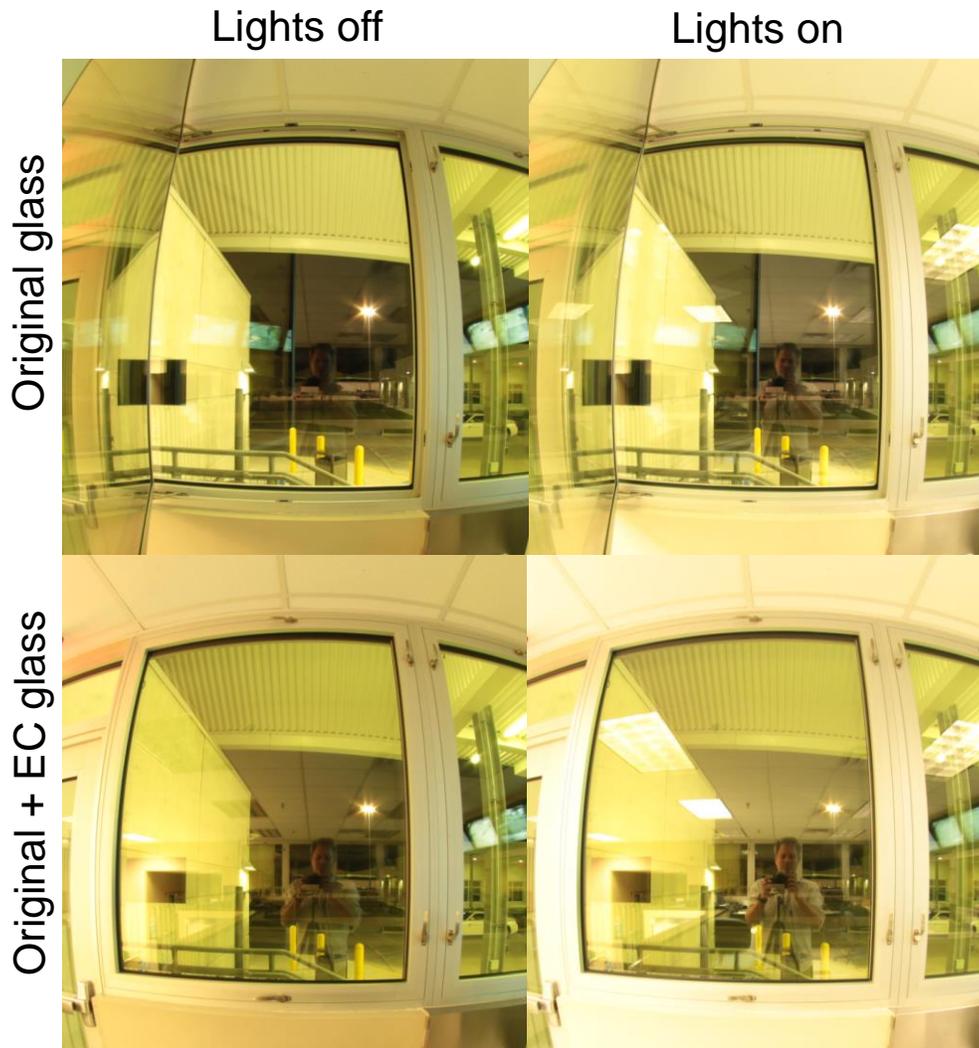


Figure 37. View of the area used for nighttime visibility measurements under the four different conditions evaluated (indoor lights on/off, original/original+EC glass). The four images shown were taken with the same exposure settings (f/8, 8 seconds).

Table 11. Average luminance of areas A and B, and contrast ratios between them.

| Glass | Lights | Luminance (cd/m ²) | | Contrast ratio |
|-------------|--------|--------------------------------|--------|----------------|
| | | Area A | Area B | |
| Original | On | 5.58 | 1.92 | 2.91 |
| Original | Off | 5.32 | 1.56 | 3.41 |
| EC+Original | On | 3.91 | 2.00 | 1.96 |
| EC+Original | Off | 3.28 | 1.13 | 2.90 |

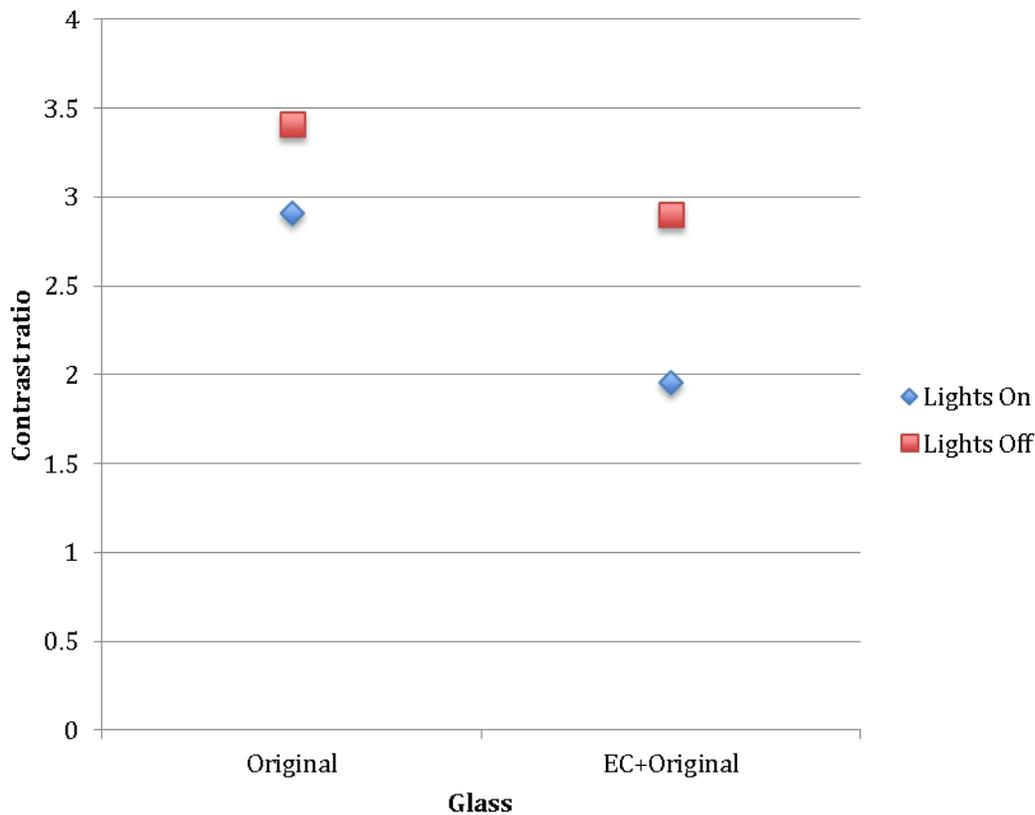


Figure 38. Contrast ratios for original and EC window configurations, with and without lights on.

Turning the interior lights on reduces the contrast ratio in both window configurations. However, the reduction is significantly greater in the case of the EC windows – a 33% reduction in this case, versus 15% for the original window configuration. With or without the lights on, contrast ratios are lower with ECs than with the original configuration. The effect is more marked with the lights on than with the lights off.

These results indicate that adding ECs to existing glass could result in significant reductions in nighttime visibility through windows. The actual impact will depend on how brightly illuminated the building interior is relative to its surroundings. At the Donna Land Port of Entry, the outdoor inspection area outside of the command center is well lit (horizontal illuminance in the 300-400 lx range, approximately), but parts of the facility grounds are considerably darker (*e.g.*, 49 lx on roadway west of command center, 8 lx on pedestrian path east of command center). Visibility of the latter areas could be significantly decreased by the addition of ECs to the windows, particularly when the interior lights are on. These effects could be mitigated by lowering indoor light levels relative to outdoor light levels. Another alternative would be to darken interior surfaces, such as walls, ceiling and furniture, by re-finishing or (in the case of furniture) replacing them.

In the case of replacing the original glass with an EC bullet-resistant IGU, the effect on nighttime visibility will depend on how the interior surface reflectance of the new IGU compares to that of the original IGU. If there is no change in visible transmittance, a decrease in interior surface reflectance should result in improved nighttime visibility. Conversely, an increase in reflectance should result in worse nighttime visibility.

D. GLASS SURFACE TEMPERATURE

Table 12 shows typical afternoon temperatures measured on October 15 and 16, 2014, for several glass surfaces. The interior surface of the EC glass was much cooler than the interior surface of the original glass (approximately 26°C vs. 42°C in the secondary inspection building and 25°C vs. 43°C in the booths), and very likely to result in a noticeable, significant increase in perceived thermal comfort⁸. Note that, in the secondary inspection building, the measurement of the interior surface temperature of the original windows (see “Original glass, indoor surface” in Table 12) could not be performed in the command center or the processing areas since they had been retrofitted; this measurement was performed in a break room that had a west-facing window.

Table 12. Glass surface temperatures at approximately 4:30- 5 PM CDT on October 15-16, 2014, under clear sky conditions.

| Surface | Temperature | |
|---|-------------|-------|
| | °C | °F |
| <i>Command Center</i> | | |
| Original glass, outdoor surface | 46.6 | 115.9 |
| Original glass, indoor surface*† | 41.3 | 106.3 |
| Original glass, cavity surface† | 42.6 | 108.7 |
| EC, cavity surface | 40.1 | 104.2 |
| EC, indoor surface† | 25.8 | 78.4 |
| <i>Inspection booths</i> | | |
| Booth 4 (original glass), W-facing, indoor† | 43.2 | 109.8 |
| Booth 3 (EC retrofit), W-facing, indoor† | 25.3 | 77.5 |

* This measurement was performed on an alternate window - see text for details.

† This measurement faced the sun; the temperature probe was not shielded from solar radiation.

This significant reduction in interior surface temperature is probably due to a combination of several factors: (a) additional panes of glass provide a reduction in solar transmittance, as well as additional thermal insulation, (b) the tint of the ECs provides an additional reduction in solar heat gains and (c) in the command center, the space between the original glass and the EC IGU is vented towards the plenum, reducing heat buildup within the window.

⁸ Because the booths are (1) much smaller and less well thermally insulated than the secondary inspection building and (2) usually operated with doors open, it might be expected that on a warm day the interior window surface temperature would be significantly higher in the booths than in the command center. Results are similar between the two locations, however, probably due to the following factors: (1) each booth has a powerful dedicated air conditioning unit that appeared, during our site visits, very effective at keeping the air cool inside the booths and (2) the temperature measurements in the booths were performed with the doors closed and after waiting a few minutes (but on a window that was not directly affected by cold air blowing down from the ceiling diffuser).

To understand the relative importance of the first two factors, we modeled the command center windows using the Optics 6 and Window 7 software [Versluis, 2002; Mitchell, 2008], which allow accurate calculation of solar-optical properties of windows. We also modeled two additional windows: one in which a double clear IGU was added to the original command center glass, and another in which a double clear IGU with spectrally selective low emissivity (low-e) coating (on surface 3) was added. The U-value and solar heat gain coefficient (SHGC) of the modeled windows are shown in Table 13. It is readily apparent that the EC retrofit improves solar-optical properties—both U-value and SHGC are significantly lower when compared to the original glass. However, the effect is not dissimilar to the addition of either a double clear or a double low-e clear IGU. This suggests that the most significant part of the improvements in thermal comfort is due to the addition of an IGU, and not to the fact that the windows are electrochromic.

Table 13. U-value, SHGC and visible transmittance for modeled command center windows.

| | SHGC | U (W/m²-K) | Tvis |
|------------------------------------|-------------|------------------------------|-------------|
| Original glass | 0.407 | 1.493 | 0.388 |
| Original + EC (clear state) | 0.289 | 0.799 | 0.245 |
| Original + EC (full tint) | 0.283 | 0.799 | 0.013 |
| Original + double spec. sel. low-E | 0.246 | 0.737 | 0.246 |
| Original + double clear | 0.317 | 0.938 | 0.309 |

VI. Summary Findings and Conclusions

A. OVERALL TECHNOLOGY ASSESSMENT AT DEMONSTRATION FACILITY

Occupant survey results clearly indicate that the addition of electrochromic (EC) technology to the existing windows at the Donna Land Port of Entry was successful in controlling glare and, thus, eliminating the need for view-obstructing shading devices. Measurements of visual comfort taken at the command center and in vehicle inspection booths are consistent with this conclusion. Even though survey results indicate that U.S. Customs and Border Protection (CBP) officers generally did not perceive nighttime visibility to be an issue, measurements indicate some degradation in the visibility outwards through the windows at nighttime, especially when interior lights are turned on. Regarding daytime visibility, survey results similarly indicate no perceived degradation, even though bright reflections on the interior surface of the windows were visible during the post-installation site visit (in sunny conditions and with windows at full tint) when looking into the booth from the outside through the open door.

The results of this study indicate that it is likely that an EC retrofit of this type would have similar performance if deployed at comparable facilities. This includes other land ports of entry, as well as military, law-enforcement or any other type of governmental or private security facility in which it is valuable to maintain visual contact with the exterior surroundings in glary, sunny conditions.

Care should be taken in attempting to extrapolate the results of this study to situations in which the original glazing is replaced by an EC IGU. In such cases the window will have a higher visible transmittance than the window assembly studied here, and, therefore, glare control is likely to be less effective and may not be sufficient to eliminate the need for view-obstructing shading. A suitable solution might be to match the visible transmittance of a bullet-/blast-resistant EC double-pane IGU to the transmittance of the whole assembly (original double-pane bullet-/blast-resistant glass + non-bullet-/blast-resistant double-pane EC retrofit) studied here⁹; the manufacturer has indicated that this would be technically feasible.

This facility had a canopy that blocked views of the sun orb for the majority of the daytime to the east, west, and south. This study demonstrates that glare from the sky is controlled more effectively with the EC windows than the existing glass. Further study is needed to evaluate visual discomfort if the sun orb is in the field of view for the majority of the day, as would occur in facilities with no overhangs in more northern areas of the U.S.

Care also should be taken when applying any of these configurations (EC IGU add-on to existing windows or transmittance-matched EC bullet-/blast-resistant IGU) in facilities with particularly stringent requirements for nighttime visibility of dark exterior surroundings. In such situations, we recommend further testing or, at a bare minimum, an analysis comparing the interior surface

⁹ The exact transmittance of the original windows installed in the command center/processing area is not known. Specifications indicate that the minimum visible transmittance would be 0.35. Given that the EC window that was added has a visible transmittance of approximately 0.60 in its clear state and 0.01 when fully tinted, this would mean that the clear-state visible transmittance of a suitable transmittance-matched bullet-/blast-resistant EC IGU could be as low as 0.21, and as low as 0.0035 for the fully tinted state.

reflectance of the EC IGU (including the original window, in the case of an add-on retrofit like the one studied here) to that of the original IGU.

In case of power failure, EC windows will gradually go to their clear state. Although border inspection facilities often have emergency power infrastructure, thereby making complete power failures uncommon, the effect of a power failure on EC windows should be taken into account in planning for this kind of eventuality. Possible mitigating actions include using temporary shading (mounted on the glass using suction cups) or powering the windows and their control system using a photovoltaic backup system.

B. BARRIERS AND ENABLERS TO ADOPTION

During this study, several issues were identified that need to be considered when adding EC windows to other, similar facilities. These included the possibility of dirt, heat and moisture build-up between the EC and the original IGUs. In this case, they were dealt with by installing the EC IGU in an operable window frame. Applicable requirements for blast- or bullet-resistance also need to be taken into account. In areas such as Donna, which might be subject to frequent hurricane weather, behavior of externally-mounted retrofits under high wind loads also could be a concern.

In the GPG demonstration of electrochromic windows at the Denver Federal Center, the installed cost of a EC window retrofit (including controls) was estimated at \$61/ft² (assuming large volume and mature market [Lee, 2014]) if the existing frame was left in place and \$79/ft² if the frame was replaced. Recent manufacturer estimates for the GPG demonstration in Sacramento, California, are in the vicinity of \$45/ft² (existing frame left in place). Costs will likely be higher when installing bullet-/blast-resistant IGUs. When adding an EC IGU to existing bullet-/blast-resistant windows the cost of designing, manufacturing and installing the additional custom frames will need to be considered.

These costs raise the question of whether there are less costly technologies that can compete in performance. Possible alternatives are fabric screens and tinted films, either applied to the exterior or interior of the window or operable in the same manner as a roller shade. These might provide some degree of glare and heat gain control – possibly to the same degree attained by the ECs in this study. Permanently applied screens or films might perform well in some conditions, but it is unlikely that they would perform well enough throughout the variety of glare and light levels usually encountered in these facilities; they would certainly reduce nighttime visibility severely. Operable screens or films could circumvent some of these issues and might be very cost-effective if manually operated, but would require frequent adjustments by the occupants if optimal viewing conditions were to be maintained. An automated solution would have the potential to perform as well as ECs in controlling glare for a reasonable cost (approximately \$5.40/ft² installed; estimate using data from [Lee et al., 2013]), although the movement of automated films/shades could distract occupants from their observation through the window.

VII. Appendices

A. SURVEYS

BASELINE SURVEY

I. WHEN IN THE COMMAND CENTER/PROCESSING AREA...

1) Indicate your level of agreement/disagreement (disagree = 1, agree = 5) with the following statements regarding the **existing** windows:

| | Disagree | | Neutral | | Agree |
|---|----------|---|---------|---|-----------------|
| | 1 | 2 | 3 | 4 | 5 ¹⁰ |
| a) Because of glare from the sun, it is often very uncomfortable to look at the outside | | | | | |
| b) Because of glare from the sun, I often need some of the blinds down in order to work comfortably | | | | | |
| c) At night, it is hard to see the outside because of reflections from bright objects inside | | | | | |
| d) Overall, outdoor visibility through the windows meets the needs of my mission | | | | | |

2) Please provide any comments on how the **existing** windows and blinds enhance or reduce your view of the exterior and your ability to perform your mission.

¹⁰ The scale actually used in the online survey was from 1 to 9 so that the scale better resembled a continuum.

II. IN A VEHICLE INSPECTION BOOTH...

1) Indicate your level of agreement/disagreement (disagree = 1, agree = 5) with the following statements regarding the **existing** windows:

| | Disagree | | Neutral | | Agree |
|---|----------|---|---------|---|-----------------|
| | 1 | 2 | 3 | 4 | 5 ¹¹ |
| a) Because of glare from the sun, it is often very uncomfortable to look through the windows at the outside | | | | | |
| b) Overall, outdoor visibility through the windows meets the needs of my mission | | | | | |

2) Please provide any comments on how the **existing** windows enhance or reduce your view of the exterior and your ability to perform your mission.

¹¹ The scale actually used in the online survey was from 1 to 9 so that the scale better resembled a continuum.

POST-INSTALLATION SURVEY

a Survey text

Switchable windows: Satisfaction Survey

Welcome!

Thank you for your participation in this pilot evaluation of switchable windows. This study is sponsored by GSA's Green Proving Ground and is being conducted by the Lawrence Berkeley National Laboratory (LBNL).

Your feedback will help understand how well the new switchable windows installed at the Donna Land Port of Entry meet your needs. Results will help GSA and CBP decide whether to deploy this technology more widely.

Survey Details

- **Time:** The survey usually takes 10 minutes to complete.
- **Confidentiality:** Your answers are confidential. Survey responses will not be linked to an individual's identity. To avoid bias, please do not discuss your impressions with anyone else.
- **Voluntary Participation:** Your participation in this study is voluntary. You are free to skip any questions you don't want to answer and to end your participation at any time. Your decision to fill out the survey or not will have no effect on your job or any benefits you receive now or in the future.
- **Questions.** If you have any other questions about the study, please contact LBNL researcher Luis Fernandes at [phone number redacted] or [e-mail address redacted].

Instructions

Please fill out this questionnaire as completely as possible, skipping any question you are unable to answer or do not want to answer. Please respond to all of the items as openly and honestly as possible. There are no right or wrong answers; it is only your opinions that are important.

When you are done with the questionnaire, please place it in the provided envelope and seal the envelope before returning it.

SWITCHABLE WINDOWS

Switchable windows are windows that can tint and untint automatically or at the press of a switch like in the images below:



Window switches in the *command center/processing area*



Window switches in the *vehicle inspection booth*

In July/August 2013, switchable windows were installed in the command center, processing area and one of the vehicle inspection booths in the Donna Land Port of Entry.

PRELIMINARY INFORMATION

Were you stationed at the Donna site before the switchable windows were installed in the command center (July 2013)?

- a) Yes
- b) No

IN THE COMMAND CENTER/PROCESSING AREA...

1) When at the command center/processing area, what percentage of time, on average, do you spend on each of the tasks below?

| Task | Percentage (%) |
|--|----------------|
| Observing outside activity directly through windows | _____ |
| Observing outside activity using surveillance monitors | _____ |
| Performing computer-based tasks | _____ |
| Performing paper-based tasks | _____ |
| Other (please specify)_____ | _____ |

2) When inside the command center/processing area, during the day, do you wear sunglasses?

- a) Yes
- b) No

3) When inside the command center/processing area, during the day, do you usually wear a cap with a visor?

- a) Yes, to protect my eyes from glare
- b) Yes, for reasons unrelated to glare
- c) No

4) At the command center/processing area, do you use the wall switches to tint or untint the windows?

- a) Yes
- b) No

5) If you use the wall switches, what are the primary reasons? (please check all that apply)

- | | |
|--|---|
| <input type="checkbox"/> To reduce glare from daylight/sunlight | <input type="checkbox"/> To decrease the brightness of reflections on my computer monitor |
| <input type="checkbox"/> To reduce glare when the sun is directly visible | <input type="checkbox"/> To test how the switches tint/untint the windows |
| <input type="checkbox"/> To reduce the overall brightness of the space | <input type="checkbox"/> Other (please specify) _____ |
| <input type="checkbox"/> To increase the overall brightness of the space | |
| <input type="checkbox"/> To get a better view of the outdoors | |
| <input type="checkbox"/> To increase privacy | |
| <input type="checkbox"/> To reduce the heat from the sun | |
| <input type="checkbox"/> To decrease the level of visual stimulus from the outside | |

6) Indicate your level of agreement/disagreement (*disagree = 1, agree = 9*) with the following statements regarding how the *new switchable windows* compare to the *original conventional windows* in the command center/processing area:

NOTE: *If you were not stationed at the Donna Land Port of Entry before switchable windows were installed (around July 2013), you may have not experienced the original command center windows. When asked about the original conventional windows below, please respond based on your impressions of command center windows in other ports of entry that you have operated at.*

| | Disagree | | | Neutral | | | Agree | | |
|--|----------|---|---|---------|---|---|-------|---|---|
| a) With the new switchable windows, I experience less glare from the sun than with the original conventional windows | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| b) With the new switchable windows, I feel the need for blinds less often than with the original conventional windows | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| c) During daytime, it is easy to observe outside activity through the new switchable windows, even when they are at their darkest tint | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| d) During nighttime, indoor reflections on the new switchable windows don't make it harder to see outside activity than with the original conventional windows | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| e) With the new switchable windows, I experience less heat from the sun while indoors than with the original conventional windows | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| f) Overall, the new switchable windows meet the outdoor visibility needs of my mission better than the original conventional windows | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |

7) Overall, if given the option, would you prefer switchable windows or conventional windows at the command center/processing area?

- a) Switchable windows
- b) Conventional, non-switchable windows

8) Please provide any comments on the new switchable windows in the command center/processing area including but not limited to how they

- enhance or reduce your view of outside activity
- enhance or reduce your thermal and visual comfort
- positively or negatively impact your ability to perform your mission

Comments

IN THE VEHICLE INSPECTION BOOTH...

1) When working at a booth, what percentage of time do you spend with on each of the tasks below?

| Task | Percentage (%) |
|--|----------------|
| Observing outside activity directly through windows | _____ |
| Interacting with vehicle occupants while inside booth | _____ |
| Interacting with vehicle occupants while outside booth | _____ |
| Performing computer-based tasks | _____ |
| Performing paper-based tasks | _____ |
| Other (please specify) _____ | _____ |

2) When working at a booth with *conventional, non-switchable windows*, in daytime, do you usually wear sunglasses while inside the booth?

- a) Yes
- b) No

3) When at the booth with *switchable windows*, in daytime, do you usually wear sunglasses while inside the booth?

- a) Yes
- b) No

4) When at a booth with *conventional, non-switchable windows*, in daytime, do you usually wear a cap with a visor while inside the booth?

- a) Yes, to protect my eyes from glare
- b) Yes, for reasons unrelated to glare
- c) No

5) When at the booth with *switchable windows*, in daytime, do you usually wear a cap with a visor while inside the booth?

- a) Yes, to protect my eyes from glare
- b) Yes, for reasons unrelated to glare
- c) No

6) In the booth with *switchable windows*, do you use the wall switches to tint or untint the windows?

- a) Yes
- b) No

7) If you use the wall switches, what are the primary reasons? (please check all that apply)

- | | |
|---|---|
| <input type="checkbox"/> To reduce glare from daylight/sunlight | <input type="checkbox"/> To increase privacy |
| <input type="checkbox"/> To reduce glare when the sun is directly visible | <input type="checkbox"/> To reduce the heat from the sun |
| <input type="checkbox"/> To reduce the overall brightness of the space | <input type="checkbox"/> To decrease the level of visual stimulus from the outside |
| <input type="checkbox"/> To increase the overall brightness of the space | <input type="checkbox"/> To decrease the brightness of reflections on my computer monitor |
| <input type="checkbox"/> To get a better view of the outdoors | <input type="checkbox"/> To test how the switches tint/untint the windows |
| | <input type="checkbox"/> Other (please specify) _____ |

8) Indicate your level of agreement/disagreement (disagree = 1, agree = 9) with the following statements regarding how the *new switchable windows* compare to the *original conventional windows* in the same booth:

NOTE: *If you were not stationed at the Donna Land Port of Entry before switchable windows were installed (around July 2013), you may have not experienced the original windows in the booth that now has switchable windows. When asked about the original conventional windows please respond based on your impressions of the conventional, non-switchable windows currently installed at the other three booths.*

| | Disagree | | | Neutral | | | Agree | | |
|--|----------|---|---|---------|---|---|-------|---|---|
| a) With the new switchable windows, I experience less glare from the sun than with the original conventional windows | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| b) With the new switchable windows, I feel the need for blinds or shades less often than with the original conventional windows | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| c) During daytime, it is easy to observe outside activity through the switchable windows, even when they are at their darkest tint | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| d) During nighttime, indoor reflections on the new switchable windows don't make it harder to see outside activity than with the original conventional windows | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| e) With the new switchable windows, I experience less heat from the sun while indoors than with the original conventional windows | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| f) Overall, the new switchable windows meet the outdoor visibility needs of my mission better than the original conventional windows | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |

9) Overall, if given the option, would you prefer switchable windows or ordinary, conventional windows at all vehicle inspection booths?

- a) Switchable windows
- b) Conventional, non-switchable windows

10) Please provide any comments on the switchable windows in the vehicle inspection booth, including but not limited to how they:

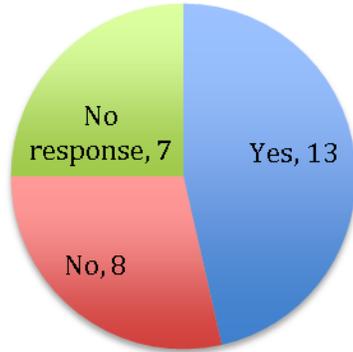
- enhance or reduce your view of outside activity
- enhance or reduce your thermal and visual comfort

- positively or negatively impact your ability to perform your mission

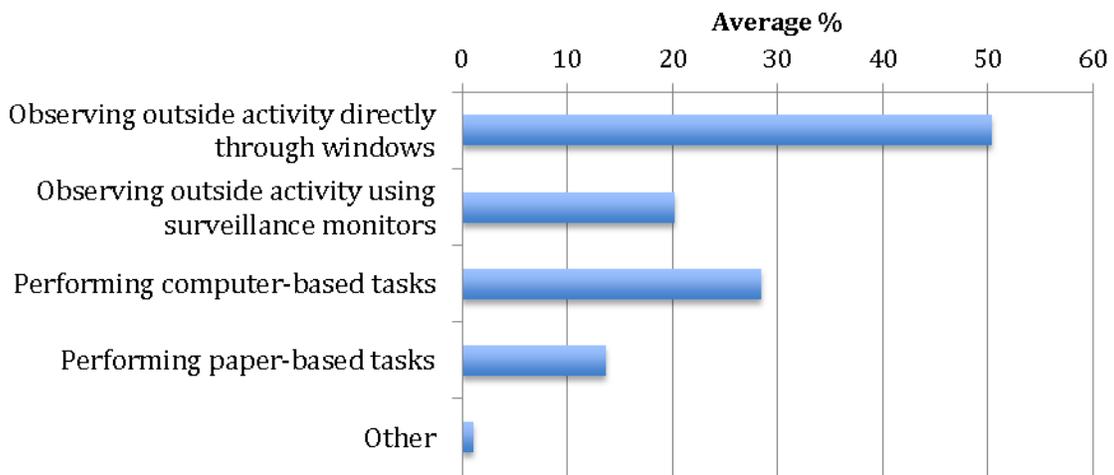
Comments

b Additional results

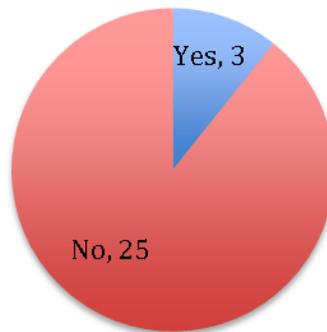
Were you stationed at the Donna site before the switchable windows were installed in the command center (July 2013)?



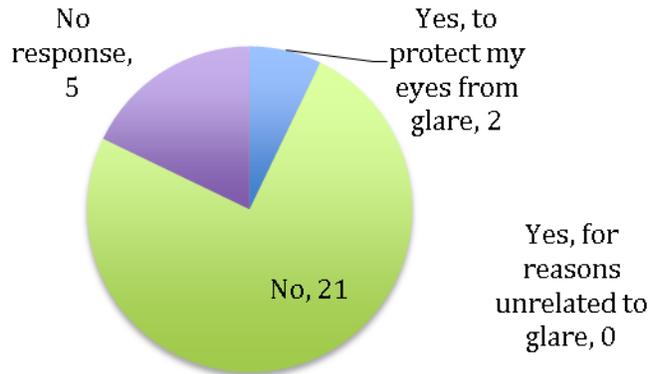
When at the command center/processing area, what percentage of time, on average, do you spend on each of the tasks below?



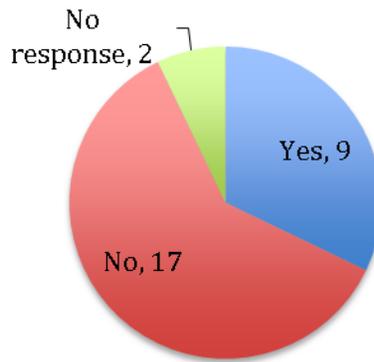
When inside the command center/processing area, during the day, do you wear sunglasses?



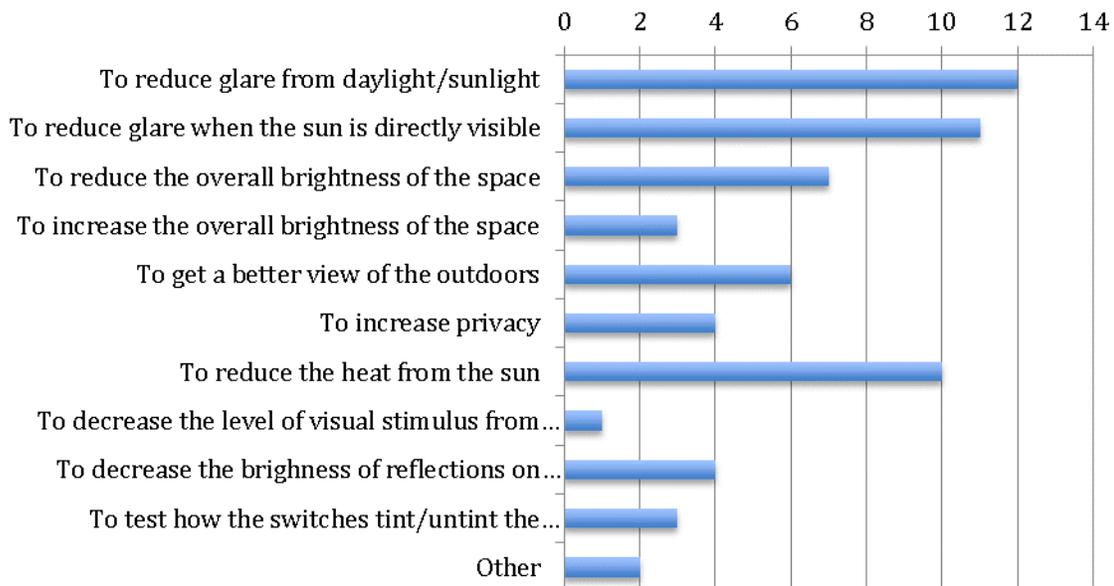
When inside the command center/processing area, during the day, do you usually wear a cap with a visor?



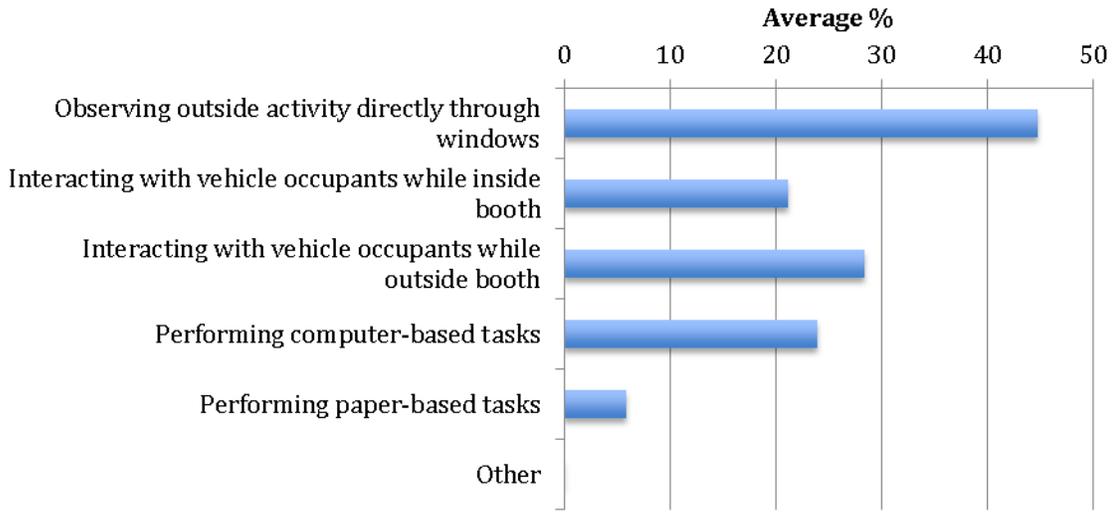
At the command center/processing area, do you use the wall switches to tint or untint the windows?



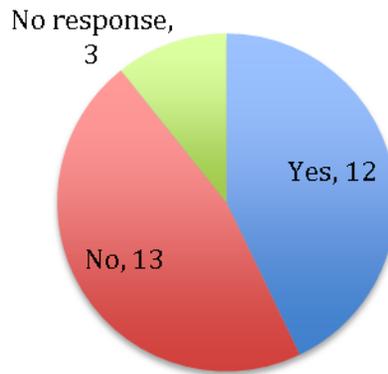
If you use the wall switches [in the command center/processing area], what are the primary reasons? (please check all that apply)



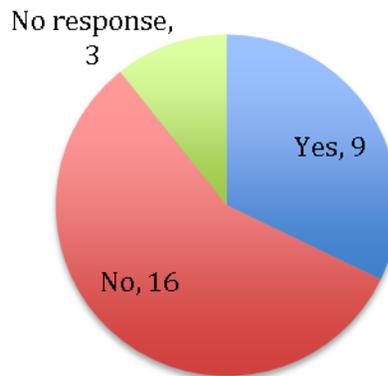
When working at a booth, what percentage of time do you spend with on each of the tasks below?



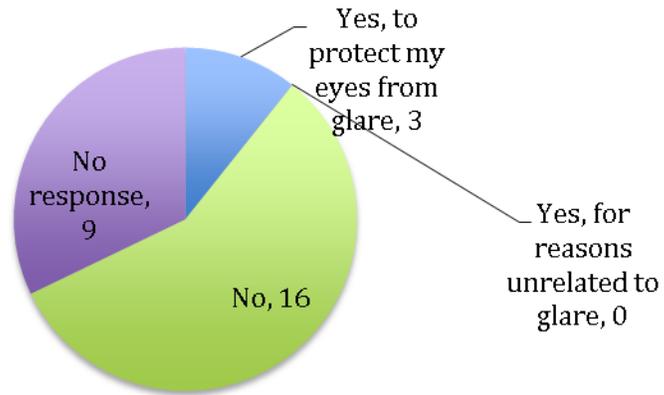
When working at a booth with conventional, non-switchable windows, in daytime, do you usually wear sunglasses while inside the booth?



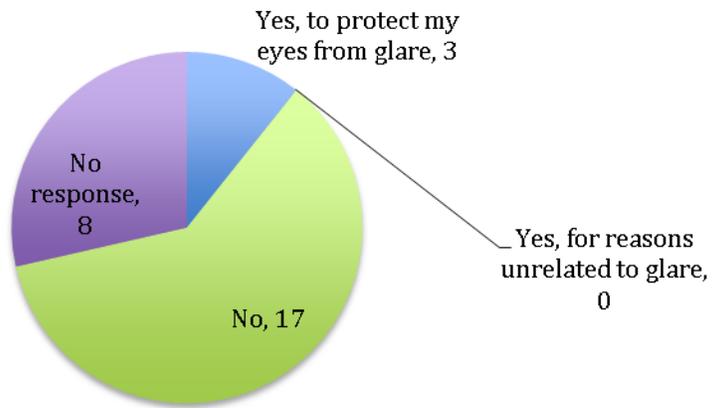
When at the booth with switchable windows, in daytime, do you usually wear sunglasses while inside the booth?



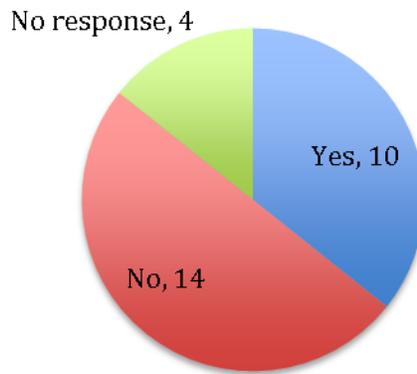
When at a booth with conventional, non-switchable windows, in daytime, do you usually wear a cap with a visor while inside the booth?



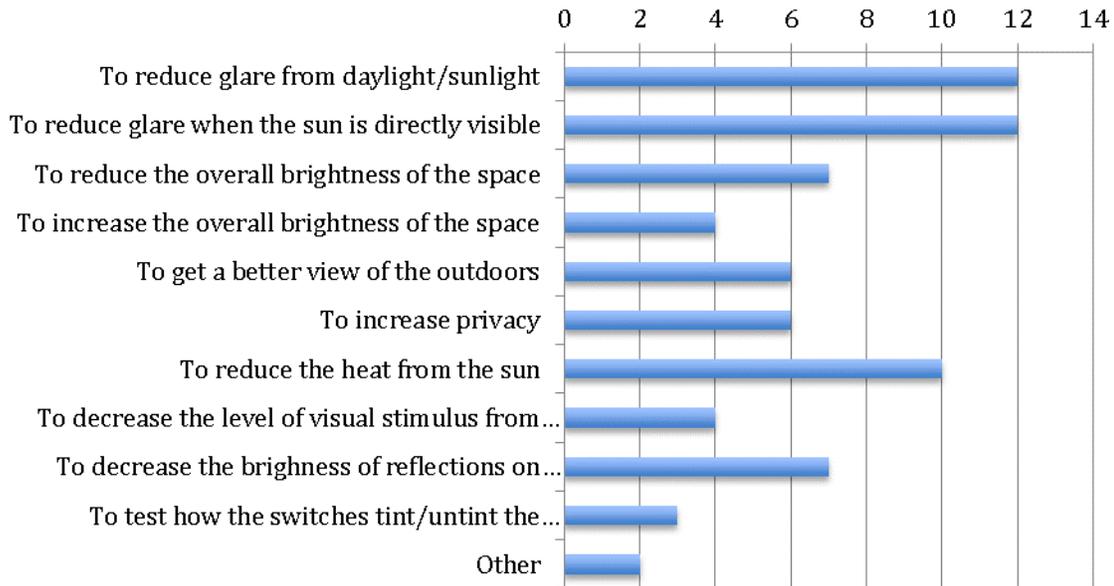
When at the booth with switchable windows, in daytime, do you usually wear a cap with a visor while inside the booth?



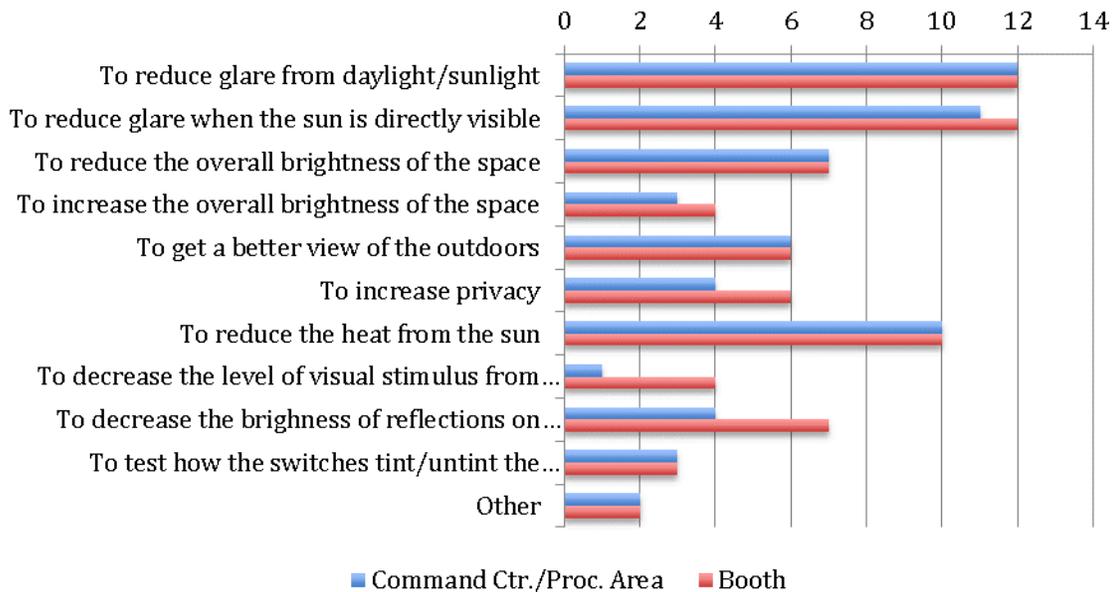
In the booth with switchable windows, do you use the wall switches to tint or untint the windows?



If you use the wall switches [in the booth], what are the primary reasons? (please check all that apply)



If you use the wall switches, what are the primary reasons? (please check all that apply)



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GLOSSARY

| TERM | DEFINITION |
|---|--|
| Daylight Glare Probability (DGP) | A metric for visual comfort. Its values range from 0 to 1, representing the probability that a person would experience disturbing glare in a particular situation. |
| Illuminance | The amount of luminous flux falling on a surface. Its customary units of measurement are lux (lx) or foot-candles (fc). It can be understood as the amount of visible light falling on a surface. |
| Luminance | The amount of luminous flux leaving a surface in a particular direction. Its customary unit of measurement is the candela per square meter (cd/m ²). It can be understood as a measure of brightness of a particular point in the field of view. |