3M™ Connected Roads

Optimized Infrastructure for Mixed Fleet, Machine and Human Vision Systems

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Lane Departure Warning / Lane Keeping

By 2023, Lane Departure Warning in 71% of all new cars

New car penetration of ADAS features is increasing with LDW reaching 71% in 2023

North America, Europe, Japan

Experts report that effective LDW/LKA* can reduce accidents and save money

“LDW would reduce rates of crashes of all severities by 11% and crashes with injuries by 21% in the United States”¹

“LKA would reduce the number of fatalities by 15.2% and injuries by 8.9% in the EU25 if fully deployed”²

“At 11% market penetration, LDW would reduce monetary and non-monetary loses in Japan by 21.9%”³

¹ Cicchino, 2018, Journal of Safety Research
² Wilmink et al., 2008, eIMPACT Consortium
Machine Vision Systems Build a Lane Model
Visibility of lane markings

- In general, improving the visibility of lane markings for humans makes them more visible to machine vision systems
  - Minimally need presence of marking on the road – consistency of implementation is helpful
  - Lane markings often include optical elements intended to provide visibility at night
  - Contrast markings help visibility on light colored pavement
  - Lane marking dimensions and performance are not uniform

- Automated vehicles rely on the sharp contrast between the luminance of the pavement marking and the luminance of its immediate background to detect the pavement marking\(^1\).
- Poor pavement markings, adverse weather conditions and glare interfere with continuous automated vehicle operation and require special consideration

- Consistent dimensions and geometries are helpful and appropriate metrics ensure markings are effective

Maximize Contrast

Increase Marking Pixel Value
(make the marking brighter)

Decrease Background Pixel Value
(make adjacent surface less bright)

Maximize the rate of change
(make transition from bright to dark as sharp as possible)

Consistent black edge

Black markings on the right and left of the main lane marking increase contrast and enhance the perception of the lane marking.
Extending the operational domain in night and rain

- **Nighttime**: only 25% of driving occurs at night, 50% of traffic deaths happen at night\(^1\)
- **Rainfall**: increases the relative risk of crash and injury rates by 71% and 49% respectively\(^2\)
- Markings need to be retroreflective and provide sufficient signal-to-noise to be seen
- Continuous wet retroreflective to provide sufficient signal-to-noise at night in the rain
- Look ahead distance depends on headlight brightness and the retroreflectivity of the markings

![Poor Daytime Road Presence](image)

![Non Reflective vs. Reflective](image)

![Non Wet Reflective vs. Wet Reflective Markings](image)

Source: \(^1\) *The Most Dangerous Time to Drive*, National Safety Council, 2018
\(^2\) *Effects of Adverse Weather on Traffic Crashes*, Transportation Research Board, 2008
Visibility and Detection in Rain

Dry Daytime Conditions | Dry Nighttime Conditions | Wet Nighttime Conditions

Yellow Line = Optimized for wet retroreflectivity
White Line & Arrow = Not optimized for wet retroreflectivity
Key Characteristics of Pavement Markings Likely Improve Detection by Machine Vision Cameras

- **High Luminance***
  Increases light return available to each pixel at all lighting conditions

- **Wet Retroreflective Optics***
  Increase light return in nighttime and low-light wet conditions

- **High Contrast***
  Improves differentiation between marking and pavement substrate at all lighting conditions

Lane Marking Performance

European technical recommendations

“The European Road Federation strongly supports the road safety approach of the European Commission.

• Based on the analysis of research taking into consideration both vehicles equipped with driver assistance systems and human requirements, the ERF proposes the establishment of an intervention and maintenance policy as follows:”

• **Night visibility** should never drop below 150 mcd/lx/m2

• **Rainy conditions** should never drop below 35 mcd/lx/m2 (recent studies in US and EU also point to even higher levels)

• Ensure a sufficiently **high contrast ratio** between marking and pavement. While a contrast ratio of 3:1 appears sufficient, increased reliability can be achieved with a 4:1 ratio, mitigating possible false readings caused by glare and other critical conditions.
Nighttime: Both $R_L$ & Cap Y plus reflective optics and distance

- Lane Centering and Navigation (L2+)
  - LKA
  - LDW

Approximately 20m

Relative Contribution To Luminance

- High $R_L$
- Low $R_L$

Cap Y

Distance


Studying the Effects of the Wet Retroreflectivity and Luminance of Pavement Markings on LDW in Nighttime Continuous Rain

- 360 feet of 4-inch wide aluminum panels placed at 10-foot intervals; both yellows and white samples were evaluated.
- Aluminum panel were constructed of preformed tape designed for specific optical properties, positioned in rain tunnel.
- Rainfall averaged 1.5 in/h over the markings.
- Data collection via a Mobileye 5 Series ADAS unit mounted on a Ford Explorer, LDW confidence ratings of 0-3 were extracted and recorded.

Study conducted on 3M’s private track in Cottage Grove, MN.

Table 1. Pavement marking properties based on ASTM standards.

<table>
<thead>
<tr>
<th>Marking</th>
<th>Cap Y</th>
<th>Qd (mcd/m²/lx)</th>
<th>Continuous R_L (mcd/m²/lx)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01W</td>
<td>58</td>
<td>248</td>
<td>24</td>
</tr>
<tr>
<td>04W</td>
<td>44</td>
<td>190</td>
<td>105</td>
</tr>
<tr>
<td>05W</td>
<td>38</td>
<td>170</td>
<td>158</td>
</tr>
<tr>
<td>06W</td>
<td>40</td>
<td>200</td>
<td>21</td>
</tr>
<tr>
<td>08W</td>
<td>65</td>
<td>220</td>
<td>490</td>
</tr>
<tr>
<td>11Y</td>
<td>31</td>
<td>150</td>
<td>25</td>
</tr>
<tr>
<td>12Y</td>
<td>34</td>
<td>148</td>
<td>64</td>
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<tr>
<td>13Y</td>
<td>32</td>
<td>139</td>
<td>77</td>
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<tr>
<td>15Y</td>
<td>32</td>
<td>145</td>
<td>140</td>
</tr>
<tr>
<td>16Y</td>
<td>28</td>
<td>128</td>
<td>35</td>
</tr>
</tbody>
</table>

Confidence is a function of luminance and retroreflectivity...

1) Different parameters matter in different conditions (e.g. day/night, dry/wet)
2) Different parameters matter for different functionality (e.g. LKA, navigation)
3) PM performance needs to be maintained over time to enable optimal MV system functionality

## Fundamental Metrics

<table>
<thead>
<tr>
<th>Who</th>
<th>Day (Cap Y %)</th>
<th>Night – Dry</th>
<th>Night – Wet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human</td>
<td>Cap Y</td>
<td>$R_L$</td>
<td>$R_{L-W}$</td>
</tr>
<tr>
<td>LKA, LDW</td>
<td>Cap Y*</td>
<td>Cap Y</td>
<td>$R_L$</td>
</tr>
<tr>
<td>L2+</td>
<td>Cap Y*</td>
<td>$R_L$</td>
<td>$R_{L-W}$</td>
</tr>
<tr>
<td>LIDAR</td>
<td>$R_L$</td>
<td></td>
<td>$R_{L-W}$</td>
</tr>
</tbody>
</table>

- Cap Y (%) - ASTM E 1349
- $R_L$ (mcd/m²/lux) - ASTM E 1710
- $R_{L-W}$ (mcd/m²/lux) - ASTM E 2832
- All levels specified are **minimum retained** values

*Multiple Cap Ys may need to be specified for the marking for varying pavement marking backgrounds*
Thank You