Video Cameras for Roadway Surveillance: Technology Review, Test Methods, and Results

CARL ARTHUR MACCARLEY, DANIEL NEED, AND ROBERT L. NIEMAN

Effective implementation of advanced traffic management strategies depends on timely, reliable, and comprehensive information on traffic conditions. Closed circuit television surveillance of the roadway network is believed to be one of the best mechanisms for providing this information to a traffic operation center. This work supports the application of video surveillance technologies to roadway traffic monitoring. The current state of the art in surveillance camera technology is reviewed. Technical considerations relevant to the selection of video cameras for traffic surveillance applications are summarized. Applicable standards are identified, and evaluation criteria and test procedures are described. A total of 32 commercially available monochrome and color video cameras are evaluated with respect to these criteria. General considerations and specific test results are reported.

Traffic surveillance is an important part of operational strategies to improve the management of roadways. Recent advances in closed-circuit television (CCTV) technology permit improved monitoring of traffic flow for data collection, traffic management, and incident detection. Closed-circuit video surveillance can serve as a valuable aid to traffic control personnel, extending their effectiveness considerably.

Until now field implementations of CCTV systems have been limited because of both technical limitations and institutional factors. The technical limitations include problems related to the collection and transmission of video images and equipment reliability and maintainability.

Improved technology has overcome many of these problems. Video camera technology has improved substantially in the past few years with the introduction of monolithic silicon photosensor arrays. These advances improve the feasibility of video surveillance as a real-time source of information for traffic operations center (TOC) personnel.

At the request of the California Department of Transportation (Caltrans), technical issues in the selection of video cameras for roadway surveillance were studied. A total of 32 monochrome (black and white) and color video cameras were selected for evaluation on the basis of manufacturers' recommendations of appropriate cameras for traffic surveillance applications. Evaluation criteria that emphasized factors of greatest relevance to roadway surveillance were established. Tests were designed to address these criteria, including laboratory video tests and field test procedures involving human observers.

Electronic and Electrical Engineering Department, California Polytechnic State University, San Luis Obispo, Calif. 93407.

The evaluation was limited to a "snapshot" of the available technology at a particular point in time, specifically, cameras available commercially in 1990. The evaluation considered only the video camera, which is one of many components that constitute a CCTV system. Other components of equal importance include the optics and electromechanical lens controls, video signal transmission network, video amplifiers, multiplexors or switchers, video signal compression equipment, and monitors.

VIDEO CAMERA CHARACTERISTICS AND FEATURES

Before the 1980s, electron tube imaging systems, best exemplified by the Vidicon system, were most common in surveillance cameras. A significant improvement in this technology occurred with the introduction of charge coupled device (CCD) solid-state imaging integrated circuits (ICs or "chips"). Costs for solid-state cameras have decreased, and quality has improved significantly, such that solid-state or chip cameras have almost completely replaced "tube" cameras in surveillance applications.

Compared with tube cameras, solid-state cameras consume less power, dissipate less heat, can provide excellent resolution, have better geometric linearity and better resistance to flair and bloom (defined later), and are more reliable. Applications in which tube technology is still used are usually those requiring extreme sensitivity.

All 32 cameras tested were considered by their manufacturers as suitable for traffic surveillance, and all used solid-state technology. A range of cost and performance was represented for each product line. As a baseline comparison, one Vidicon camera, representative of the state of the art in approximately 1980, was also evaluated. (Data are not reported for this camera because it was not intended for traffic surveillance.)

Cameras in this class generally provide analog signals with video information content in the range of 0 to 0.7 V, which equilibrates to 0 to 100 IRE (Institute of Radio Engineers) units.

The spectral response of most monochrome solid-state cameras extends well into the nonvisible infrared (IR) range. Some cameras are provided with removable IR filters to reduce the problems associated with IR sensitivity, such as reporting hot surfaces (such as vehicle tires and black roadway surfaces) as bright objects.

Surveillance cameras generally are available with photographic standard Type C lens mounts, although smaller lens systems are also popular.

Most cameras contain both the imaging array and associated electronics in a common package. However, for discrete surveillance, some cameras incorporate two modules: the main imaging head and the electronics or power supply. Some cameras have enclosures that are sufficiently durable and weathertight, whereas others require separate environmental enclosures.

Video cameras designed for surveillance applications differ from those designed for general usage or broadcast. Surveillance cameras are designed for optimum imaging of a stationary field of view, containing a very wide range of light intensities. This requires higher-than-normal resolution and a wide dynamic range (light to dark range). Good sensitivity for best night vision also may be important. Surveillance cameras often are calibrated for a nearly linear response (a proportional relationship between incident light and the corresponding video signal voltage). It is known that this type of calibration often produces images that are less aesthetically pleasing and somewhat "flat" in appearance. Some cameras use contrast enhancement circuits, which accentuate light-to-dark or dark-to-light transitions in the image. This feature has advantages and disadvantages in traffic surveillance applications: vehicle outlines are more crisply defined in low light or fog conditions, but signs and license plates become washed out because of the overshoot.

Traditionally, surveillance-type cameras are monochrome rather than color. Monochrome cameras generally provide greater resolution and sensitivity than color cameras, although several high-resolution color video cameras, specifically designed for surveillance applications, have been introduced recently.

Some of the electronic features that distinguish different video cameras include the following:

Gamma

Most cameras provide either a continuous adjustment or switch-selectable setting for gamma. This parameter affects the camera linearity in translating light levels to voltage levels.

White Balance (Color Cameras Only)

A feature that distinguishes various color video cameras is an adjustment for its ability to define the color white, which is an equal mix of all primary colors. Some cameras have automatic white balance capabilities, whereas some have none or only manual static adjustments.

Automatic Gain Control and Auto-Iris Control

Automatic gain control (AGC) electronically adjusts the overall camera sensitivity in response to the average light level. This feature has the effect of maintaining a reasonably constant brightness level in the picture. On some cameras, the AGC may be switched off for testing purposes or special applications.

The effect of the AGC is similar to that of another feature called an auto-iris, which controls the sensitivity by electromechanical adjustment of the aperture (iris) in response to the average light level. Auto-iris control produces a higher-quality image than one controlled by the AGC. However, AGC can respond instantaneously to light level changes, whereas an auto-iris is relatively slow because of the response time of the mechanical components.

Imager Size

CCD cameras typically utilize imaging ICs with diagonally measured imaging surface dimensions of between ⅓ and ⅔ in., ½ in. being typical. Generally, the larger the chip, the better the image resolution capability, although this also depends on the size of each CCD imaging cell or pixel. Resolution in CCD cameras is directly proportional to the number of pixels on the chip, typically between 200,000 and 400,000. Reducing the pixel size will have a positive effect on the price of the camera because the cost is directly related to the silicon surface area of the chip. Improvements are directly related to developments in IC process technology. The focal length of a lens must be matched with the imaging chip size to yield the correct field of view.

Shutter Speed

Unless specifically designed for high-speed (slow-motion) photography, mechanical shutters are not used in video cameras. Shuttering is accomplished electronically. Electronics Industry Association (EIA)/National Television Standards Committee (NTSC) cameras have an effective shutter speed of less than 1/30 sec, the rate at which complete video frames are produced (even though they are transmitted as two raster fields at 1/60 sec each). Some cameras are designed for faster shutter speeds; however, faster speeds reduce camera sensitivity because of reduced photon integration time.

A common use of fast shutter speeds is to avoid smearing when capturing fast-moving objects. For typical camera placements, the motion of roadway traffic in the field of view was not found to warrant faster shutter speeds.

Synchronization

When multiple cameras are integrated into a network, synchronization becomes an issue. If the cameras are not synchronized when switched successively onto the same monitor, picture roll occurs while the monitor is attempting to resynchronize with the frame rate of the new camera. Surveillance cameras are manufactured with one of the following three frame timing control options:

- *Internal clock*: camera frame rate is unsynchronized, timed independently from an internal clock.
- *Phase lock*: cameras use the alternating current (AC) line frequency from the power supply for frame synchronization. An initial phase adjustment is usually provided to compensate for phase shift over a large network.

• *Line lock or external synchronization*: an external synchronization generator provides a common-frame synchronization signal to all cameras in the network.

Cameras using phase lock or external synchronization will switch smoothly without picture roll. Phase synchronization usually is considered only when all cameras are powered from a common AC source. This would be the case for a surveillance system within one building or within one industrial installation using a common secondary power transformer. However, a surveillance network with cameras spread out over miles of freeway probably would not meet this requirement. The line-lock external synchronization option is technically the superior approach but is more expensive to implement.

APPLICABLE STANDARDS

Several video display and signal formats are in use internationally. The basic frame rate and vertical resolution (number of scan lines) for video signals usually conforms with one of two international standards:

1. EIA of the United States specifies a standard frame rate of 30 full video image frames per second, each frame displayed as two interlaced fields (half resolution frames) at a rate of 60 fields per second. A total of 525 vertical lines of resolution are specified, each field consisting of 262.5 scan lines (*1*). The color image signal format based on the EIA basic display format is that established by NTSC of the United States. The EIA and NTSC standards are adhered to in the United States, Canada, Mexico, most of South America, and Japan.
2. The International Radio Consultive Committee (CCIR) operates under the auspices of the International Telecommunications Union based in Geneva, Switzerland. The recommendations of the CCIR (1966) permit a variety of color video signal formats, most notably the phase alteration line rate (PAL) standard used throughout most of Europe and the sequential color with memory (SECAM) Standards 1 through 3 used in France and most Eastern Block countries. The basic display format of CCIR-derived formats is 25 frames per second full frame rate, displayed as 50 interlaced fields per second and 625 vertical lines (312.5 per field). Video cameras manufactured for use in Europe generally conformed to CCIR display formats and PAL or SECAM color standards.

Commercial broadcast NTSC, PAL, and SECAM signals usually are allocated approximately a 6-MHz signal bandwidth, compatible with the channel separation of broadcast television in both the United States and Europe. For CCTV systems, this channel capacity limitation does not necessarily exist because the signal does not need to conform with commercial broadcast channel bandwidth restrictions.

Signal bandwidth equilibrates directly to horizontal display resolution expressed in lines, to be discussed later. Commercial broadcast color video signals usually are limited to 200 to 300 lines of horizontal resolution. By comparison, a high-quality monochrome CCTV surveillance camera may provide 600 lines of horizontal resolution.

Our laboratory and field test apparatuses were equipped to handle both EIA/NTSC and CCIR/PAL video formats.

CAMERA PERFORMANCE REQUIREMENTS

The performance requirements for surveillance videocameras include consideration of the following criteria (D. Larkins, of the Ampex Corporation, Redwood City, California, provided assistance in compilation in 1990):

System-Level Considerations

1. *Information requirements*: images should contain sufficient data to support judgments pertaining to traffic control.
2. *Surveillance density—images per mile*: different monitoring requirements require different image densities. A sparse camera placement density would require greater information content in the image.
3. *System cost*: the contribution of the video camera to the overall deployed system expense, relative to the surveillance area.
4. *Operating environment*: a wide range of environmental factors must be considered.
5. *System reliability, maintainability, and security*: these considerations directly affect the service costs and usefulness of the system.
6. *Technology life span—expandability, compatibility, and life*: the life span in terms of obsolescence and future availability and maintainability should be considered.

Surveillance Objectives

Camera performance must be adequate to allow the CCTV system to acquire the following data:

1. *Traffic flow metrics*: vehicle speed, traffic volume, and density determined from visual analysis or computer image processing.
2. *Vehicle classification*: for roadway utilization data acquisition.
3. *Roadway surface conditions—ice, snow, rain, flood, glare, and surface flaws*: adverse road surface conditions affecting driver safety.
4. *Visibility*: roadway visibility as perceived by drivers.
5. *Incident detection—collision or stalled vehicle*: roadway incidents such as collision, stalled vehicles, or other situations impeding normal traffic flow.
6. *Hazardous or impaired drivers*: nonconforming vehicle behavior suggestive of driver impairment.
7. *Specific vehicle identification*: identification of specific vehicles.

Camera Placement Considerations

1. *Effective camera range and field of view*: required effective camera range will vary depending on the detection criteria. Use of remote pan, tilt, or zoom may mitigate this requirement.

2. *Coverage, redundancy, and overlap requirements*: the extent of roadway coverage by a single camera will be reduced on curved roadways and hilly terrain. Overlap or dedicated coverage may be required for isolated areas, for example, tunnels or interchanges.

3. *Number of personnel in control room*: the number of personnel in the TOC will limit the useful number of camera placements, assuming some maximum number of monitors assigned to each operator.

Environmental Considerations

1. *Aesthetic requirements*: for minimum public impact, the enclosure and mounting system should be as incongruous as possible.

2. *Serviceability*: serviceability represents a significant portion of the ongoing system costs. Tradeoffs include minimal maintenance at a higher installed cost versus difficult service at a minimal installed cost.

3. *Rain survival and removal*: the camera system must be capable of withstanding rain from all angles and high humidity. Rain droplets that adhere to the foremost optical transmission element could significantly reduce the image. Possible rain removal methods include windshield wipers, spinning windows, forced air deflection, and rain-avoiding enclosures.

4. *Snow and ice survival and removal*: snowflakes that adhere to the foremost optical transmission element could significantly reduce the image quality from the camera. Ice could also present significant problems with the mechanical components, such as pan and tilt mechanism or zoom lens. Possible snow and ice removal methods include those mentioned for rain removal and the use of a heated front window.

5. *High temperature survival*: sustained operations at elevated temperatures may be required. Some mechanism for dissipation of external as well as internally generated heat may be necessary.

6. *Dust and grime removal and survival*: dust and grime reduce light transmission by the front window and may cause scoring of the window or damage to the mechanical components. Some means for automatic lens washing may be an alternative to field service.

7. *Ozone and acidic pollution survival*: the camera housing must be impervious to the effects of corrosive atmospheric conditions that are present in some urban areas.

8. *Spectral filtering*: filters may assist in the elimination of certain image artifacts. A polarizing filter may reduce road glare, an IR filter may correct false imaging caused by the IR sensitivity of the camera, and an ultraviolet filter may improve contrast during overcast conditions.

9. *Projectile survival*: the enclosure may be required to withstand impacts from various projectiles. Outdoor CCTV cameras are often targets of vandalism.

10. *Electromagnetic noise immunity*: the camera must be sufficiently immune to the effects of local sources of electromagnetic radiation, such as automotive ignition systems, high-pressure vapor lamps, police radar, and mobile citizens band or cellular phone transmitters.

11. *Lightning survival*: the possibility exists of a direct or indirect hit by lightning. Suitable lightning protection is required to protect both the camera and other electronic devices in the signal path or connected to the same power circuit.

12. *Power supply noise immunity*: the camera and associated electronics should be tolerant of poor power quality, such as low voltage, noise, spikes, and brief interruptions.

TEST PROCEDURES AND RESULTS

Thirty-two sample video cameras were subjected to tests designed to assess their performance relative to the aforementioned requirements. The test procedures and relevance of the test results to traffic surveillance are described in the following.

Laboratory tests involved measurements of electronic parameters that underly many of the surveillance requirements. These parameters included resolution, sensitivity, noise, dynamic range, grayscale linearity, geometric linearity, flair, bloom, lag, comet tail, vertical or horizontal smear, and back-focus accuracy. In addition, the color cameras were tested for color fidelity, as indicated by color vector magnitude and phase accuracy and white balance.

The tests may be divided into two categories: static tests that involve images that contain no motion and dynamic tests that use images with moving objects or light sources.

The following static and dynamic laboratory tests were conducted. More than one parameter is measured in each test setup.

Test	*Static/Dynamic*	*Camera Types*
Horizontal resolution	Static	Monochrome/color
Sensitivity and bloom	Static	Monochrome/color
Gray scale linearity	Static	Monochrome/color
Geometric linearity	Static	Monochrome/color
Lag, comet tail, smear	Dynamic	Monochrome/color
Color fidelity	Static	Color

A video test bench was fabricated, upon which the camera under test is mounted and focused on a test chart or moving light source. The following video test charts manufactured by Hale Color Consultants, which conformed to EIA standards, were used:

- One RETMA resolution chart, EIA 1956,
- Two 11-step grayscale reflectance charts,
- One window chart,
- One EIA/RETMA linearity chart, 1961,
- One EIA/RETMA registration chart, and
- One color calibration chart.

In addition, a "black hole" test chart for sensitivity and transient response tests was fabricated, consisting of a maximum reflectivity white chip placed in front of a 3.0-m-deep hole lined with black felt, having essentially zero reflectivity.

All tests used a set of laboratory standard F1.4 C-mount lenses. Focal lengths were adjusted to match the various imaging chip dimensions.

The test illumination was designed to duplicate natural daylight. The NTSC illumination standard for color television is defined as CIE (Commission Internationale de l'Eclairage) Illuminant C, representative of average daylight according to available data in 1931. The definition of daylight has since been upgraded to CIE standard D65; however, Illuminant C is still the definition incorporated into the NTSC standard.

Therefore, Illuminant C was used as the illumination standard for these laboratory tests (*2*).

Illuminant C has a correlated color temperature of 6800 K. This was achieved using 3400 K tungsten lamps with Kodak Wratten sheet filters stacked to achieve a −148 Mired shift, yielding a corrected color temperature of 6844 K.

The use of incandescent illumination in the laboratory introduces a larger-than-natural IR component. The Tektronix standard light meter in this study was insensitive to IR radiation. EIA-referenced test procedures predate solid-state cameras and have not yet been updated to deal with the significant IR sensitivity. Experimentation indicated that it was not possible (or desirable) to completely remove the IR component; however, it was possible to reduce it using IR blocking filters.

Resolution

The horizontal resolution of the camera generally correlates with the amount of information present in the video signal generated by the camera. Greater resolution means that either (a) for a given angular resolution requirement, a larger field of view may be imaged or (b) for a given field of view, a finer grain in the image may be discerned.

Resolution is a factor of primary importance in terms of the ability of the TOC operator to interpret the camera image on a monitor. Although the camera optics may be used to trade surveillance area for the minimum resolvable feature size in the image, the electronic resolution of the camera is a constant, representing a product of these two factors.

Resolution as viewed by the TOC operator can also be limited by the monitor or the bandwidth of the communications path from the camera to the monitor. In view of this, it is concluded that camera resolution is important but only up to the resolution-related limits of the other components of the CCTV system.

Resolution is quantified by the number of "television lines" that can be distinguished electronically in image. This is measured as the maximum number of black and white bars of equal width that can be distinguished along the entire width (horizontal) or height (vertical) dimension of the television picture. Because the ratio of the horizontal dimension to the vertical dimension of the image is 4:3, ⅓ more lines are required in the horizontal compared with the vertical dimension to achieve equal vertical and horizontal resolution.

Vertical resolution is fixed by the EIA/NTSC vertical line specification (525 lines interlaced). Because solid-state cameras separate line scans with separate rows of pixels, the vertical resolution is some number slightly less than 525 (depending on the number of scan lines displayed), divided by an integer (usually 1 or 2).

For solid-state cameras, horizontal resolution is fundamentally limited by the horizontal pixel density of the imaging chip. However, bandwidth limitations in the signal path may also limit horizontal resolution.

The EIA standard test chart for resolution measurement contains horizontal and vertical wedges of converging groups of lines. With the camera focused on the test chart, a single scan line is isolated using a video waveform analyzer. Increasingly narrow areas of the line wedges are scanned, and the video signal is displayed on a digital oscilloscope. The signal amplitude variation is reported (in decibels) relative to the direct current (DC) black and white level difference. The resolution limit was defined as the line density that yields −15 dB of the DC black and white amplitude spread.

Sensitivity and Dynamic Range

Sensitivity is an indication of the ability of the camera to form an image in low-light conditions. Daytime illumination levels greatly exceed the lower sensitivity limits. At night, the brightness of vehicle headlights is much greater than the reflected light from the vehicles or roadway features. The ability to detect features in the image other than just the headlight spots depends primarily on the dynamic range of the camera and secondarily on the actual low-light limit, assuming at least some minimum level of reflected light from the features.

Most manufacturers specify sensitivity as the minimum illumination level necessary for either full or usable video. However, the definition of full or usable video is often manufacturer specific or nonrigorously defined. Measurement of sensitivity is further complicated by AGC, IR cut filters, and the spectral characteristics of the illumination itself. The video signal path gain can be increased, making a camera appear more sensitive in terms of its output voltage versus illumination level relationship. However, the intrinsic camera noise increases proportionally.

These ambiguities were avoided by measuring camera sensitivity relative to the camera noise level, an approach that cancels the effect of any gain in the signal path that acts on both the image information and the noise. We define the low-light sensitivity limit as the incident illumination on the black hole chart (in lux), which yields a 0-dB RNS ratio of signal to noise for a scan line through the white chip.

The dynamic range of the camera was measured at the same time by increasing the illumination level from the sensitivity limit to the saturation limit.

The ratio of signal to noise (S/N) of a camera system is defined as the ratio between the camera peak signal output and the root-mean-square (*RMS*) noise output. S/N is evaluated by measuring the *RMS* noise output of the system when no light is permitted to enter the pickup device and comparing this with the rated camera output. This measurement cannot be reliably made unless the AGC and black clip circuits of the camera can be disabled, which was not possible for all cameras tested.

An attempt was also made to measure bloom during the sensitivity test. Bloom is the spread of the image around the original image caused by charge leakage in the pickup device. Bloom can also be observed as a result of faulty optics, usually a result of poor or nonexistent lens coatings. Although bloom can be a significant problem for tube cameras, solid-state cameras usually are unsusceptible. None of the cameras tested exhibited significant problems with bloom.

Flare is manifested as fluctuations in the black level of an image related to varying white levels. Flare is not known to be a common problem with solid-state cameras, so it was not specifically measured in these tests.

Gamma/Grayscale Linearity

Gamma is a metric of the linearity of the relationship between the incident light intensity and the signal voltage produced by the camera, with gamma = 1.0 corresponding to a truly linear relationship. However, a unity setting is not always desirable because the human eye, and often the monitor also, have nonlinear responses. A gamma setting of 0.45 usually produced a grayscale that appeared linear to the eye as rendered on the laboratory monitor. Gammas higher than 0.45 tended to emphasize the contrast between black and white.

Although it is important to the accurate reproduction of the image, linearity does not appear to be a factor of primary concern in traffic surveillance. From a TOC operator's point of view, the shade of gray representing a particular object in the scene is probably of little relevance (monochrome assumed). The relative intensity differences between features in the image convey the greatest information. Provided that the image is not overly flattened out or binary from excessive contrast, deviations from perfect linearity are probably acceptable.

Linearity was tested using the Hale/EIA grayscale test chart under standard illumination. A linear response would correspond to an equal voltage difference between each of the nine gray levels on the chart. Linearity is reported as the percent average absolute difference between the signal voltage levels and truly linear increments, for a single scan line through the grayscale field.

As previously discussed, there were problems performing the grayscale linearity measurement for most of the monochrome cameras because, although the visible light reflectivity increment of each successive gray level is constant, the IR reflectivity is not. For cameras that were highly IR sensitive, the darkest gray level appeared nearly as bright as the white reference chip because of its high IR emissivity. This problem occurs even under natural daylight illumination. The only solution was to ignore the darkest gray level in the linearity measurement.

Geometric Linearity

The geometric linearity of a camera is a measure of its tendency to introduce dimensional distortion in the image. This could be an important factor in the inference of distances or shapes in a traffic scene displayed on a TOC monitor. The monitors in the TOC also introduce geometric distortion, and the human eye tends to tolerate minor distortions.

Geometric linearity was tested using a Hale/EIA geometry test chart consisting of a grid of evenly spaced dots. Ideally, this should be reproduced by the camera without any dimensional distortion. The signal from the camera viewing the test chart is mixed with a reference linear signal produced by a video signal generator. Registration of the dot pattern from the camera signal with that of the reference signal is measured on a monitor. Geometric linearity is reported as the percentage average absolute dimensional misregistration at five key positions on the test chart (center and four corners).

Tube technology (such as Vidicon) cameras are susceptible to geometric distortion because of the electron-beam scanning action that produces the video signal. This is not the case for solid-state (CCD) cameras because precise photolithography locates the imaging elements (pixels) on a wafer of silicon. Because all surveillance cameras tested (except one reference camera) were solid state, the geometric linearity of all the cameras was nearly perfect. Detected differences were probably more a result of optical flaws than of variations between imagers.

Color Fidelity

For color cameras, the TOC operator would expect a reasonably faithful reproduction of the colors and their relative intensities in the image. Although color fidelity is only an aesthetic issue in entertainment, it could become a critical issue in traffic surveillance. For example, a TOC operator might observe a car that appears to be a particular color on his or her monitor involved in a hit-and-run accident and then dispatch appropriate law enforcement. Poor color reproduction might cause the vehicle color to be incorrectly reported, leading to a questionable arrest by the officer.

Color fidelity is tested using a standard video test instrument called a vectorscope. Using a standard color bar chart under standard illumination, three primary colors and three color combinations are tested, each yielding a color vector displayed on a vectorscope.

Each color bar is associated with a vector with a characteristic magnitude and phase. The phase corresponds to the color hue, whereas the magnitude corresponds to the relative color intensity. A camera with perfect color reproduction would produce color vectors of the correct magnitude and phase on the vectorscope, for a line scan through the color bars. The difference between the actual vector magnitude and phase produced by the camera and the correct values is reported as magnitude and phase errors for each color vector. The absolute values of all six magnitude errors are averaged together and reported as percent average magnitude and phase errors.

White balance is an indication of a color camera's ability to faithfully produce the neutral color white. True white reproduction results in a centered dot on the vectorscope. White balance is reported as the actual position of the white dot relative to the center, usually stated as a magnitude and phase deviation characteristic of a particular hue and intensity. Most of the 10 color cameras tested exhibited acceptable color fidelity. None was perfect, and two were unacceptable.

The other half of the color reproduction system is the monitor. All color monitors provide adjustments for both color hue and intensity. The monitor adjustments can be used, to some degree, to compensate for the poor color fidelity of a camera. This may be acceptable if each monitor is connected to the same camera all the time. However, in a TOC, the capability must exist for any monitor to switch to any camera. Any differences in color fidelity between cameras would yield distorted color reproduction on all but the original setup camera.

It is concluded that color fidelity is an issue of primary importance for color cameras. Poor color fidelity could lead to problems in traffic surveillance.

Dynamic Tests

Some metrics of camera performance are related to motion in the image. Comet tail describes a problem when a bright object moves across a dark field, leaving a decaying afterimage. Similarly, lag refers to the after-image visible when a nonsaturated (gray) object moves across a dark background.

These problems are not common in solid-state cameras but are sometimes observed.

However, vertical or horizontal smear are problems common to MOS/CCD cameras. The problem is manifested as a white vertical or horizontal bar extending from a bright-point light source in the image, across the entire image. This usually occurs only at sufficiently wide aperture settings such that the light source is saturated while the background is dark. Although not a dynamic problem, the dynamic test apparatus also facilitated the observation of vertical smear.

A camera possessing any of these problems could be seriously limited in the use of traffic surveillance because the field of view contains significant motion and numerous bright-point light sources (headlights) at night.

An apparatus was constructed on the test bench for movement of either a point light source or a gray chip across the field of view at nearly constant velocity.

Only three of the cameras tested exhibited lag or comet tail. In this study, none of these exhibited a problem significant enough to be of concern in traffic surveillance. However, all except one monochrome and one color camera exhibited problems with smear (usually vertical) at wide aperture settings.

Field Tests

Field tests were conducted at two sites. The ARDFA test track at California Polytechnic State University, a 0.55-mi straight roadway instrumented for vehicle position and velocity measurements, was used for the daytime field tests. The cameras under test were mounted on a 25-m tower at one end of the track. Position markers and several typical road signs were placed along the track. Vehicles and test symbols were placed or driven along the track at various speeds and distances from the camera.

For the night field tests, a camera platform was set up on a local overpass on California Highway 101. Both approaching and departing traffic scenes were viewed. These night tests were primarily intended to evaluate low-light camera characteristics.

The field evaluations relied on human vision. Images from each camera were recorded on Super-VHS videotape. Human evaluators in the laboratory compared the recorded video images, displayed on reference monitors, with each other and with synchronized and time-coded photographs taken with a 35-mm photographic camera. Evaluators completed written questionnaires that were intended to determine both the information they could extract from the image and qualitative issues such as sharpness, clarity, and color accuracy (when applicable).

The assessment of image quality by human subjects may be considered, in one sense, the ultimate test criteria. But the limitations of the video recording process, the monitors, and the subjective nature of human reactions suggest only cautious inclusion of these results in the overall evaluation.

The ability of the human observers to identify specific features in the scene is duplicative of the more precise laboratory resolution tests. However, the relative values of color or grayscale linearity to a TOC operator are well addressed in these tests—assessments that could not be done in a laboratory. Color, to some degree, can replace resolution in aiding a human observer in discerning features in the image. This is fortunate because color detection by an imaging chip (or chip triad) usually comes at the expense of resolution. Color information might also help to distinguish vehicles and other objects from the shadows that they cast.

TEST RESULTS

Table 1 summarizes the test results. Individual cameras are identified by descriptor codes of the format vv:cb, where vv is the vendor code number, b is nonzero for monochrome cameras, and c is nonzero for color cameras. Complete test details, including specific camera manufacturer and model information, are available in MacCarley and Dotson (*3*) on public release of this document by Caltrans. The following applies to Table 1:

1. Horizontal line resolution is compared at the −15-dB point and is reported as an equivalent number of lines resolvable in the image along a single horizontal scan.
2. Low-light sensitivity is the illumination at an S/N ratio of 0 dB reported in lux.
3. Grayscale (gamma) linearity is stated as average absolute deviation from the ideal, reported in percent.
4. Geometric linearity is measured as the magnitude of the spacial misregistration over five points on the test chart. It is reported as a percentage.
5. Vertical smear (VS) and lag and comet tail (L/C) are given as simply yes or no values, indicative of whether or not these problems were observed.
6. Field test scores are reported as ratios of the total points received to the maximum number of points possible.
7. Color fidelity measurements are reported as the absolute phase error in degrees and magnitude error in percent over six standard color vectors.
8. Cameras are numerically rated on a scale of 1 (worst) to 3 (best) according to overall performance in the laboratory tests, field tests, and finally a composite of all tests, indicative of the overall suitability of the camera for traffic surveillance applications. The rating system is defined as follows: 1, unacceptable performance; 2, acceptable performance; and 3, outstanding performance.

CONCLUSIONS AND RECOMMENDATIONS

The majority of the video cameras that were evaluated would probably be suitable for traffic surveillance applications. Cameras not recommended generally were rejected for reasons of very poor resolution, image distortion, or specific operational problems. Cameras that receive high recommendations usually provided excellent resolution and adequate sensitivity and were free of any operational limitations (with the exception of vertical smear and IR sensitivity).

Operational problems of critical concern are those related to the basic usefulness of the camera in its intended application. Synchronization problems, serious image distortion, extreme grayscale nonlinearity, very poor color trueness (phase error), chronic backfocus problems, excessive dead pixels, unusually poor resolution, or unusually low saturation limits are considered causes for a recommendation against a camera.

TABLE 1 Summary of Camera Test Results

Camera Code	Perf. Class	Cost Class *	Horizontal Resolution (Lines at -15 dB of dynamic range)	Low Light Sensitivity (Lux at 0 dB s/n ratio)	Gamma Linearity (scaled avg. dev.)	Geometric Linearity	Color Fidelity (color cameras only) (mean abs. error)		Dynamic					Field Test 1 (comp. score)	Field Test 2 (comp. score)	Rating by Class			Comments
									Saturated				Unsat.						
									Horiz. Scan		Vertical Scan					Lab Tests	Field Tests	Over-all	
							Mag.(%)	hase(Deg	VS	L/C	VS	L/C	L/C						
101	Med.	Low	280	0.004	1.70%	<0.5%			yes	no	yes	no	no	21\32	12\22	1	2	1	Low res., back focus problem
102	Med.	Mod.	500 (-6.78 dB)	0.004	1.80%	<0.75%			yes	no	yes	no	no	28\32	10\22	3	2	2	
103	Med.	Mod.	400 (-10.35 dB)	0.003	1.80%	<0.75%			yes	no	yes	no	no	27\32	9\22	3	1	2	
210	Color	High	290	0.81	0.80%	<0.5%	28.39	7.33	yes	no	no	no	no	15\35	15\25	2	2	2	
202	High	High	600 (-6.16 dB)	0.004	3.00%	<0.5%			yes	no	yes	no	no	27\32	18\22	3	3	3	Highest rated monochrome camera
201	Med.	Mod.	362	0.006	3.30%	<0.5%			yes	no	yes	no	no	19\32	17\22	2	2	2	
310	Color	High	278	5.13	1.20%	<0.5%	45.94	4.17	no	no	no	no	no	16\35	14\25	2	1	2	Immune to vertical smear
301	High	High	203	0.004	2.20%	<0.5%			yes	no	yes	no	no	19\32	13\22	1	2	1	Poor res., very high IR sensitivity
302	Low	Mod.	250 (-10.95 dB)	0.856	1.60%	<0.5%			no	no	no	no	no	8\32	13\22	2	1	2	Immune to vertical smear
1401	Med.	Mod.	400	0.003/0.284	1.90%/2.10%	<0.5%			yes	no	yes	no	no	25\32	15\22	2	3	2	
1402	High	High	376	0.004/0.155	1.90%/1.00%	<0.75%			yes	yes	yes	yes	no	21\32	9\22	2	2	2	Lag and comet tail
1410	Color	High	450 (-4.27 dB)	0.585	1.20%	<0.5%	14.85	5.5	yes	no	no	no	no	19\35	18\25	3	2	3	Excellent res. for color camera
901	High	Mod.	485	0.002/0.001	1.40%	<0.5%			yes	yes	yes	yes	no	27\32	16\22	2	3	2	Lag and comet tail
1101	Med.	Low	450 (-8.08 dB)	0.003	3.30%	<0.5%			yes	no	yes	no	no	23\32	14\22	3	2	2	
1102	High	Mod.	489	0.003/0.074	4.10%	<0.5%			yes	no	yes	no	no	25\32	14\22	3	2	2	Very nonlinear grayscale
1110	Color	Mod.	396	1.976	3.80%	<0.5%	54.1	10.83	yes	no	yes	no	no	18\35	11\25	2	2	2	High res. but poor color fidelity
1001	Med.	Mod.	467	0.005	1.40%	<0.75%			yes	no	yes	no	no	22\32	15\22	2	2	2	
1002	High	High	512	0.005	1.80%	<0.5%			yes	no	yes	no	no	21\32	11\22	3	1	2	Dead pixels
610	Color	High	283	0.49	1.60%	<0.5%	21.6	11.83	yes	no	yes	no	no	21\35	14\25	2	2	2	Good sensitivity for color, low res.
601	Med.	Mod.	400	0.005	1.40%	<0.5%			yes	no	yes	no	no	24\32	11\22	2	2	2	
1301	Med.	Low	450 (-11.90 dB)	0.01	3.40%	<0.75%			yes	no	yes	no	no	28\32	13\22	2	3	2	
401	High	Mod.	470	0.346	2.10%	<0.5%			yes	no	yes	no	no	23\32	20\22	2	3	2	IR-immune, noise problem
410	Color	Mod.	450 (-8.09 dB)	1.113	0.90%	<1.0%	35.37	9	yes	no	yes	no	no	21\35	22\25	2	3	2	
501	High	Low	550 (-12.74 dB)	0.009/0.014	1.60%	<0.5%			yes	no	yes	no	no	21\32	15\22	2	3	2	
502	Med.	Mod.	450 (-10.42 dB)	0.004/0.004	2.20%	<0.75%			yes	no	yes	no	no	21\32	14\22	2	2	2	
510	Color	High	294	1.722/1.722	1.80%	<1.0%	18.38	13.17	yes	no	yes	no	no	19\35	18\25	2	2	2	Poor color "trueness" (phase error)
810	Color	High	263	0.319/0.314	1.10%	<0.5%	28.98	10	yes	no	yes	no	no	16\35	19\25	1	2	1	unstable color balance
801	Med.	Mod.	400 (-11.83 dB)	0.002/0.002	3.20%	<0.75%			yes	no	yes	no	no	20\32	15\22	3	2	2	Electronic auto-iris
1201	Med.	Mod.	459	0.005	1.60%	<0.5%			yes	yes	yes	yes	yes	24\32	13\22	2	2	2	Lag and comet tail
1210	Color	High	328	1.58	1.20%	<0.75%	29.96	10	yes	no	no	no	no	21\35	21\25	2	3	2	
701	Med.	Low	254	0.004	1.30%	<0.5%			yes	no	yes	no	no	23\32	11\22	1	2	1	Low resolution, image distortion
710	Color	Low	260	2.47	1.60%	<0.5%	n/a see test		yes	no	no	no	no	13\35	10\25	1	1	1	Poor resolution, sensitivity, synch

* Price Class: <$500 Low, $500<cost<$1000 Moderate, >$1000 High

Operational issues of less concern, although still important, include moderate grayscale nonlinearity, a few dead pixels, minor image artifacts (such as dot-grid pattern noise), color intensity fidelity (magnitude error), poor sensitivity, marginal resolution (at least 250 lines), and lag/comet tail problems, if not excessive.

Vertical smear potentially could be a serious impediment to nighttime traffic surveillance. Vertical smear problems prevent the use of wide apertures at night. A wide aperture is necessary if the TOC operator needs to see complete vehicles rather than just headlight pairs. Indeed, the excellent low-light sensitivity of most cameras is of no value if a bright headlight spot in the image causes vertical smear. With as many as 100 cars in the field of view, 200 bright vertical smear lines render the image useless. This is especially true if the camera is to be used as the input to a traffic video image processing system.

All monochrome cameras tested that were not equipped with IR block filters were sensitive to IR radiation, usually in the 1- to 3-μm near IR range. This radiation is invisible to the human eye and generally correlates with the heat emanating from or reflected by a surface in the scene. IR sensitivity causes false intensity levels in the image: black tires and hot asphalt surfaces appear white. A red car appears whiter than a green car of equal visible reflectivity. It is difficult to say summarily whether this is a real problem in traffic surveillance because enough other visual queues exist in the image to correctly identify surfaces regardless of temperature. Color cameras, by virtue of their color distinguishing mechanism, are insensitive to IR radiation, at least relative to the monochrome cameras tested.

Human subjects in the field tests seemed to accept color information in exchange for decreased resolution. Although color information will never substitute for the resolution required to read a sign or identify a particular vehicle model, it could aid considerably in identifying particular vehicles or distinguishing a vehicle from its own shadow.

Quoted camera costs generally correlated well with performance as measured by the tests in this study, although a few significant exceptions were encountered. However, high cost is often associated with special features, such as a ruggedized housing or accessible controls, which were not primary evaluation factors in our study. Within the context of the overall system, the cost of the camera is probably a minor issue. Consider that the cost of the environmental enclosure and the remotely controlled pan-tilt-zoom mount for a camera usually exceeds the cost of the camera itself. In view of the installation and maintenance expense, as well as the projected service lifetime, it is recommended that the camera purchase price be considered only as a secondary issue.

Overall, it is concluded that most of the higher-performance cameras surveyed would be adequate for roadway surveillance applications, although significant deficiencies were noted in several cases. The ideal video camera for roadway surveillance would probably be a solid-state color camera with at least a horizontal resolution of 450 lines; a sensitivity of 0.5 lux; and complete immunity to bloom, lag, comet tail, and especially vertical smear. At the time of this evaluation, such a camera was not commercially available. The vertical smear problem is the most noteworthy deficiency, and further development is suggested to eliminate this problem. The rapid pace of video technology may be expected to bring significant improvements within the next few years.

ACKNOWLEDGMENTS

This work was supported by the California Department of Transportation and FHWA.

REFERENCES

1. *EIA Standard RS-170, Rev. TR-135*. Electronic Industries Association, Washington, D.C., 1957.
2. Benson, K. B., ed. *Television Engineering Handbook*, Section 2.3. CIE System, McGraw-Hill, New York, 1986.
3. MacCarley, C. A., and S. Dotson. *Evaluation of Closed-Circuit Television Technology for Application in Highway Operations*. Final Project Report, Caltrans Contract 51J932. California Polytechnic State University, San Luis Obispo, 1992.

Publication of this paper sponsored by Committee on Vehicle Counting, Classification, and Weigh-in-Motion Systems.