# Evaluation of Infrared and Millimeter-wave Imaging Technologies Applied to Traffic Management

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# Background

- Effective traffic management requires knowledge of conditions on highways.
- Traffic Management Center (TMC) personnel rely upon video surveillance for monitoring traffic conditions.
- Video information is also used be used by computer vision system to detect traffic flow parameters.
- Conventional video cameras utilize the visible 400-700 nanometer (nm) electromagnetic spectrum.
- Visible imaging is adequate for most highway surveillance applications.

# Background Continued

- Exceptions exist however:
  - Dense fog
  - Snow
  - Rain
  - Airborne particulates (smoke or dust)
  - Night or low natural illumination
- Yet, it is precisely in these low-visibility conditions that the greatest need exists for reliable traffic monitoring, especially if the objective is the recognition of impending dangerous traffic situations.
- In addition, substantially different and potentially valuable information is available outside the visible spectrum.

# Objectives

- This project examined and evaluated alternative imaging technologies for traffic surveillance and detection which:
  - have superior ability to "see through" fog and particulates
  - do not depend on natural visible-spectrum illumination, and
  - may contain additional information of potential value in traffic management
- Technologies considered:
  - infrared (IR) sensitive cameras
  - passive millimeter-wave radiometric imaging

# Evaluation Criteria

- Useful information content of images
- Noise content of images
- Standard video performance metrics (resolution, dynamic range, image artifacts, geometric and intensity linearity, image time constant and effective frame rate)
- Technical advantages and limitations
- Human interface factors
- Reliability and robustness in traffic surveillance environment
- Potential for sensor fusion

# Evaluation Methods

- Acquire video images using samples of each technology for a range of traffic, environmental and illumination conditions
- Develop a suite of spectrum-independent performance metrics tailored to the requirements of roadway surveillance
- Mechanize these metrics as a suite of computer image sequence analysis applications
- Apply metrics to comparable image sequences produced by each device
- Consider non-image quality factors (deployment requirements and restrictions, reliability, environmental compatibility, service requirements, cost)
- Rank results based upon spectral band, scene conditions, and technology
- Disseminate results - final report, video training film, on-line video library

# Review of Field Data Collection

- Parameters Obtained at Various Sites:
  - Spectral Ranges
    - Visible (.30-.70 μm)
    - Infrared: VNIR (.75-2 μm), SWIR (3-5 μm), LWIR (8-12 μm)
    - Millimeter Wave (94 GHz)
  - Weather Conditions
    - Clear, Rain, Snow, Fog (Radiation & Convection)
  - Traffic Conditions
  - Level of Service (LOS)
  - Lighting Conditions
    - Overhead Sun, Steep Shadows, Dusk / Dawn, Night

# Field Deployment

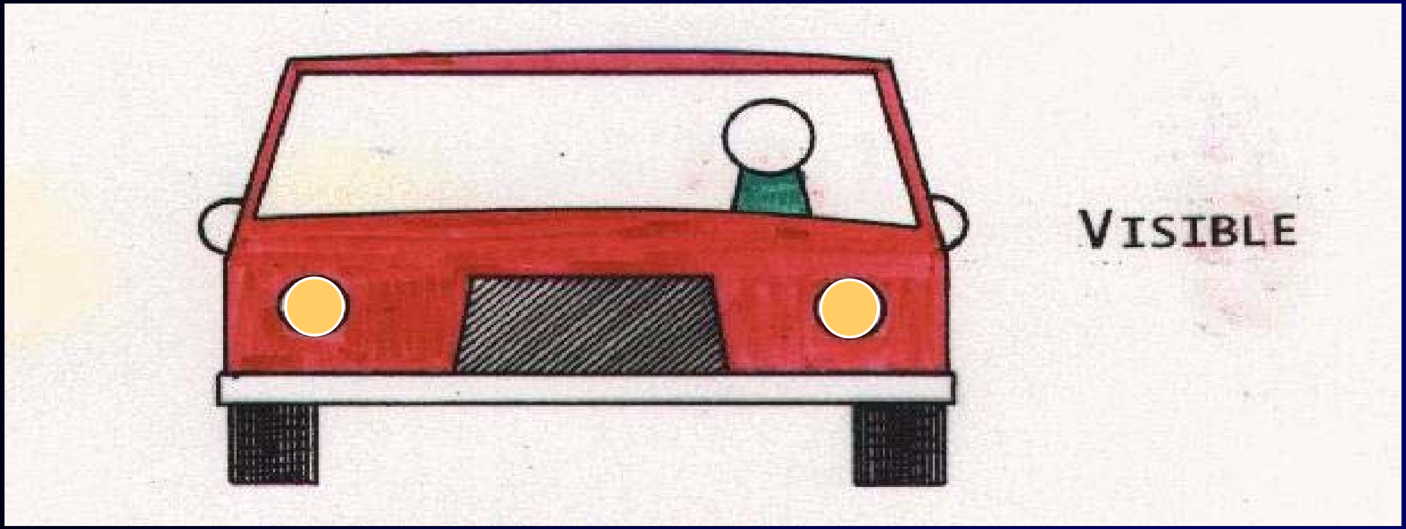
# Imaging Systems Tested

| Company and Product | Received Wavelength Band (μm) | Focal Plane Temperature and Cooler Type | Detector Type | Array Size (pixels) |
|---|---|---|---|---|
| AGEMA Thermovision | 8 to 12 | 77 K Sterling | HgCdTe | 5 elements, X-Y mechanical scan |
| Cincinnati Electronics IRRIS-256ST | 3 to 5 | 77 K Sterling | InSb | 256 x 256 |
| FSI PRISM | 3.6 to 5 | 77 K Sterling | PtSi | 320 x 244 |
| GEC/Marconi Sentry IR20 | 8 to 14 | Ambient | Microbolometer | 200 x 200 |
| Inframetrics 600 | 3 to 5 and 8 to 12 | 77 K Cryogenic | PtSi and HgCdTe | 1 element, X-Y mechanical scan |
| Inframetrics 760 | 8 to 12 | 77 K Sterling | HgCdTe | 1 element, X-Y mechanical scan |
| Inframetrics InfraCam | 3 to 5 | 75 K Sterling | PtSi | 256 x 256 |
| Insight/Starsight | 8 to 14 | Ambient | Pyroelectric BST | 256 x 256 |
| Mitsubishi IR-M300 | 3 to 5 | 77 K Sterling | PtSi | 256 x 256 |
| TI Nightsight | 8 to 14 | Ambient | Pyroelectric BST | 256 x 256 |
| TRW Multispectral Scanner | 94 GHz (millimeter-wave) | Ambient | HEMT*-heterodyne | 1 element, X-Y mechanical scan |

* HEMT = high electron mobility transistor

# Parallel Camera Tests

# Image Characteristics: Visible and Very Near Infrared (VNIR)

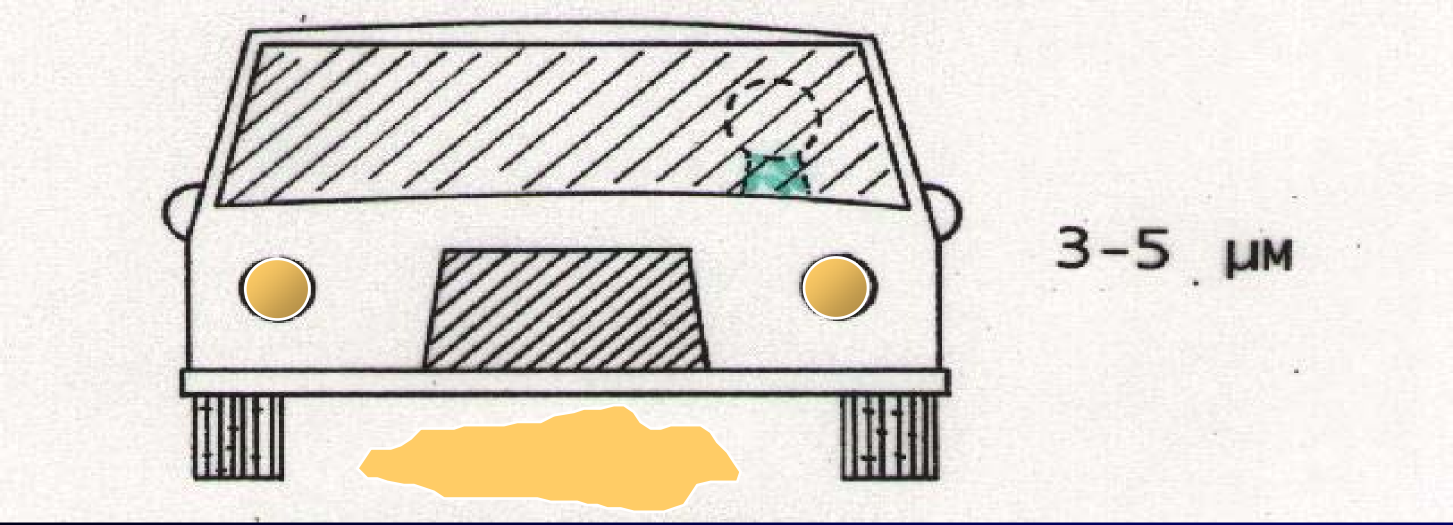



- No or Very Little Thermal Information
- Low Transmissivity in Fog
- Visible Spectrum Contains Chromatic Information
- Inexpensive High-resolution Sensors

# Visible (0.3-0.7 μm) & VNIR (0.7-2.0 μm)

Visible:  Burle TC9388-1,  Panasonic SVHS Camcorder
VNIR:  GBC CCD-300 with TIFFEN 49mm VNIR Filter

# Image Characteristics: 3-5 μm IR

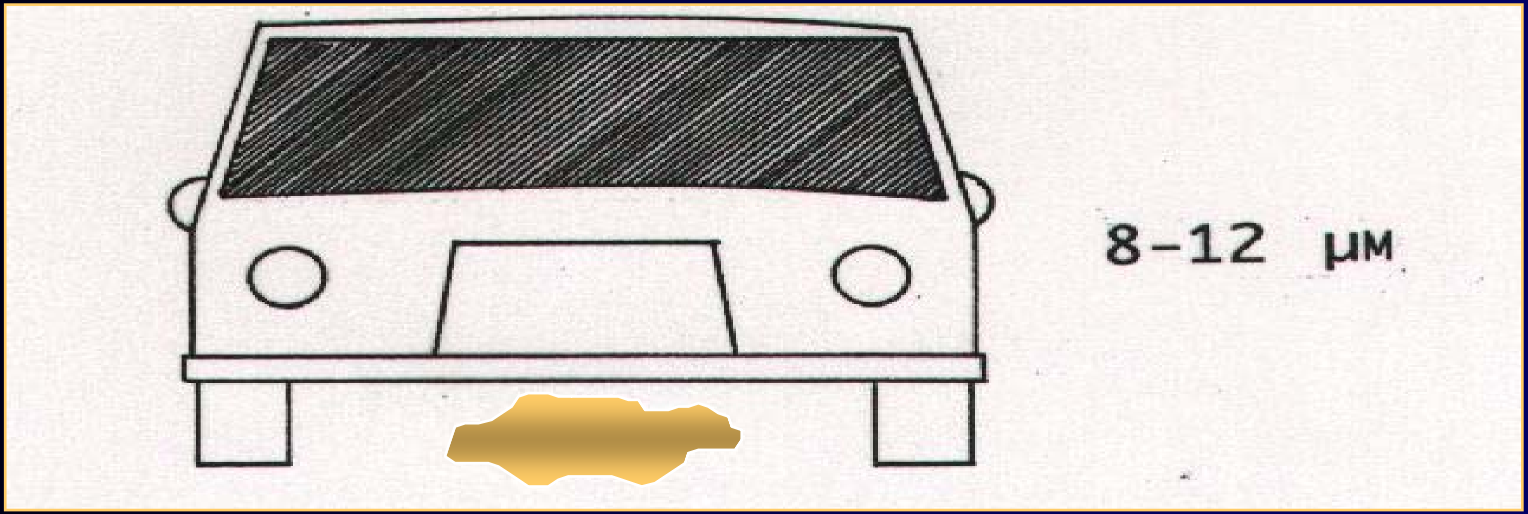



- No Chromatic Information
- Some Thermal Information
- High Specular IR Return from Pavement
- Reduced Transmission Through Windshield Glass
- Moderate Fog Penetration

# 3-5mm SW Infrared

3-5mm: Cincinnati Electric “Iris”, FSI Prism
Inframetrics 600, Mitsubishi IR-M300

# Image Characteristics: 8-12 $\mu m$ IR




- Primarily Surface Temperature Information (used for remote thermography)
- Non-transmissive Through Windshield Glass
- No Chromatic Information
- Superior Transmissivity Through Fog

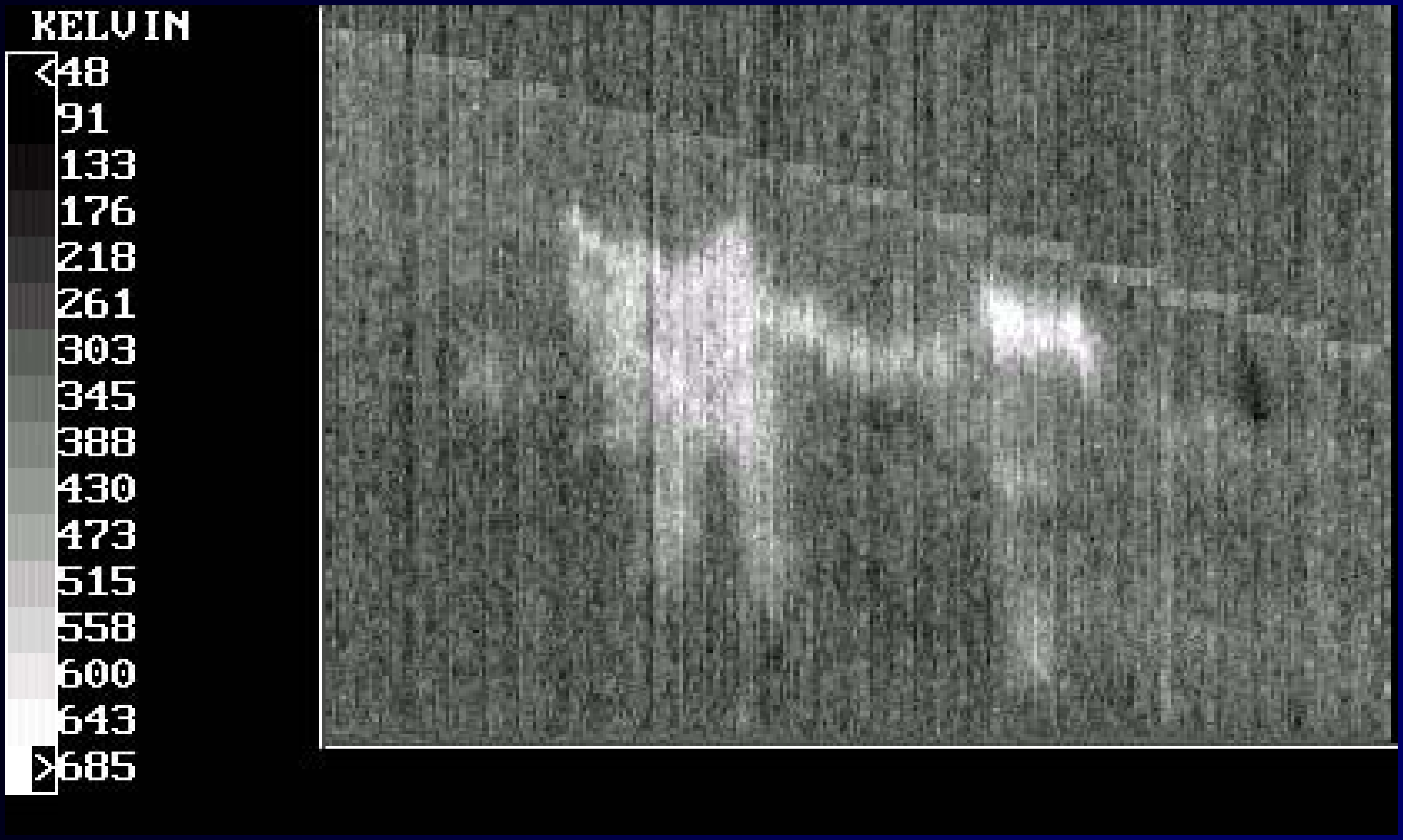
# 8-12mm LW Infrared

8-12 mm:  AGEMA Thermovision 1000,  Inframetrics 600 & 700

# Image Characteristics: 94 Ghz (3.2 mm)

- Millimeter Wave Technology
  - Still in the Early Stages of Development
  - Penetrates Fog with Very Little Attenuation
- Millimeter Wave Images
  - Very Low Resolution (Antenna Limited)
  - Experimental Imager Did Not Produce a Real Time Image
  - Image Information Primarily from Black Body Temperature & Surface Emissivity

# 94 GHz mm-wave Image




TRW - Experimental Multispectral Scanner

# mm Wave Image: Visible Image Equivalent

# Data Base of Videorecorded Images

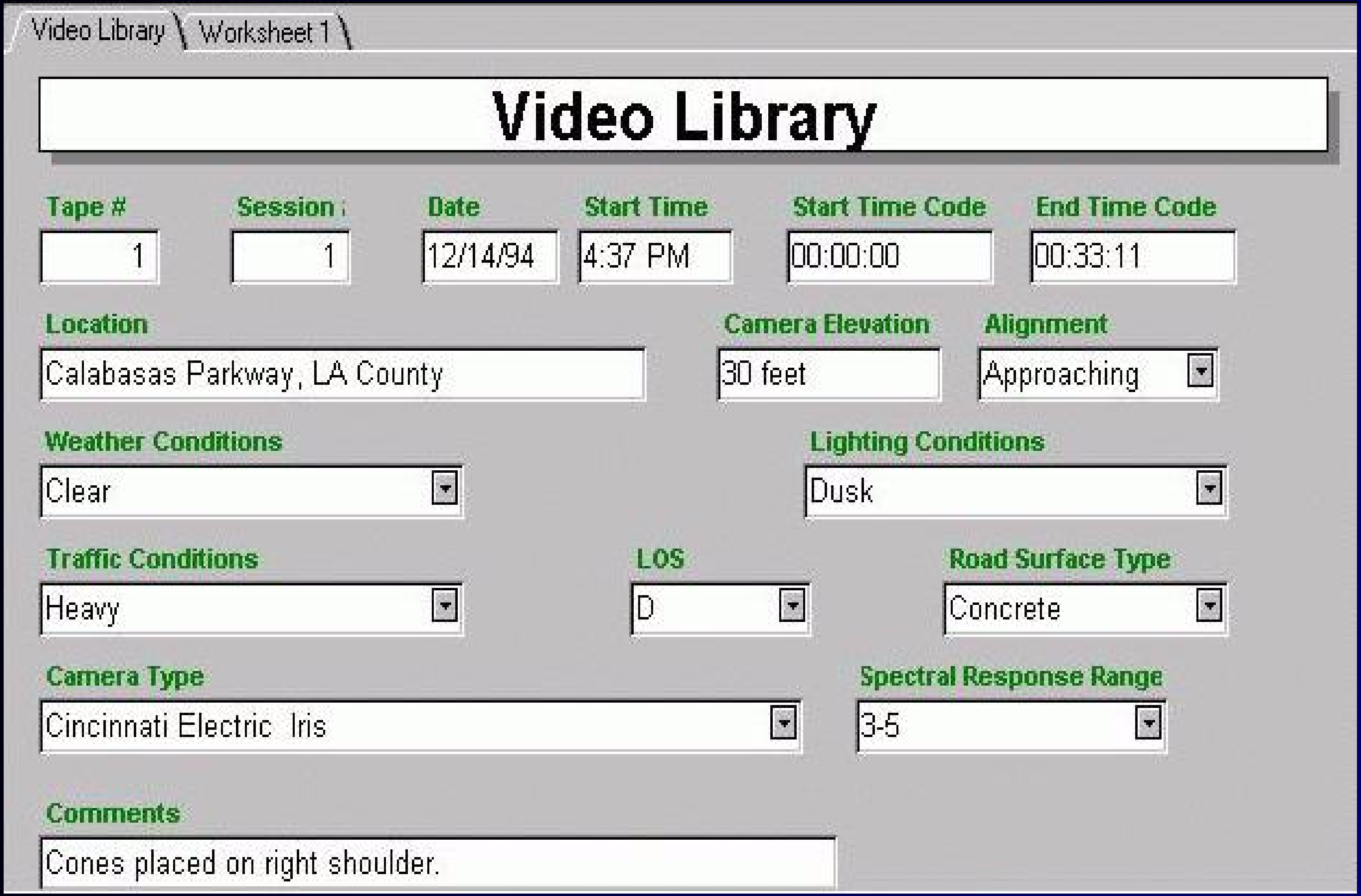
Search Parameters Include:

- Imager and Cooling Technology
- Spectral Response
- Weather Conditions
- LOS (A-F)
- Traffic Condition
- Time of Day
- Lighting Conditions

Accessible via Web at:

www.ee.calpoly.edu/depart/research/telab

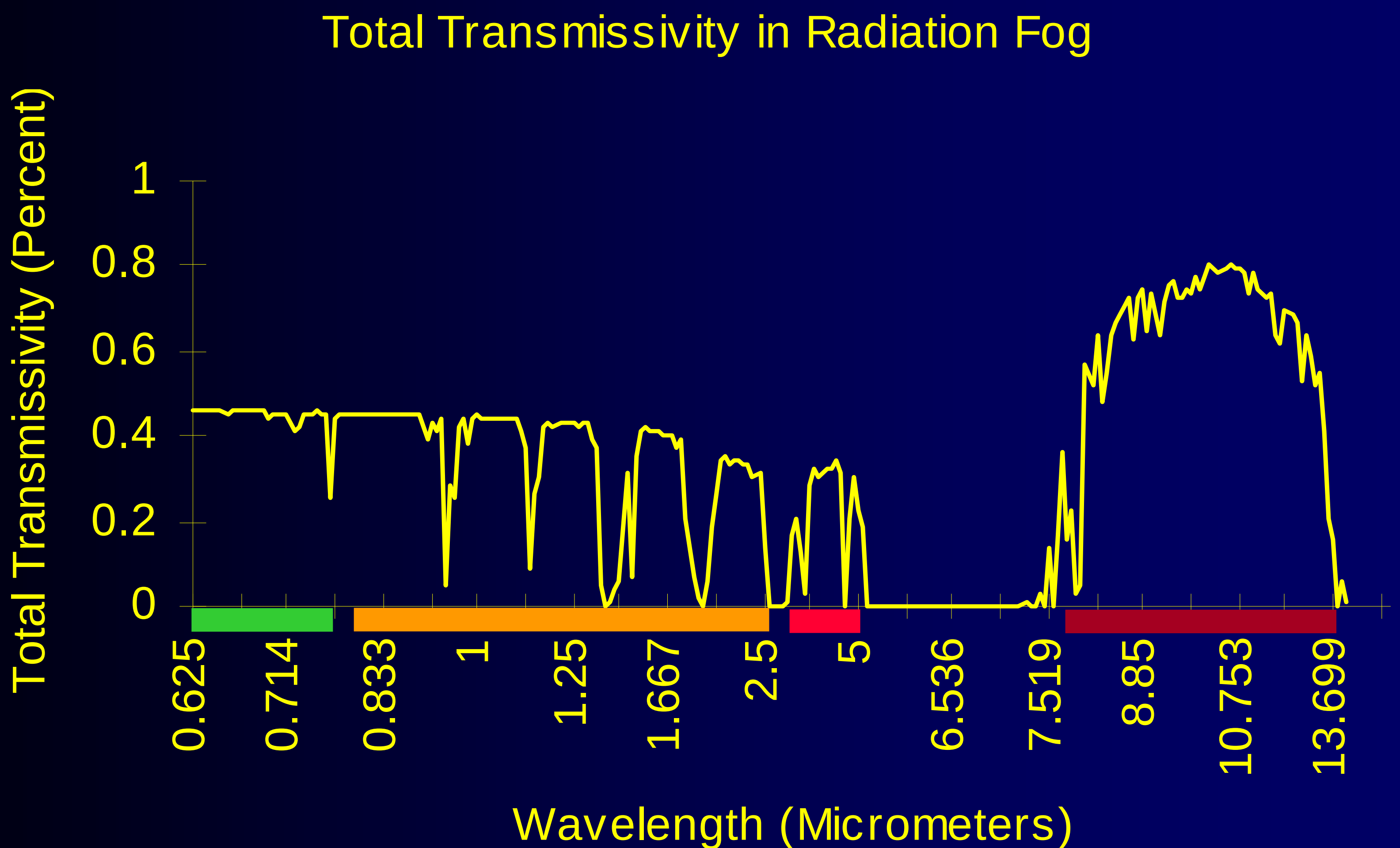
# Typical Data Base Search Entry



# Simulation of Atmospheric Transmission

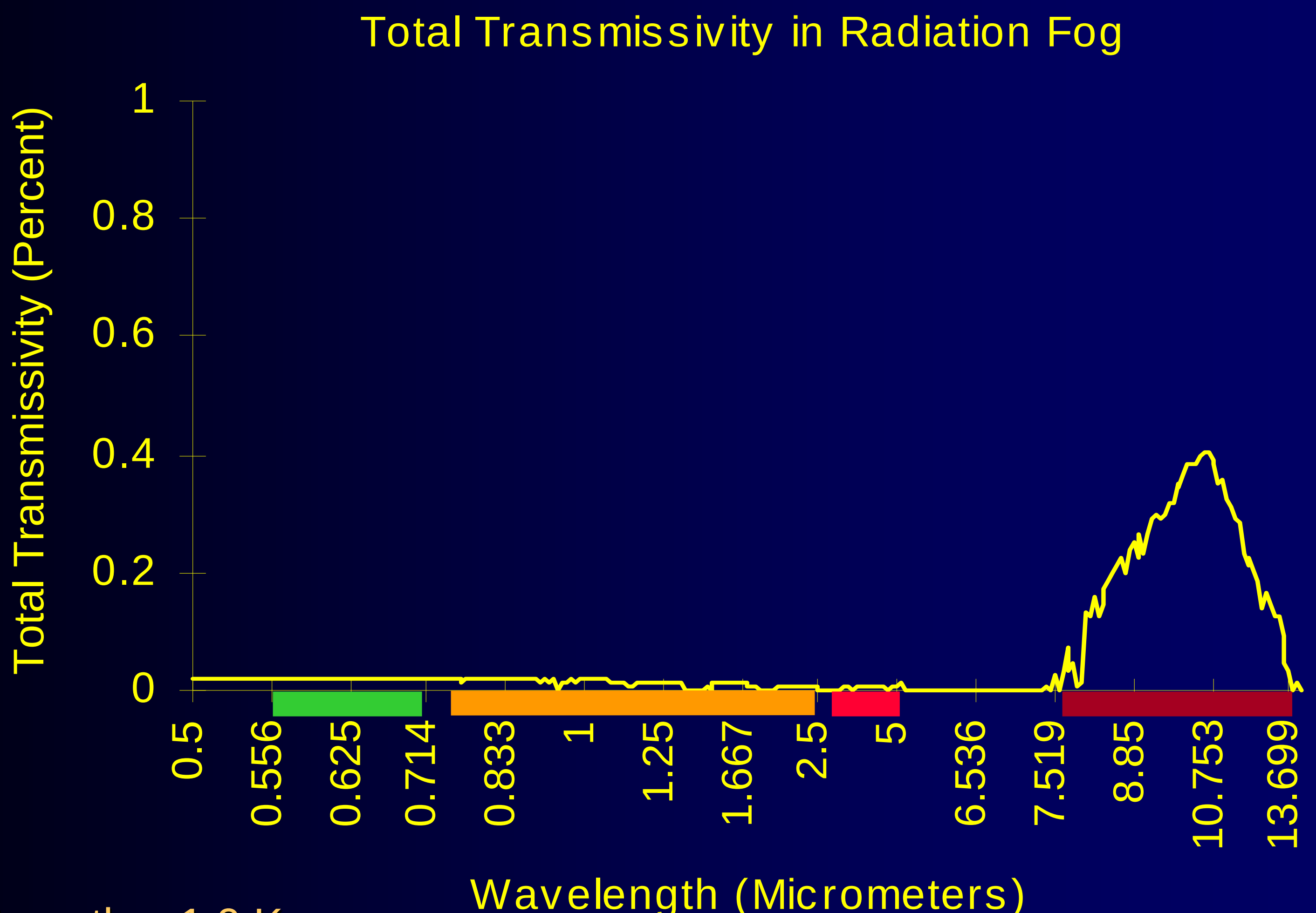
- Based on MODTRAN 3 , V 1.4 (2/96)
  - Atmospheric Transmissivity Based Upon Gas Composition
  - Covers Visible, IR and mm Wave Ranges
- Configured for Highway Conditions
  - Developed Radiation and Convection Fog Models for Hazardous Highway Conditions
  - Examined Attenuation in Various Atmospheric Aerosols, Parametric with Particle Size, Composition and Density

# Simulation: Good Visibility



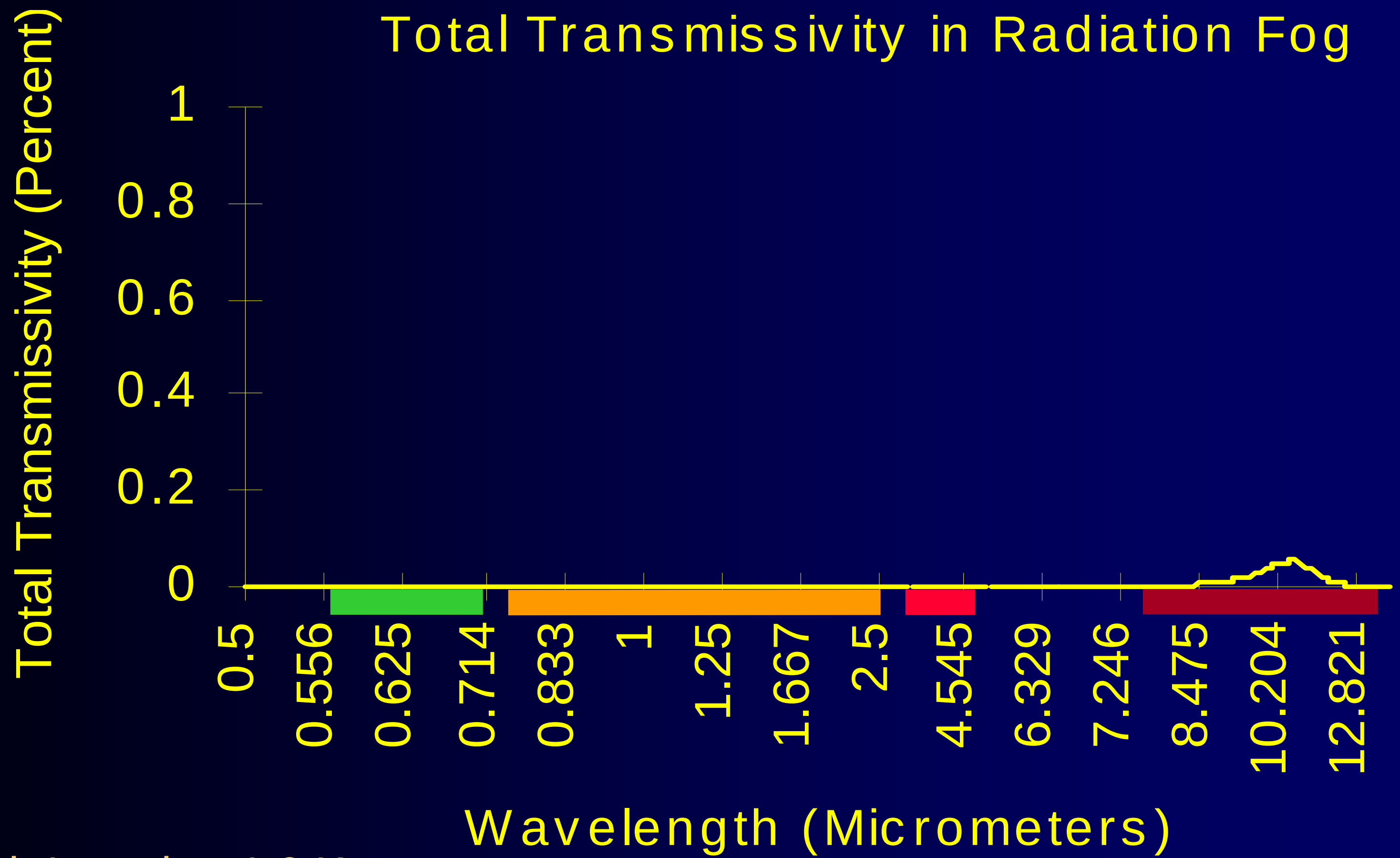

Path Length = 1.0 Km
Visibility = 5.0 Km

# Simulation: Limited Visibility




Path Length = 1.0 Km
Visibility = 1.0 Km

# Simulation: Extremely Limited Visibility




Path Length = 1.0 Km
Visibility = 0.3 Km

# Spectrum-Independent Image Information Metric

$$\text{Information/Noise Ratio (INR)} = \frac{\text{Foreground Information}}{\text{Background Noise}}$$

$$\text{Background Noise} = \sum_{j=1}^{q} \left[ \frac{\sum_{k=1}^{m} \left[ B_j[k] - BKG[k] \right]^2}{m} \right]^{1/2} \cdot \frac{1}{q \cdot 255}$$

j is the video field index
q is the total number of background fields
k is the pixel index
m is the total number of pixels in each field

Each pixel can range in value from 0-255

Final result is divided by 255 to normalize the result to a range of 0.0 to 1.0.

# Background Information Calculation

*BKG[k]* is the mean intensity of the $k^{th}$ pixel value across all *q* background fields:

$$BKG[k] = \frac{\sum_{j=1}^{q} B_j[k]}{q}$$

$B_j[k]$ is the $k^{th}$ pixel of the $j^{th}$ field in the set of background images.

# Foreground Information Calculation

$$\text{Foreground Information} = \sum_{j=1}^{n} \left[ \frac{\sum_{k=1}^{m} \left[ I_j[k] - \text{BKG}[k] \right]^2}{m} \right]^{1/2} \cdot \frac{1}{n \cdot 255}$$

$I_i[k]$ is the intensity of the $k^{th}$ pixel in the $i^{th}$ field of the foreground set

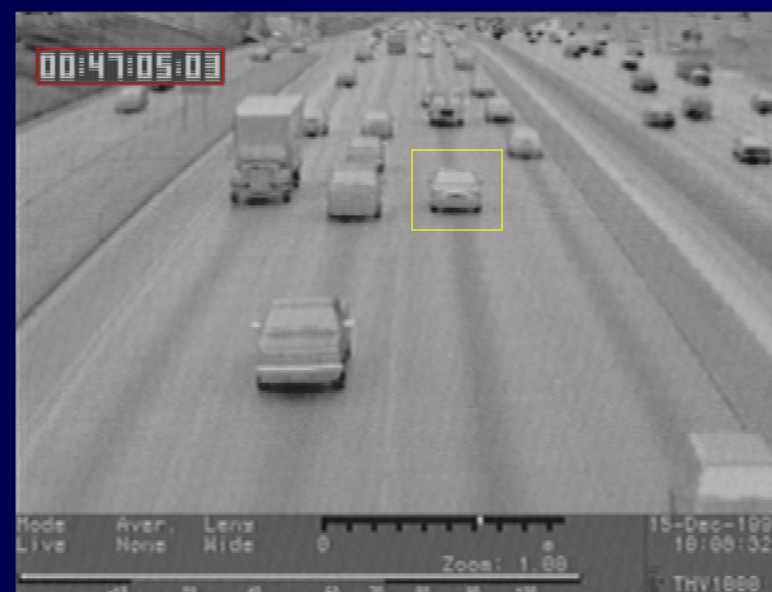
$n$ is the total number of foreground fields

$n$ need not equal the total number of background fields $q$, since the foreground and background sets are normalized independently.

# Placement of Analysis Window in Comparable Images

Texas Instruments NightSight
Pyroelectric Longwave IR

Agema ThermoVision 1000
HgCdTe Quantum Detector
Longwave IR



# Relative Value of Chromatic Information (Color CCD Cameras Only)

Color information incorporated in a modified form of the metric by summing the intensity information content of each fundamental color component (red, green and blue). For example, background information found as sum of:

$$BKG.red = \frac{\sum_{k=1}^{m} B[k].red}{m} \quad BKG.green = \frac{\sum_{k=1}^{m} B[k].green}{m} \quad BKG.blue = \frac{\sum_{k=1}^{m} B[k].blue}{m}$$

# Chromatic vs Monochromatic Images


Burle TC209 Color CCD
Camera (Visible Reference)

Agema ThermoVision 1000
HgCdTe Quantum Detector
Longwave IR

# Factoring in Resolution

- INR as defined above is independent of the resolution of the camera and the field of view, since it is normalized to the number of pixels in the image.
- It measures the intrinsic imaging quality of a sensor technology rather than the performance of a particular imaging device.
- For comparisons of competing products, a modified version of the INR de-normalizes the information content to yield *Total* information metric for a camera.
- Image-to-Noise * Resolution (INRR) is calculated by simply multiplying INR by the camera resolution in pixels.

# Imager Resolution

| Camera | Horiz. | Vert. | H x V | Resolution Multiplier |
|---|---|---|---|---|
| Cincinnati Elect. 3-5 μm | 256 | 256 | 65536 | 4.26 |
| FSI Prism 3-5 μm | 320 | 244 | 78080 | 5.07 |
| TI NightSight 8-14 μm | 320 | 164 | 52480 | 3.41 |
| AGEMA 8-12 μm | 320 | 240 | 76800 | 4.99 |
| Burle Security Visible | 768 | 494 | 379392 | 24.65 |
| StarSight 8-14 μm (round) | 140 | 140 | 15394 | 1.00 |
| Inframetrics 600 8-12 μm | 194 | 240 | 46560 | 3.02 |
| Inframetrics 600 3-5 μm | 194 | 240 | 46560 | 3.02 |
| M300 3-5 μm | 256 | 256 | 65536 | 4.26 |
| Marconi 8-14 μm | 200 | 200 | 40000 | 2.60 |
| Inframetrics 760 8-12 μm | 194 | 240 | 46560 | 3.02 |
| Infracam 3-5 μm | 256 | 256 | 65536 | 4.26 |
| TRW Imager | NA | NA | NA | NA |

NA = not applicable

# Limitations of Metrics

- Sensitivity of the metric to size of the analysis window
  - Window is typically sized to be slightly larger than the size of typical vehicle, or approximately the width of a traffic lane in the scene
  - Relative window size must be the same for video images produced by each device
- Sensitivity to features of test scene, such as the types and colors of vehicles and the effects of shadows or changing light conditions
  - Same image sequences should be used to generate the metric for each pair-wise camera comparison
- Test Procedure
  - All comparisons from three or four cameras viewing the same traffic scene concurrently.
  - Linear SMPTE (Society of Motion Picture and Television Engineers) standard time code (LTC) used for frame-by-frame synchronization between all cameras in group.

# Imaging Performance in Fog


Inframetrics 760
HgCdTe 8-12 um IR


Inframetrics Infracam
FPA 3-5 um IR


Burle TC209 Color
CCD Camera
(Visible Reference)

# Sample Raw Data

| ID | Condition | Session | Raw INR | FG | BKG | Camera |
|---|---|---|---|---|---|---|
| 1 | Approaching | Dusk1 | 11.889 | 0.095 | 0.008 | Cincinnati Elect. 3-5 μm |
| 2 | Approaching | Dusk1 | 4.308 | 0.106 | 0.025 | FSI Prism 3-5 μm |
| 3 | Approaching | Dusk1 | 6.425 | 0.067 | 0.010 | TI NightSight 8-14 μm |
| 4 | Approaching | Dusk1 | 8.247 | 0.086 | 0.010 | AGEMA 8-12 μm |
| 5 | Approaching | Night2 | 1.894 | 0.169 | 0.089 | StarSight 8-14 μm |
| 6 | Approaching | Night2 | 5.518 | 0.105 | 0.019 | Inframetrics 600 8-12 μm |
| 7 | Approaching | Night2 | 5.648 | 0.114 | 0.020 | Marconi 8-14 μm |
| 8 | Approaching | Night2 | 1.178 | 0.024 | 0.020 | Inframetrics 600 3-5 μm |
| 9 | Approaching | Night2 | 14.350 | 0.208 | 0.015 | Mitisubishi M300 3-5 μm |
| 17 | Approaching | Day5 | 11.526 | 0.124 | 0.0101 | Cincinnati Elect. 3-5 μm |
| 18 | Approaching | Day5 | 6.569 | 0.095 | 0.014 | FSI Prism 3-5 μm |
| 19 | Approaching | Day5 | 8.625 | 0.078 | 0.009 | TI NightSight 8-14 μm |
| 20 | Approaching | Day5 | 9.237 | 0.090 | 0.010 | AGEMA 8-12 μm |

# INR Composite Results, No Fog

| Camera | INR Normalized with Respect to Visible Camera | Rank |
|---|---|---|
| Cincinnati Elect. 3-5μm | 0.345 | 2 |
| FSI Prism 3-5μm | 0.130 | 7 |
| TI NightSight 8-14μm | 0.186 | 5 |
| AGEMA 8-12μm | 0.248 | 4 |
| Burle Security Visible | 1.000 | 1 |
| StarSight 8-14μm | 0.044 | 10 |
| Inframetrics 600 8-12μm | 0.136 | 6 |
| Inframetrics 600 3-5 μm | 0.028 | 11 |
| Mitsubishi M300 3-5μm | 0.336 | 3 |
| Marconi 8-14μm | 0.107 | 8 |
| TRW Mulispectral Imager | 0.084 | 9 |

# INRR Composite Results, No Fog

| Camera | INRR Normalized with Respect to Visible Camera | Rank |
|---|---|---|
| Cincinnati Elect. 3-5 μm | 0.060 | 2 |
| FSI Prism 3-5 μm | 0.027 | 5 |
| TI NightSight 8-14 μm | 0.026 | 6 |
| AGEMA 8-12 μm | 0.050 | 4 |
| Burle Security Visible | 1.000 | 1 |
| StarSight 8-14 μm | 0.002 | 10 |
| Inframetrics 600 8-12 μm | 0.017 | 7 |
| Inframetrics 600 3-5 μm | 0.003 | 9 |
| Mitsubishi M300 3-5 μm | 0.058 | 3 |
| Marconi 8-14 μm | 0.011 | 8 |
| TRW Mulispectral Imager | NA | NA |

NA = not applicable

# INR Composite Results, Dense Fog

| Camera | Average INR Normalized with Respect to Visible Camera | Rank |
|---|---|---|
| Burle Security Visible | 1.000 | 2 |
| Inframetrics 760 8-12 μm | 0.248 | 3 |
| Inframcam 3-5 μm | 1.408 | 1 |

# INRR Composite Results, Dense Fog

| Camera | Average INRR Normalized with Respect to Visible Camera | Rank |
|---|---|---|
| Burle Security Visible | 1.000 | 1 |
| Inframetrics 760 8-12 μm | 0.046 | 3 |
| Infracam 3-5 μm | 0.243 | 2 |

# Conclusions and Observations

- INR Metric address detectability of vehicles and objects
- INRR metric addresses identifiability of vehicles and objects
- Without fog, INR and INRR results best for visible camera, followed by the 3-5 mm cameras
- Under dense fog conditions, the 3-5 mm camera best, with visible still acceptable
- In fog, superior performance of visible and 3-5 mm IR cameras relative to 8-12 mm attributable to the significant value of the chromatic information available in the visible, and the headlight information available in the visible, VNIR and 3-5 mm IR bands.
- Fog-related results apply only to natural scene illumination; source-related (e.g., headlight) backscatter can significantly reduce the usability of visible spectrum imaging in fog.
- Longwave IR (8-12 mm) and millimeter-wave (94 GHz) bands have some intrinsic advantage under combined conditions of darkness. Also immune to headlight or streetlight backscatter effects

# Conclusions and Observations Continued

- VNIR images so similar to monochromatic visible spectrum images, no identifiable advantage for traffic monitoring, other than possibly covert surveillance with artificial VNIR illumination
- The 94 GHz passive millimeter-wave virtually unaffected by atmospheric obscurants, but resolution too poor to be of practical value
- The information content of infrared and mm-wave images is significantly different than that of visible spectrum imagery.  These differences affect our subjective sense of the quality of the imagery, especially if no special consideration was given to the unique value of the additional information available in the IR images.
- In the 8-12 mm longwave IR band, the windshield appears opaque and the engine, tire, and exhaust signatures appear more prominent
- IR reflections from pavement (such as reflected engine radiation) are strong in midwave IR images and somewhat weaker in longwave images
- In longwave IR, solar shadows cannot be detected, although slight differences in pavement temperature, such as on surfaces below an overcrossing, are clearly evident
- Solar IR shadows are also evident in the mid-wave IR band, but pavement temperatures are less detectable.

# Conclusions and Observations Continued

- Except for a limited number of surveillance situations, infrared and millimeter-wave imaging technologies provide marginal or no net advantage compared with conventional color CCD video cameras.
- Special situations that may warrant the use of IR or millimeter-wave imaging:
  - Recurrent dense fog, smoke or dust, in combination with recurrent hazardous traffic patterns, where surveillance and intervention by TMC personnel could reduce traffic incidents or loss.
  - Situations in which temperature information in the scene is useful, for example, detection of overheated truck brakes for HOV inspection.
  - Machine vision applications in which consistent scene illumination is critical, or the rejection of shadows and/or glare is required for accurate detection or measurement.
- Sensor fusion opportunities promising, due to fundamentally different information content and transmission characteristics of IR and mm-wave images.