Phenomenological study of passive image-based observables used to determine standard from overladen vehicles

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Objective

• To determine if the
  – shape of the tire, or
  – Temperature of the brake rotor

Measured using passive image-based remote sensing techniques can be used to determine if a vehicle is carrying a heavy load.
Purpose

• DOE is interested in tracking illicit trafficking of nuclear materials
  – Assume proper shielding
  – Assume use of a standard commercial vehicle

• UAV cued for persistent surveillance if vehicle is determined to be suspicious
Experimental Protocol

Drive 300 ft at 30mph to stopping cones
6 weight classes (0 to 3625lbs)
Experimental Protocol

• Measurements taken while the vehicle was stopped:
  
  – Surface temperatures of brake, door, side bumper, tire, hub cap and hub center (Exergen)
  
  – Height from the ground to the wheel well for purposes of calibration

  – Tire imagery – 3 VIS (Nikon D50), 1 Thermal (FLIR A20)

  – Weather readings - wind speed, temperature, relative humidity (Kestrel)
Experimental Protocol

• Between trials:
  – Brakes allowed to cool to approximately 40°C
  – Images were acquired of both a hot and cold blackbody for purposes of thermal calibration
VISIBLE IMAGERY & DATA
Tire Shape

Initially a region growing algorithm was developed to use in combination with thresholding techniques in order to segment the tire and hub.
Proof of Concept
Hub Threshold
Hub Segmentation
Tire Threshold
Tire Segmented
Thresholded Image
Segmentation Technique

• Thresholding alone was unsuccessful with a single threshold

• Tire ratio itself was more important than segmentation

• Images were segmented by hand in Adobe Photoshop CS3 using the magnetic lasso tool
Final Segmentation
Height to Width (HTW) Ratio

Ratio = Vertical Height / Horizontal Width
Bottom to Top Cumulative Radius (BTTCR) Ratio

Ratio = Sum of Bottom Rays / Sum of Top Rays
Back Right BTTCRR Tire Ratio

◊ - BTTCR$_S$  □ - BTTCR$_1$

BTTCRR Ratio

Weight [lbs]
Constrained Bottom to Top Cumulative Radius (CBTTCR) Ratio

Ratio = Sum of Bottom Rays / Sum of Top Rays
Front Right CBTTCRR Tire Ratio

CBTTCC Ratio

- CBTTCR$_5$ - CBTTCR$_1$

Weight [lbs]
THERMAL IMAGERY & DATA
Absolute Contact Temperature of Brake Rotor

Temperature (°C)

Weight [lbs]
Experimental Image

FLIR System A20
FLIR Calibration

\[ L_{\text{sensor}}(\lambda) = \epsilon(\lambda)L_{BB,T}(\lambda) + [1 - \epsilon(\lambda)]L_4(\lambda) \]
FLIR Calibration

\[ L_{\text{sensor}}(\lambda) = \epsilon(\lambda)L_{BB,T}(\lambda) + [1 - \epsilon(\lambda)] L_\perp(\lambda) \]

\[ L_{\text{sensor,cold}}(\lambda) = \epsilon(\lambda)L_{BB,T_{\text{cold}}}(\lambda) + [1 - \epsilon(\lambda)] L_\perp(\lambda) \]

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\[ L_{\text{sensor,hot}}(\lambda) = L_{BB,T_{\text{hot}}}(\lambda) \]

\[ DC_{\text{cold}} = m \int_{\lambda} L_{\text{sensor,cold}}(\lambda) \beta(\lambda) d\lambda + b = m \int_{\lambda} L_{BB,T_{\text{cold}}}(\lambda) \beta(\lambda) d\lambda + b \]

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\[ DC_{\text{hot}} = m \int_\lambda L_{\text{sensor, hot}}(\lambda) \beta(\lambda) d\lambda + b = m \int_\lambda L_{BB,T_{\text{hot}}}(\lambda) \beta(\lambda) d\lambda + b \]

\[ L_{\text{sensor}} = \frac{DC - b}{m} \]
**Brakes should be the same temperature all the way around**

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</table>
Calculating Angles

\[ \sim 1^\circ \]

FLIR

20 ft

\sim 38 \text{ ft}
Downwelling Radiance

• Based on angle/distance measurements, there is a mixture of sky, grass, building, etc composing the downwelling radiance component

• Can’t use MODTRAN to model

• Calculate downwelling radiance based on known values
Brake Radiance
Downwelling Calculation

\[
L_{\text{sensor}}(\lambda) = \epsilon(\lambda)L_{BB,T}(\lambda) + [1 - \epsilon(\lambda)] L_\perp(\lambda)
\]

- Calibrated Radiance values between 54 and 63 [W/m\(^2\)/\(\mu\)m] computed from digital count values
- Average Calculated Downwelling Radiance
  - Hole 1: \(~50\) [W/m\(^2\)/\(\mu\)m] \(\rightarrow\) 20°C
  - Hole 3: \(~57\) [W/m\(^2\)/\(\mu\)m] \(\rightarrow\) 29°C
  - Hole 4: \(~56\) [W/m\(^2\)/\(\mu\)m] \(\rightarrow\) 28°C
  - Hole 5: \(~52\) [W/m\(^2\)/\(\mu\)m] \(\rightarrow\) 23°C
Brake Radiance Downwelling Calculation

\[ L_{sensor}(\lambda) = \epsilon(\lambda) L_{BB,T}(\lambda) + [1 - \epsilon(\lambda)] L_{\downarrow}(\lambda) \]

- Calibrated Radiance values between 54 and 63 [W/m\(^2\)/μm] computed from digital count values
- Background

- Average Calculated Downwelling Radiance
  - Hole 1: ~50 [W/m\(^2\)/μm] → 20°C
  - Hole 3: ~57 [W/m\(^2\)/μm] → 29°C
  - Hole 4: ~56 [W/m\(^2\)/μm] → 28°C
  - Hole 5: ~52 [W/m\(^2\)/μm] → 23°C
\[ L_{sensor}(\lambda) = \epsilon(\lambda)L_{BB,T}(\lambda) + [1 - \epsilon(\lambda)]L_{\perp}(\lambda) \]

Calibrated Brake Temperature

◊ - Measured  □ - Calculated Absolute
Procedure Re-Cap

- Use known sample temperatures to calculate downwelling radiance
- Average downwelling radiance component
- Use the average downwelling radiance to derive the sample temperature
# Downwelling Radiance

<table>
<thead>
<tr>
<th>Vehicle Part</th>
<th>Min [W/m²/μm]</th>
<th>Max [W/m²/μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Door</td>
<td>-4.3</td>
<td>32.6</td>
</tr>
<tr>
<td>Side</td>
<td>-8.7</td>
<td>24.9</td>
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<tr>
<td>Tire</td>
<td>9.8</td>
<td>66.5</td>
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<tr>
<td>Hubcap</td>
<td>-75.5</td>
<td>6.5</td>
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<tr>
<td>Bumper</td>
<td>-92.7</td>
<td>36.0</td>
</tr>
</tbody>
</table>
Error Propagation

• Partial Derivative Error Analysis
  – $\Delta L = 0.2 \text{ W/m}^2/\mu\text{m}$ (gives change of 1 DC)
  – $\Delta \varepsilon = 0.01, 0.1, 0.4$
  – $\Delta T = 0.1^\circ\text{C} \text{ to } 1^\circ\text{C}$ (error in Exergen measurement)

• Error Results: 0.5 to 6 W/m$^2$/μm

• Can’t calculate downwelling/background radiance
Apparent Temperature (Camera)

- Trust that the camera temperature is linear over digital count

\[ T = \frac{60 \times DC + 25}{255} \]
Brake Temperature From Blackbody Radiance

Sensor Derived Apparent Temperature (°C)

- Measured  □ - Calculated Camera
Conclusions

• The observed phenomena match the initial predictions
  – An increase in weight leads to a decrease in the tire ratio for all studied metrics
  – An increase in weight leads to an increase in the relative temperature differences for all measured temperatures