Luminous Intensity for Traffic Signals:  
A Scientific Basis for Performance Specifications

J. D. Bullough, P. R. Boyce, A. Bierman, K. M. Conway,  
K. Huang, C. P. O’Rourke, C. M. Hunter and A. Nakata

Lighting Research Center  
Rensselaer Polytechnic Institute  
Troy, New York 12180-3590

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Appendices to Final Report

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Pacific Gas and Electric Company

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Appendix 1

Mean Reaction Times for Individual Subjects

The following figures show the mean reaction time plotted against the signal luminance, for each subject when viewing each combination of luminance and color used. The y-axis error bars correspond to one standard deviation about the mean reaction time. The x-axis error bars correspond to one standard deviation about the mean measured luminance. The x-axis error bars are only given for the measurements made in the first experiment. For that study, the luminance of the signals was measured in several different ways and the results averaged. No additional luminance measurements were made in the third experiment, the relationship between mean measured luminance and current through the LED established in the first experiment being used to predict the current required to achieve the desired signal luminance in the third experiment. The three curves in each figure are power law fits through the mean reaction times, the mean reaction times plus one standard deviation and the mean reaction time minus one standard deviation. The power law fits through the mean reaction times plus and minus one standard deviation have been calculated to provide a sensitivity test for the normalized equations predicting the percentage change in reaction time (See Appendix 3).
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject A, Green Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation
For Subject A, Yellow Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject A, Red Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject B, Green Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject B, Yellow Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation
For Subject B, Red Signal

[Graph showing reaction time vs. luminance with different conditions, including LED and incandescent options.]
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject C, Green Signal
Best Fitted Curves through Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation
For Subject C, Yellow Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject C, Red Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject D, Green Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject D, Yellow Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject D, Red Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation
For Subject E, Green Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject E, Yellow Signal
Best Fitted Curves through Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation
For Subject E, Red Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One
Standard Deviation, and Mean Reaction Time Minus One Standard Deviation
For Subject F, Green Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation
For Subject F, Yellow Signal

![Graph showing the relationship between luminance and mean reaction time.](image-url)
Best Fitted Curves through Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject F, Red Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject G, Green Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject G, Yellow Signal
Best Fitted Curves through Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject G, Red Signal
Best Fitted Curves through Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject H, Green Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject H, Yellow Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation
For Subject H, Red Signal

Mean Reaction Time (ms)

Luminance (cd/m²)

LED
Incandescent
Plus one S.D.
Minus one S.D.
Mean reaction time
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject I, Green Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject I, Yellow Signal

![Graph showing reaction time vs. luminance]
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject I, Red Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject J, Green Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject J, Yellow Signal
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation
For Subject J, Red Signal
Appendix 2

Percentage Change in Reaction Time Normalized to Performance Level 2 of the Draft European Standard for a 200 mm Diameter Signal

The following three figures show the percentage change in mean reaction time for the red, yellow and green LED signals calculated from the best fitting curves through the mean reaction times for each individual subject (see Appendix 1 for the curves). For the red, yellow and green LED signals, 100% reaction time is at a luminance of 6366 cd/m².
Percentage Reaction Time Change for Green Signal:
PL2 Standard.

\[ y = 838.65 \times^{-0.241} \]

Percentage change in mean reaction time

Luminance (cd/m²)

Dimmer
Brighter

PL2 - Green

Luminous Intensity (cd)

(157) (471) (314) (785) (628) (785)
Percentage Reaction Time Change for Yellow Signal:
PL2 Standard

\[ y = 446.9 \times x^{-0.170} \]

Dimmer - Brighter

Luminous Intensity (cd)

Luminance (cd/m^2)

(157) (314) (471) (628) (785)
Percentage Reaction Time Change for Red Signal:
PL2 Standard

\[ y = 378.24 \times^{-0.151} \]

Luminance (cd/m\(^2\))

Percentage change in mean reaction time

Dimmer

Brighter

PL2 - Red

Luminous Intensity (cd)

(157) (314) (471) (628) (785)
Appendix 3

Percentage Change in Reaction Time Based on Different Individual Curves

The following three figures show the percentage change in mean reaction time for the red, yellow and green LED signals calculated from the best fitting curves through the mean reaction times, the mean reaction times plus one standard deviation and the mean reaction times minus one standard deviation for each individual subject (see Appendix 1 for the curves). For the red LED signal, 100% reaction time is at a luminance of 5000 cd/m$^2$. For the yellow LED signal, 100% reaction time is at a luminance of 23,121 cd/m$^2$. For the green LED signal, 100% reaction time is at a luminance of 10,000 cd/m$^2$. The fact that the percentage changes are very similar for all three curves, for the same signal color, indicates the predictive equations for percentage change in reaction time are robust.
Percentage Reaction Time Change for Green Signal:
ITE Standard

\[ y = 959.19x^{-0.245} \text{(Mean RT)} \]

\[ y = 1010.3x^{-0.251} \text{(Plus 1 S.D.)} \]

\[ y = 874.36x^{-0.235} \text{(Minus 1 S.D.)} \]
Percentage Reaction Time Change for Yellow Signal:
ITE Standard

\[ y = 586.82 x^{-0.177} \] (Mean RT)

\[ y = 664.7 x^{-0.189} \] (Plus 1 S.D.)

\[ y = 477.85 x^{-0.157} \] (Minus 1 S.D.)
Percentage Reaction Time Change for Red Signal:
ITE Standard

\[ y = 355.98 x^{-0.148} \]  (Mean RT)

\[ y = 414.97 x^{-0.166} \]  (Plus 1 S.D.)

\[ y = 286.96 x^{-0.123} \]  (Minus 1 S.D.)
Appendix 4

Missed Signals for Individual Subjects

The following figures show the mean number of signals missed plotted against the signal luminance, for each subject when viewing each combination of luminance and color used in the first and third experiments. The y-axis error bars correspond to one standard deviation about the mean number of signals missed. The x-axis error bars correspond to one standard deviation about the mean measured luminance. The x-axis error bars are only given for the measurements made in the first experiment. This is because for that study the luminance of the signals was measured in several different ways and the results averaged. No additional luminance measurements were made in the third experiment, the relationship between mean measured luminance and current through the LED established in the first experiment being used to predict the current required to achieve the desired signal luminance in this study.
Subject A - Missed Signals

Mean number of missed signals vs. Luminance (cd/m²)

- Green - LED
- Yellow - LED
- Red - LED
- Green - Inc
- Yellow - Inc
- Red - Inc
Subject B - Missed Signals

Mean number of missed signals as a function of luminance for different colors:
- Green - LED
- Yellow - LED
- Red - LED
- Green - Inc
- Yellow - Inc
- Red - Inc

Luminance (cd/m²)
Subject C - Missed Signals

![Graph showing mean number of missed signals vs. luminance for different LED and incandescent light colors.](image-url)
Subject D - Missed Signals

Mean number of missed signals

Luminance (cd/m²)

- Green - LED
- Yellow - LED
- Red - LED
- Green - Inc
- Yellow - Inc
- Red - Inc
Subject E - Missed Signals

Mean number of missed signals

Luminance (cd/m$^2$)

Green - LED
Yellow - LED
Red - LED
Green - Inc
Yellow - Inc
Red - Inc
Subject F - Missed Signals

Mean number of missed signals vs. Luminance (cd/m²)

- Green - LED
- Yellow - LED
- Red - LED
- Green - Inc
- Yellow - Inc
- Red - Inc
Subject G - Missed Signals

Mean number of missed signals vs. Luminance (cd/m²)

- Green - LED
- Yellow - LED
- Red - LED
- Green - Inc
- Yellow - Inc
- Red - Inc
Subject H - Missed Signals

Mean number of missed signals

Luminance (cd/m²)

- Green - LED
- Yellow - LED
- Red - LED
- Green - Inc
- Yellow - Inc
- Red - Inc
Subject I - Missed Signals

Mean number of missed signals vs. Luminance (cd/m²)
Subject J - Missed Signals

Mean number of missed signals vs Luminance (cd/m$^2$)

- Green - LED
- Yellow - LED
- Red - LED
- Green - Inc
- Yellow - LED
- Red - Inc
Appendix 5

Percentage of Missed Signals Predicted from the Best Fitting Equations

The percentage of missed signals for each signal color are predicted from the best fitting equation, for the range of luminances used in the measurements. The best fitting equation for the yellow LED goes slightly negative at luminances higher than 10,500 cd/m² (-0.66% at a luminance of 23,500 cd/m²). As this is impossible, the negative percentages have been replaced with a zero value, above 10,500 cd/m².

<table>
<thead>
<tr>
<th>Luminance (cd/m²)</th>
<th>Green LED</th>
<th>Yellow LED</th>
<th>Red LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>62</td>
<td>38</td>
<td>12</td>
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<tr>
<td>1500</td>
<td>41</td>
<td>13</td>
<td>3.8</td>
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<tr>
<td>2000</td>
<td>27</td>
<td>7.5</td>
<td>2.3</td>
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<td>2500</td>
<td>18</td>
<td>5.1</td>
<td>1.6</td>
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<td>3000</td>
<td>12</td>
<td>3.7</td>
<td>1.2</td>
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<td>5.8</td>
<td>2.2</td>
<td>0.86</td>
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<td>4500</td>
<td>4.3</td>
<td>1.8</td>
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<td>5000</td>
<td>3.3</td>
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<td>0.66</td>
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<td>2.6</td>
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<td>0.53</td>
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<td>0.48</td>
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<tr>
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<td>0.34</td>
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<td>0.12</td>
<td>0.32</td>
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<td>1.0</td>
<td>0.06</td>
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<td>10500</td>
<td>0.94</td>
<td>0.00</td>
<td>0.29</td>
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<td>0.00</td>
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</table>
# Appendix 6

Means and Standard Deviations of Ratings of Brightness, Conspicuity and Comfort, for all Three Signal Colors at the Luminances Used.

<table>
<thead>
<tr>
<th>Light source</th>
<th>Luminance (cd/m²)</th>
<th>Brightness Mean</th>
<th>Brightness Standard deviation</th>
<th>Conspicuity Mean</th>
<th>Conspicuity Standard deviation</th>
<th>Discomfort Mean</th>
<th>Discomfort Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED - Red</td>
<td>13704</td>
<td>8.00</td>
<td>1.53</td>
<td>8.33</td>
<td>1.42</td>
<td>2.87</td>
<td>1.93</td>
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<tr>
<td>LED - Red</td>
<td>8205</td>
<td>7.13</td>
<td>1.89</td>
<td>7.63</td>
<td>1.94</td>
<td>2.33</td>
<td>1.54</td>
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<tr>
<td>LED - Red</td>
<td>5319</td>
<td>6.77</td>
<td>1.98</td>
<td>7.00</td>
<td>2.07</td>
<td>2.37</td>
<td>1.43</td>
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<td>LED - Red</td>
<td>3626</td>
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<td>1.61</td>
<td>6.40</td>
<td>1.75</td>
<td>2.47</td>
<td>1.76</td>
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<td>LED - Red</td>
<td>2115</td>
<td>4.70</td>
<td>1.56</td>
<td>4.83</td>
<td>1.70</td>
<td>2.53</td>
<td>1.89</td>
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<tr>
<td>LED - Red</td>
<td>1049</td>
<td>3.00</td>
<td>1.20</td>
<td>3.17</td>
<td>1.42</td>
<td>3.17</td>
<td>2.73</td>
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<tr>
<td>Incandescent - Red</td>
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<td>6.17</td>
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<td>1.77</td>
<td>2.80</td>
<td>1.75</td>
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<tr>
<td>LED - Yellow</td>
<td>22253</td>
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<td>7.17</td>
<td>1.60</td>
<td>2.57</td>
<td>1.48</td>
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<tr>
<td>LED - Yellow</td>
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<td>7.10</td>
<td>1.73</td>
<td>7.27</td>
<td>1.60</td>
<td>2.53</td>
<td>1.63</td>
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<tr>
<td>LED - Yellow</td>
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<td>6.77</td>
<td>1.25</td>
<td>6.63</td>
<td>1.43</td>
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<tr>
<td>LED - Yellow</td>
<td>8119</td>
<td>5.77</td>
<td>1.50</td>
<td>5.67</td>
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<td>1.77</td>
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<tr>
<td>LED - Yellow</td>
<td>5321</td>
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<td>4.73</td>
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<td>3.10</td>
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<td>0.96</td>
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<td>Incandescent - Green*</td>
<td>11819</td>
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<td>2.04</td>
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<td>Incandescent - Green*</td>
<td>7171</td>
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<td>2.36</td>
<td>2.87</td>
<td>2.06</td>
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<td>Incandescent - Green*</td>
<td>6352</td>
<td>5.10</td>
<td>1.92</td>
<td>4.73</td>
<td>2.03</td>
<td>2.77</td>
<td>1.79</td>
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<td>LED - Green</td>
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<td>1.55</td>
<td>4.70</td>
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<td>1.01</td>
<td>2.03</td>
<td>0.96</td>
<td>3.63</td>
<td>3.31</td>
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<td>9587</td>
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<td>2.05</td>
<td>4.53</td>
<td>2.30</td>
<td>2.83</td>
<td>2.31</td>
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</tbody>
</table>

* Incandescent source filtered to provide similar color to green