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

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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

![Graph showing mean reaction time vs. luminance for different light sources and standard deviations.](image)

- **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 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
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

![Graph showing reaction time vs. luminance for different light sources and standard deviations.](image)
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 through Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject D, Green Signal

Mean Reaction Time (ms)

Luminance (cd/m²)
Best Fitted Curves through 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 through 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 though 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 through 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 mean reaction time vs. luminance, with symbols for LED and incandescent lights, and error bars indicating one standard deviation.]
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, 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 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 though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject G, Red Signal

![Graph showing reaction time against luminance with various curves and error bars.](image)
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 through Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject H, Yellow Signal

![Graph showing the relationship between luminance (cd/m²) and mean reaction time (ms) for different light sources and their standard deviations.](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 H, 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 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
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

Luminous Intensity (cd)

Dimmer

Brighter

Luminance (cd/m²)

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

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

<table>
<thead>
<tr>
<th>Luminance (cd/m²)</th>
<th>Percentage change in mean reaction time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5000</td>
<td>50</td>
</tr>
<tr>
<td>10000</td>
<td>100</td>
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<tr>
<td>15000</td>
<td>150</td>
</tr>
<tr>
<td>20000</td>
<td>200</td>
</tr>
<tr>
<td>25000</td>
<td>250</td>
</tr>
</tbody>
</table>

Dimmer (157) PL2 - Yellow (471) Brighter (785)

Luminous Intensity (cd)
Percentage Reaction Time Change for Red Signal: PL2 Standard

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

Luminance (cd/m²)

Percentage change in mean reaction time

Brighter

Dimmer

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/m². For the yellow LED signal, 100% reaction time is at a luminance of 23,121 cd/m². For the green LED signal, 100% reaction time is at a luminance of 10,000 cd/m². 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.)

![Graph showing percentage reaction time change with luminance in cd/m².](image-url)
Percentage Reaction Time Change for Red Signal:
ITE Standard

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

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

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

0 20 40 60 80 100 120 140 160 180 200

0 5000 10000 15000 20000 25000

Luminance (cd/m^2)

0 20 40 60 80 100

Percentage change in mean reaction
time

Dimmer
ITE - Red

(157)
Luminous Intensity (cd)

Brighter

(785)

(157)
(314)
(471)
(628)
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

![Graph showing the mean number of missed signals against luminance for different LED and incandescent colors. The x-axis represents luminance in cd/m², and the y-axis represents the mean number of missed signals.]
Subject B - Missed Signals

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

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

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

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

[Graph showing the effect of luminance on missed signals for different LED colors and incandescent lights.]
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

![Graph showing mean number of missed signals against luminance for different colors and light sources. The graph includes lines and symbols for Green - LED, Yellow - LED, Red - LED, Green - Inc, Yellow - Inc, and Red - Inc.]
Subject I - Missed Signals

- Mean number of missed signals
- Luminance ($\text{cd/m}^2$)

- Green - LED
- Yellow - LED
- Red - LED
- Green - Inc
- Yellow - LED
- Red - LED

Graph showing the relationship between luminance and the mean number of missed signals for different colors and types of lights.
Subject J - Missed Signals

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

- Green - LED
- Yellow - LED
- Red - LED
- Green - Inc
- Yellow - LED
- Red - Inc
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>
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<tbody>
<tr>
<td>1000</td>
<td>62</td>
<td>38</td>
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<tr>
<td>1500</td>
<td>41</td>
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Appendix 6

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

<table>
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<tr>
<th>Light source</th>
<th>Luminance (cd/m²)</th>
<th>Brightness Mean</th>
<th>Standard deviation</th>
<th>Conspicuity Mean</th>
<th>Standard deviation</th>
<th>Discomfort Mean</th>
<th>Standard deviation</th>
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<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>
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<td>1.93</td>
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<td>7.63</td>
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<td>2.37</td>
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<td>LED - Yellow</td>
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<td>2.30</td>
<td>2.83</td>
<td>2.31</td>
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</table>

* Incandescent source filtered to provide similar color to green