Pavement Markings for MN State Roadways

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Office of Traffic Engineering

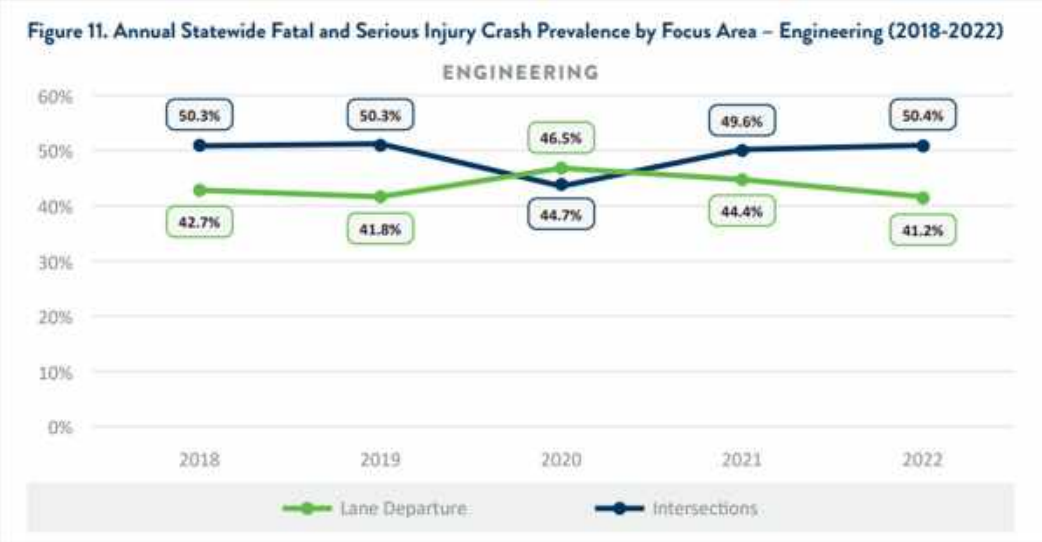
9/11/25

DEPARTMENT OF TRANSPORTATION

mndot.gov

Importance

- Single vehicle road departures are over 40% of all Minnesota fatalities and serious injuries.
  - These crashes were widely distributed across the entire state and local network, with horizontal curves making up a disproportionate amount.
  - When looking at how low the crash density (~0.01 severe road departure/mile/year) is, pavement markings are extremely cost effective to cover an entire system.
  - Road departures are especially prevalent on rural county highways, which is why MnDOT has been an advocate for local safety planning and providing HSIP money for locals.
  - It's not the road departure that's the main concern, it's what happens afterwards!



When Are Pavement Markings Needed

- According to the MN MUTCD:
  - Center line markings shall be placed on:
    - all paved urban arterials and collectors that have a traveled way of 20 feet or more in width and an Average Daily Traffic (ADT) of 6,000 greater.
    - two-way streets or highways that have three or more lanes for moving motor vehicle traffic
  - Edge line markings shall be placed on paved streets or highways with the following characteristics:
    - Freeways
    - Expressways
    - Rural arterials with a traveled way of 20 feet or more in width and an ADT of 6,000 vehicles per day or greater.

MnDOT's PM Goal

- Due to the safety benefits, MnDOT installs center lines and edge lines on all their paved roads.
- "Provide an appropriate pavement marking on all highways, 365 days per year."
- An appropriate pavement marking is one that meets or exceeds the standards defined in the MN MUTCD.
- During winter weather events, pavement markings should provide presence after pavement is clear of snow and ice.

Retroreflectivity

- Research has shown that the threshold between an acceptable and an unacceptable pavement marking based on nighttime driver visibility needs is between 80 and 120 MCD/m2 /lux.
- MnDOT has adopted a minimum performance of 100 MCD/m^2/lux for both white and yellow. As markings approach this threshold they will be replaced.
- Minimum initials have been set to get the desired longevity of the pavement markings. These are tested via mobile retroreflectometer.

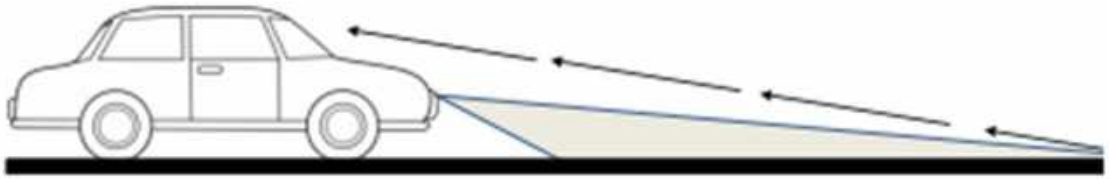


Table 2582.3-3
Minimum Initial Pavement Marking Retroreflectivity

	White	Yellow
PREF TAPE	600 mcd/ m^2/lux	500 mcd/m^2/lux
PREF THERMO	300 mcd/ m^2/lux	200 mcd/ m^2/lux
PREF THERMO, ESR (Enhanced Skid Resistance)	250 mcd/ m^2/lux	150 mcd/ m^2/lux
MULTI COMP	300 mcd/ m^2/lux	200 mcd/ m^2/lux
PAINT	275 mcd/ m^2/lux	180 mcd/ m^2/lux

MnDOT Provisions for Pavement Marking Operations

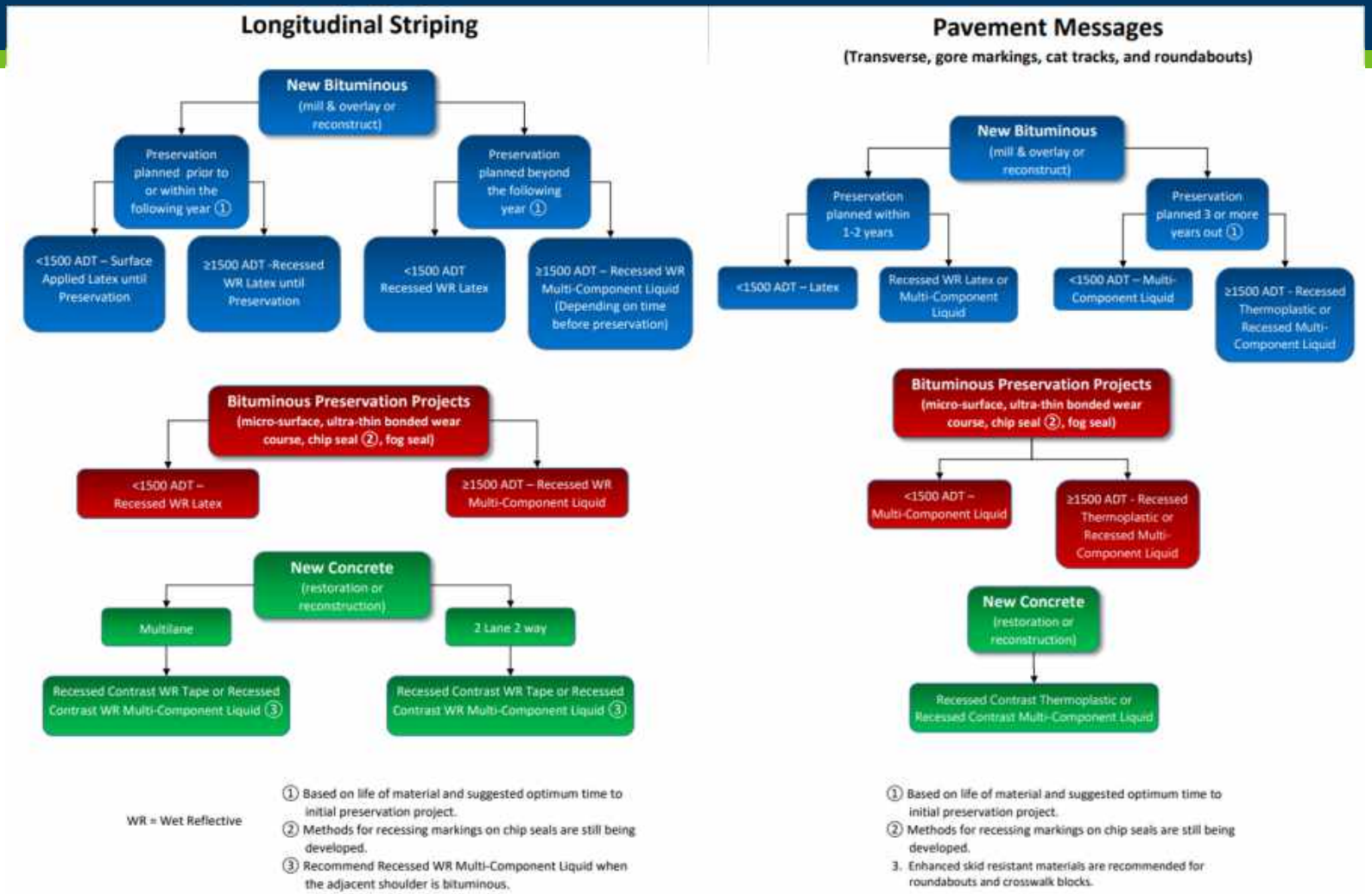
Expected Life of Surface Applied Markings

Material	ADT	
	<1,500	>1,500
Latex Paint	>1 yr.	1 yr.
Multi-Component Liquid	>5 yr.	3-5 yr.
Preformed Polymer Tape or Thermoplastic	>5 yr	>5 yr

Expected Life of Recessed Markings

Material	ADT	
	<1,500	>1,500
Latex Paint	>3 yr.	3 yr.
Multi-Component Liquid	>6 yr.	5-7 yr.
Preformed Polymer Tape or Thermoplastic	>7 yr	>7 yr

MnDOT Provisions for Pavement Marking Operations



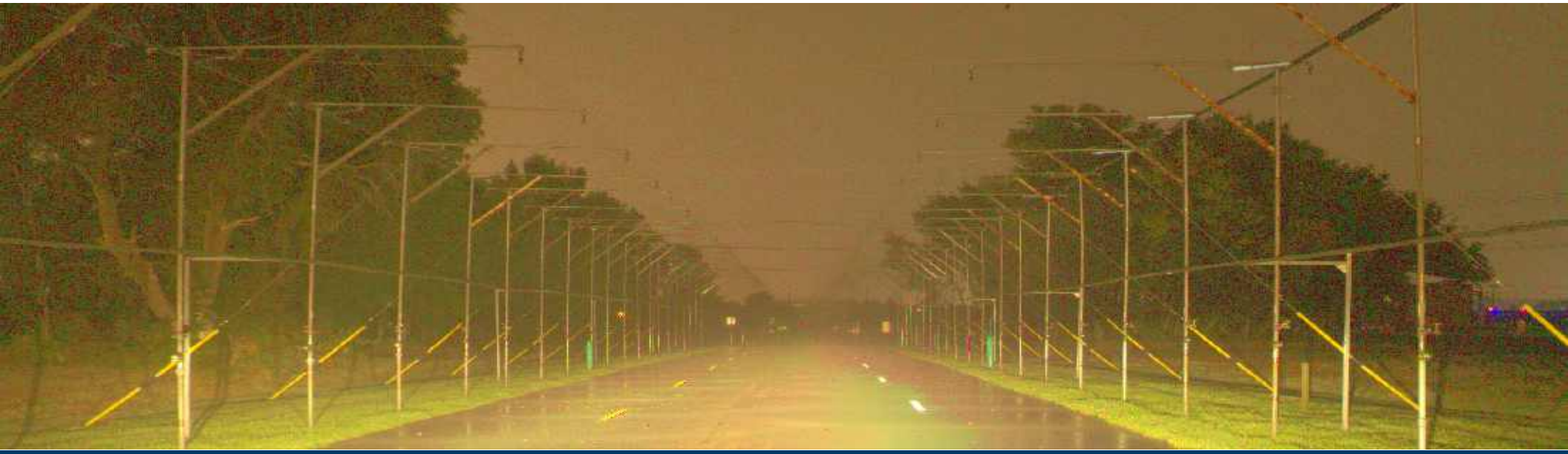
Recessed Marking

- A vast majority of new surface and preventative maintenance projects call for recessing on MnDOT roadways.
- Significantly increases longevity due to wear
- Reduces installer exposure to traffic
- Lifecycle cost equal to or less than yearly latex install

Enhanced Skid Resistance

- Low skid resistance of pavement messages and colored pavements can be an issue for the safety of vulnerable road users (motorcyclists, bicyclists, and pedestrians) when traversing intersections on state roadways.

- The enhanced skid resistance option (added aggregate) is recommended for any situation where deceleration, turning movements, or pedestrian and bicyclist traffic is occurring:
  - Crosswalk blocks
  - Pavement messages in roundabouts
  - Bike lanes that utilize colored pavement
  - Railroad crossing pavement messages
  - Stop lines
  - Stop ahead pavement messages



Wet Reflective Markings

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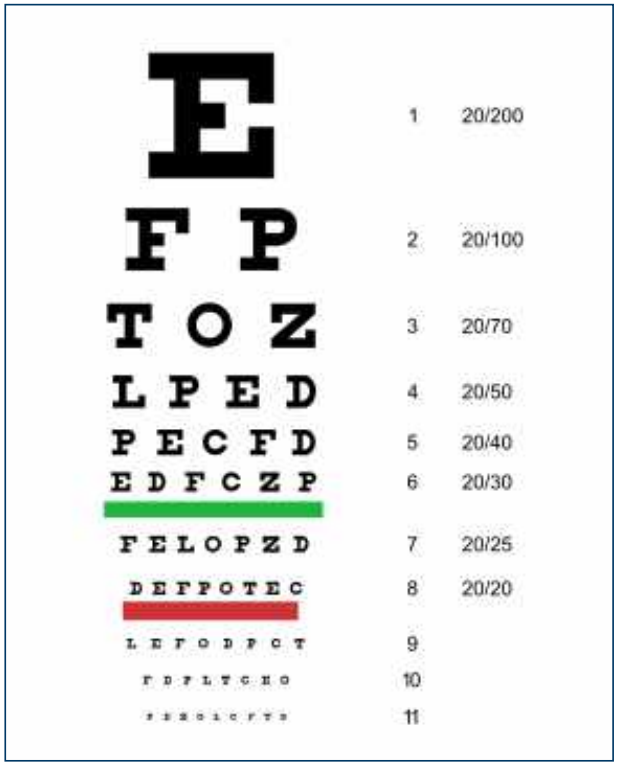
Wet Retroreflectivity Study

"Pavement Markings - Wet Retroreflectivity Standards" research study

- Wet Condition Testing
  - Participants counted skip markings visible in the 3M rain tunnel from a stationary position (2 sets of markings at a time)
  - Skip count was converted to observation distance
  - Subjective ratings of the marking adequacy were also collected (1 to 5 scale)
- Dry Condition Testing
  - Data was collected by slowly driving toward a separate test area that had an isolated 10 foot long marking in the center of the lane
  - Participants indicated to the researcher when the marking became visible
  - Participants rated marking adequacy at the 30-meter distance (1 to 5 scale)
- After the group of participants viewed the markings, the marking samples would be changed and the observation process repeated

Participant Information

- 43 participants from Minneapolis/St. Paul area
- Average age: 58.5
  - 51 percent 65 or older
- 24 male, 19 female
- Average Snellen visual acuity approximately 20/25
  - 15 participants 20/20 or better
  - 18 participants 20/25 or 20/30
  - 10 participants 20/40 or 20/50



Data Overview

- 1209 Human Factors Observations
- 403 dry, 162 rain rate 1 (higher), 644 rain rate 2 (lower)
- Two markings simultaneously observed during each trip through the rain tunnel. One marking observed individually under dry conditions.
- 20 marking samples evaluated (11 white, 9 yellow)
- Dry retroreflectivity range: 35 – 1250 mcd/m2/lux
- Continuous wet retroreflectivity range: 21 – 480 mcd/m2/lux

Rain Tunnel CCD Image

Rain Tunnel CCD Image

Wet Retroreflectivity

“Pavement Markings - Wet Retroreflectivity Standards” research study

- 50 mcd/m2/lux wet continuous retroreflectivity was found to be the minimum to make emergency maneuver at 55 mph
- Through analyzing degradation of markings in MN, 200 mcd/m2/lux was suggested for initial install
  - Through tracking installed projects, MnDOT will likely adjust this requirement for yellow in the near future.
- A Special Provision was put together to test and require the minimum initial
  - WR testing can be done through mobile retroreflectometer contractors using ASTM E 2832 Continuous Wetting method or approved equivalent
  - Has been used widespread on MnDOT resurfacing projects since 2022

Wet Retroreflectivity Research

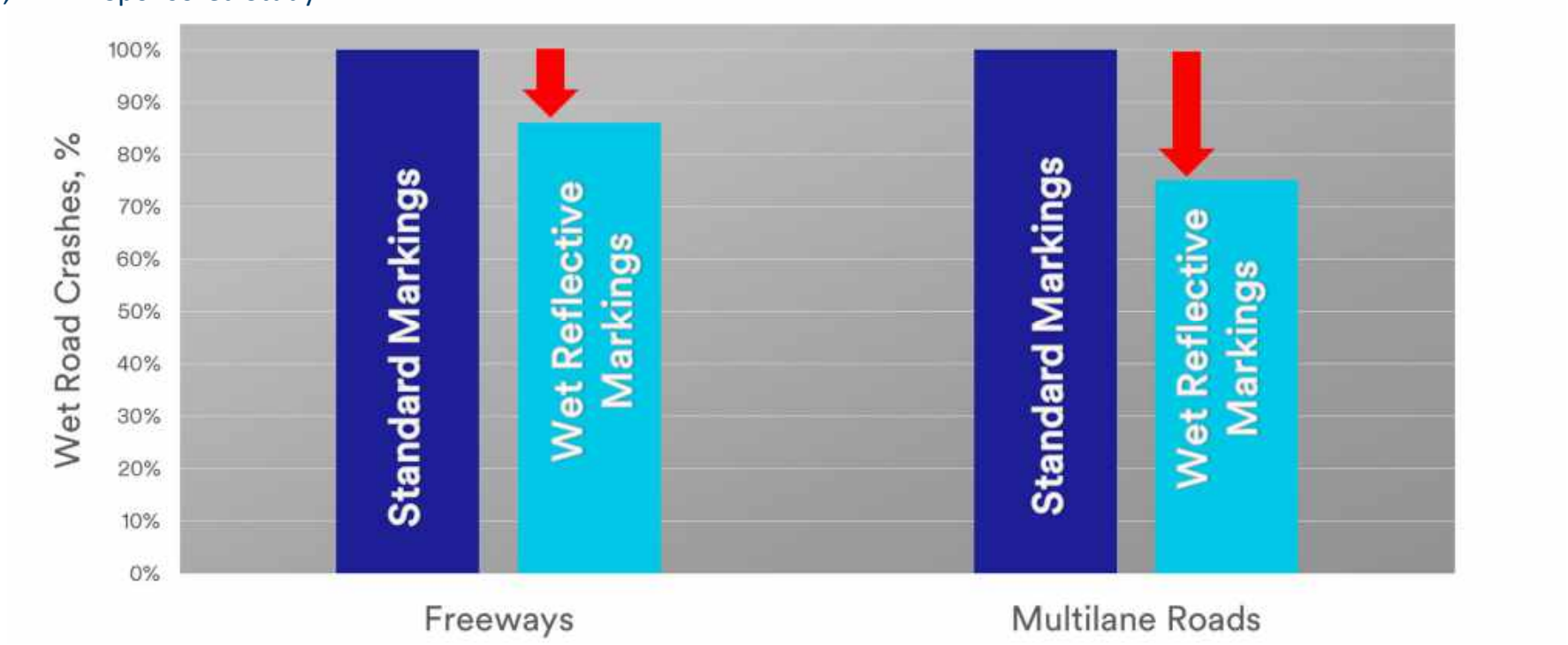
- **Study: Safety Evaluation of Wet Reflective Pavement Markers**
  - Wet-reflective markings on freeway sections in Minnesota, North Carolina, and Wisconsin; treated two-lane rural road locations in Minnesota; and treated multilane road sections in Wisconsin were evaluated.
    - Crash Modification Factors (CMFs) found:
      - On freeways for all injury crash types **0.881**
      - On freeways for wet-night crashes **0.861**
- **Study: Safety Effects of Wet-Weather Pavement Markings**
  - Safety assessment of wet-weather pavement markings in the Atlanta District of the Texas Department of Transportation
    - CMFs found:
      - Wet-night crashes **0.72**,
      - Wet-night injury crashes **0.466**

Wet Retroreflectivity Benefits

Safety Evaluation of Wet Reflective Pavement Markings

Craig Lyon, Bhagwant Persaud, and Kimberly Eccles. Vanasse Hangen Brustlin, Inc. (VHB) and Persaud Lyon, Inc. 2015

U.S. DoT, FHWA Sponsored Study



Wet Retroreflectivity Benefits

Wider Markings

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Safety Case for 6” Edgelines

Safety effects of wider edge lines on rural, two-lane highways (Park et al, Texas A&M, 2012)

- Kansas - 1178 miles 4" to 6" edgelines
- Michigan 4" to 6" edgelines - close to all State roadways switched to 6” in 2004
- Illinois - 1446 Miles 4" to 5" edgelines

Safety Case for 6” Edgelines

Table 8
Percent crash reduction estimates for wider edge lines on rural, two-lane highways based on the crash data from three states.

Crash type	Percent crash reduction			
	KS	MI (analysis 1)	MI (analysis 2)	IL (without animal collisions)
Total	**17.5**	**27.4**	**19.4**	**30.1**
Fatal plus injury	**36.5**	15.4	16.1	**37.7**
PDO	**12.3**	**30.5**	**19.6**	**23.9**
Day	**28.6**	**20.3**	12.0	**29.1**
Night	3.7	**30.7**	**18.8**	**29.9**
Daytime fatal plus injury	**41.5**	8.2	23.0	**36.0**
Nighttime fatal plus injury	12.7	22.6	−5.8	**34.2**
Wet	**22.9**	**67.2**	**62.6**	**34.7**
Wet night	24.3	**76.9**	**79.2**	35.7
Single vehicle	**27.0**	**30.0**	**18.7**	**37.0**
Single vehicle wet		**73.8**	**65.9**	**32.8**
Single vehicle night	**18.4**	**29.4**	**18.0**	**29.5**
Single vehicle fatal plus injury	**36.8**	10.0	−1.9	**42.2**
Single vehicle night fatal plus injury	18.7	9.7		**36.3**
Older driver				**24.1**
Fixed object	**19.0**			**29.5**

Note: Estimates in bold are significant at 95% confidence level.

Safety Case for 6” Edgelines

“*Benefit/Cost Evaluation of MoDOT’s Total Striping and Delineation Program: Phase II”*

- 2,300 Miles - 6" on all markings
  - Without resurfacing on urban multilane divided highways (B/C = 29:1)
  - Without resurfacing on rural freeways (B/C = 24:1)

- Crash reduction of 22% for all crash types and severities

- Crash reduction of 21% for K/A severities

Safety Case for 6” Edgelines

“Safety Impacts of Using Wider Pavement Markings on Two-Lane Rural Highways in Idaho”

- 175 miles were painted with 6" edgelines
- 2 lane rural highways: B/C 25:1
- K/A nighttime crash rate reduction = 39% (95 percent confidence interval)

Table 1. Comparison Group Before-and-after T-Test Results for Average Crash Rate

Crash type	Before (2010-2014)	After (2016)	Percent Change	P-Value
Total Crashes	63.84	56.04	-12.22	0.148
Night Crashes	26.46	24.13	-8.81	0.261
Fatal and severe injury crashes	17.67	14.37	-18.68	0.095
Fatal and severe injury night crashes	8.85	5.32	-39.89	0.006

Table 4. Evaluated CMF of wider pavement markings

Crash type	CMF	Variance (CMF)	SE of the CMF
Total Crashes	0.96	0.07	0.27
Night Crashes	0.56**	0.05	0.23
Fatal and severe injury crashes	0.46***	0.06	0.24
Fatal and severe injury night crashes	0.75	0.16	0.40

* Significant at a 85% confidence level,** Significant at a 90% confidence level,*** Significant at a 95% confidence level.

Safety Case for 6” Edgelines

“Evaluation of Potential Benefits of Wider and Brighter Edge Line Pavement Markings” (Texas A&M)

- **NLKGs were given longer times in curves with wider markings, which suggests a reduced driver workload for lane keeping and therefore affords more time to focus on other critical driving tasks.**

Safety Research Summary

- Severe crashes can be reduced 20-40% by increasing the width of edgelines.
- Research has shown that 6” edgelines provide a Benefit/Cost of ~25:1

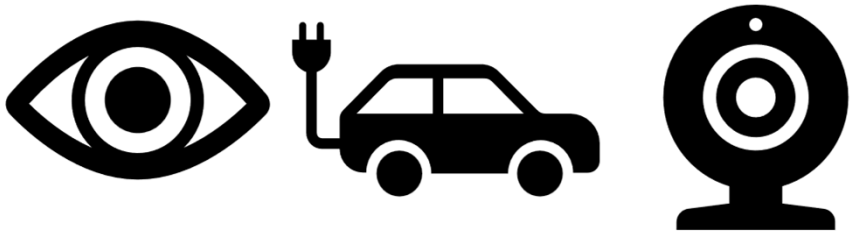
Effectiveness

10% to 35% consistent crash decrease reported

CAV Support

- From 12/10/20 AASHTO Committee on Traffic Engineering Meeting (Andy Whydell, ZF): **“Automated system cameras are akin to a highly attentive, near-sighted driver.”**

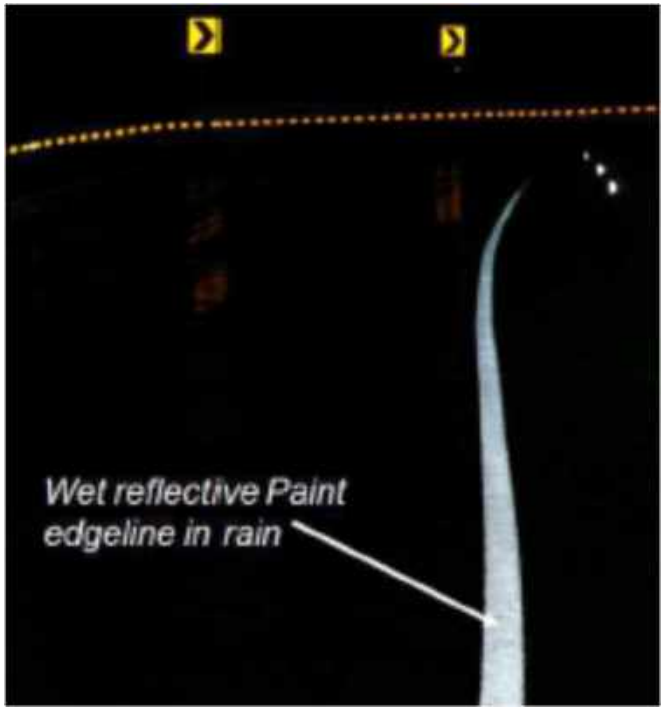
- Cameras largely mimic human vision. Improvements for human vision therefore are improvements for machine vision.

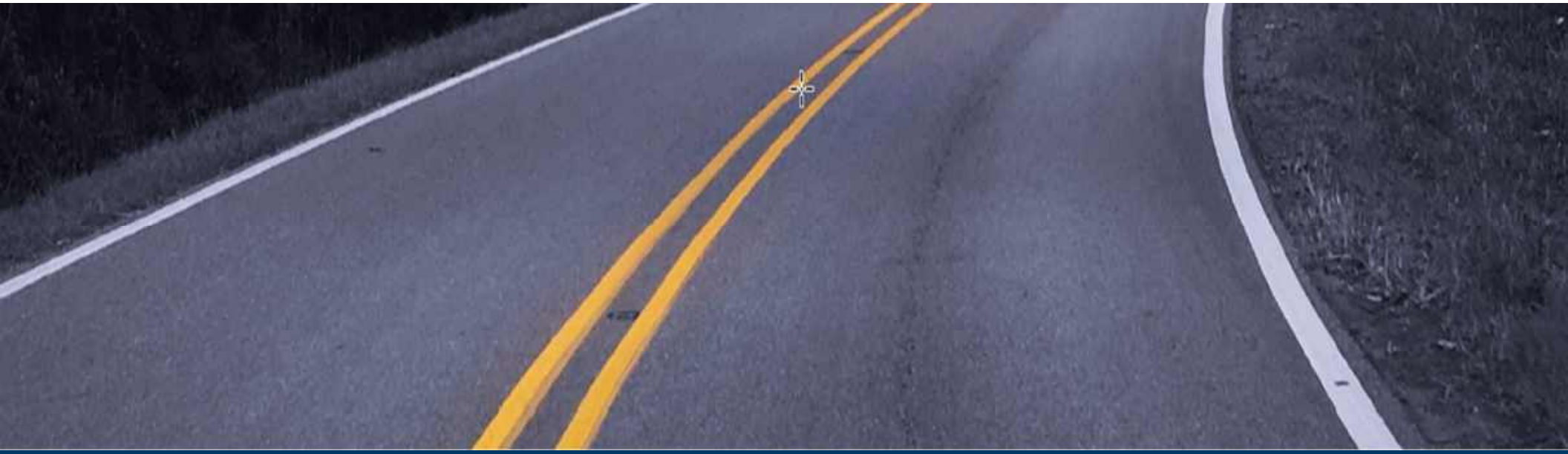


Cost Difference

Varies significantly based on material.

- A 6-inch line will cost approximately a 1/3 more than the typical 4-inch edgeline.





MN Studies for Marking Width and Line Cycles

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Pavement Marking Patterns and Widths – Human Factors Study

- MN 336 and I-94 Test Area
- Evaluated changes in the broken lane line markings
  - 4 vs 6 inch width (MN 336 all 6-inch, I-94 all 4-inch)
  - 10-30, 15-25, 10-40, 12.5-37.5, 15-35, 20-30 stripe to gap ratios
  - Bordered and shadow contrast patterns

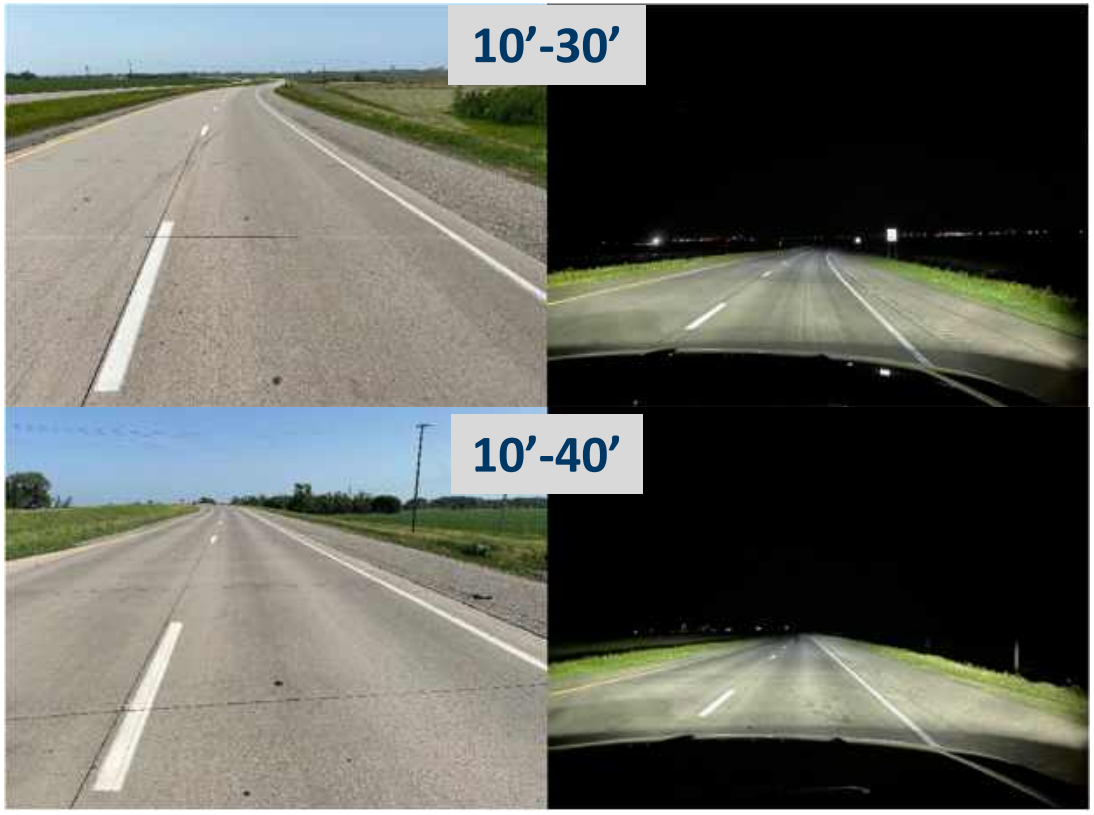
Study Approach

- Pavement Marking Patterns and Widths – Human Factors Study
  - Participants drive TTI test vehicle through test areas and rate marking visibility and preference toward the marking designs, day and night evaluations
  - Participants take closeout survey comparing marking patterns

Participant Demographics

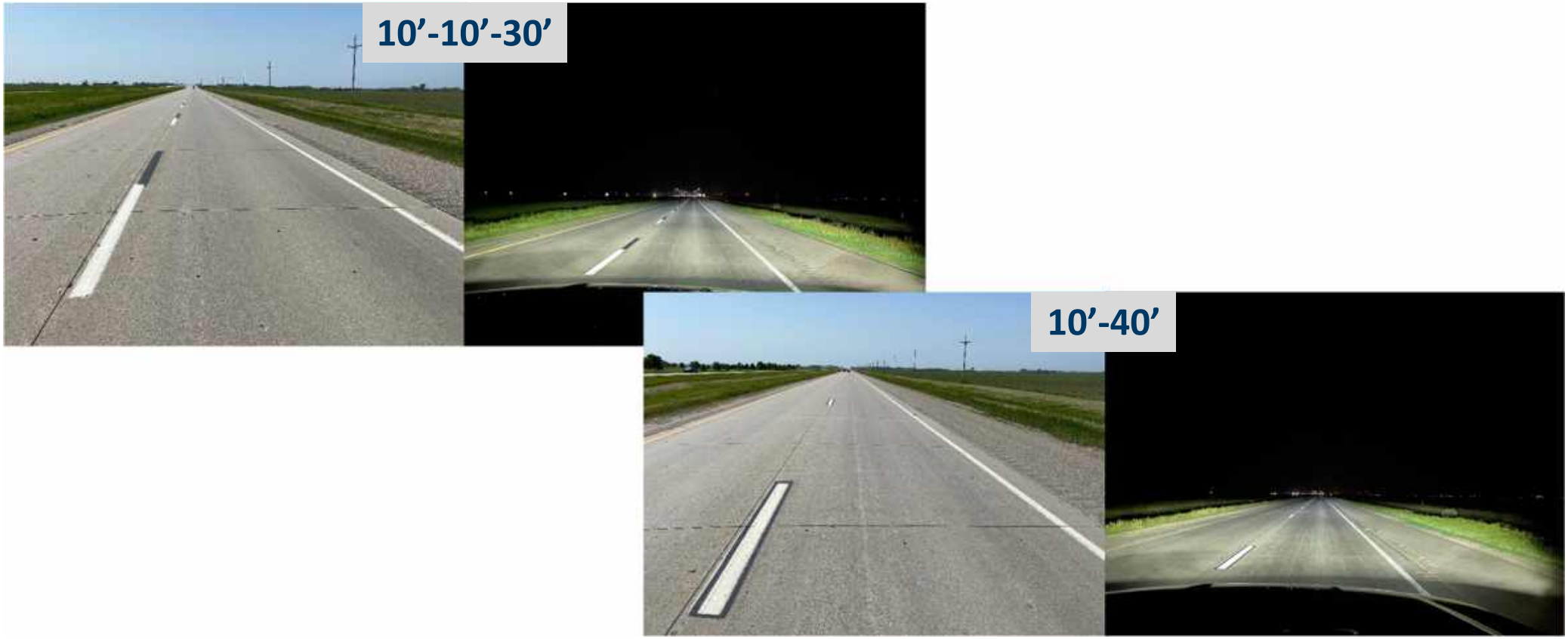
Gender	Age Group	Day Participants	Night Participants	Total by Age Group	Total by Gender
Male	18-29	3	4	7	27
	30-44	5	5	10	
	45-60	2	2	4	
	60+	3	3	6	
Female	18-29	4	3	7	29
	30-44	4	6	10	
	45-60	6	3	9	
	60+	2	1	3	
Total by Day/Night	-	29	27	-	-

MN 336 Marking Examples



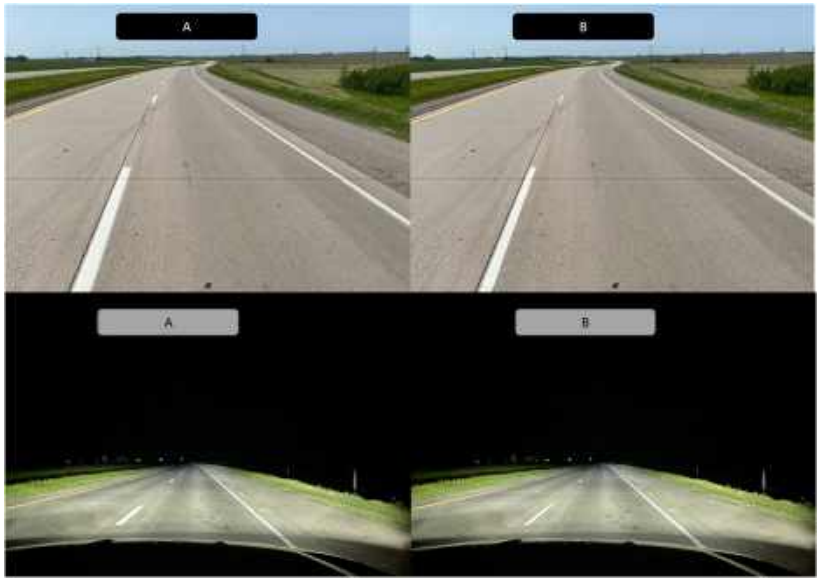
MN 336 Marking Examples

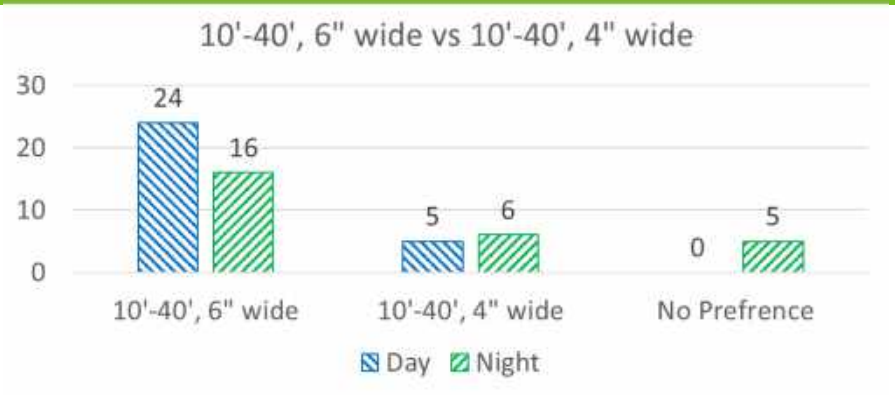
MN 336 Marking Examples

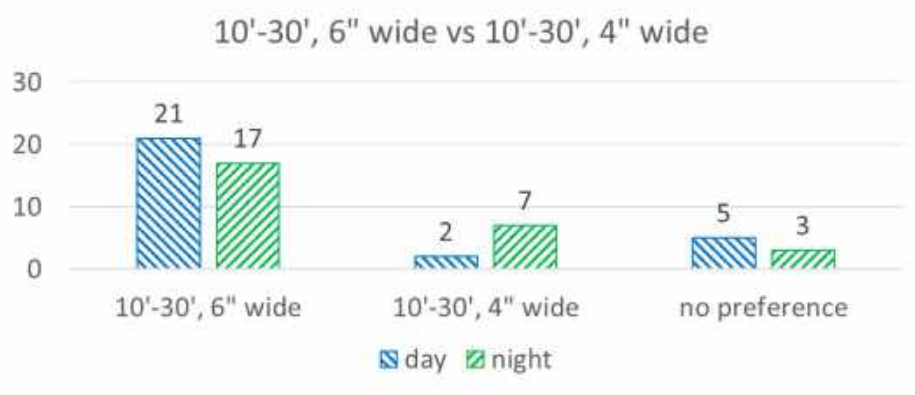


MN Human Factors Study

- 6-inch wide markings preferred over 4-inch wide markings







Human Factors Findings

- In-vehicle visibility ratings resulted in all test areas being rated higher during the day than at night.
- The 12.5-37.5, 20-30, and 15-25 configurations were rated the highest during the day and at night for both visibility and preference.
- The 10-40 section was rated as one of the least visible and lowest preferred sections.
- The restriped section had daytime and nighttime visibility and preference increase of about 1 after being restriped. This increase was larger than the differences between most of the marking configurations.

Human Factors Findings

- Closeout surveys indicate 6-inch markings are preferred over 4-inch markings, this is true for both 10-40 and 10-30 configurations.
- Closeout surveys indicated that participants favored the 40’ cycle at night, but not as much during the day.
- At 50’ cycle length longer skip lines were preferred. The 12.5’ skip line was rated equally to the 15’ skip line but not as high as the 20’ skip line.
- Contrast marking results were mixed. Some participants liked them, others did not. Some mentioned potential benefit in snowy weather. The results did not strongly indicate the bordered or shadow as the preferred configuration.

Recommendations from Human Factors Study

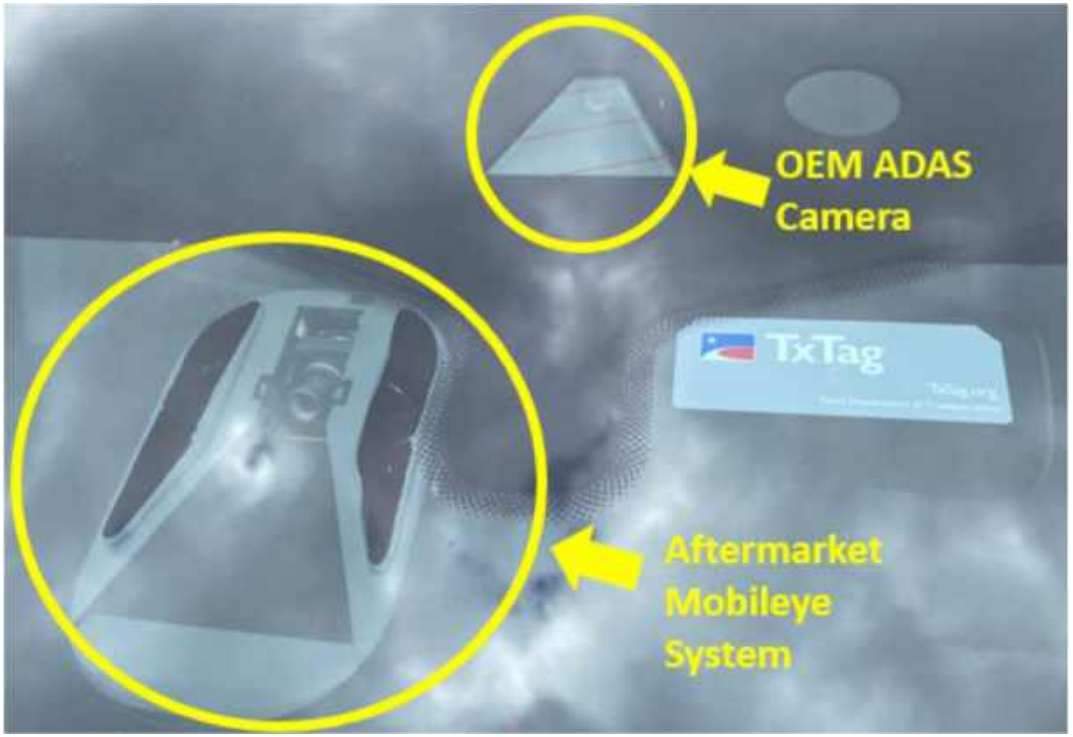
- Change from 10’-40’ broken lane line pattern to 12.5’-37.5’
  - Maintains 50’ cycle
  - Preferred by drivers and improves machine vision detection
  - Meets MUTCD 1:3 ratio
- Use 6-inch wide markings
  - Preferred by drivers
  - Increase in safety and suggested by MUTCD as an upgrade for AV operations
  - If cost is a concern, start with:

1. White (edge and broken) and yellow (edge) markings that are warranted
2. Markings on higher speed roadways
3. Edge lines on two-lane two-way roadways

Machine Vision Study

- Assessing Pavement Markings for Automated Vehicle Readiness
  - Utilize different systems to evaluate tracking of different markings configurations
    - TTI/TAMU camera system – provides quantitative data output, Texas testing
    - Mobileye 8 EyeQ4 ADAS – provides quantitative data output, All test areas
    - Ford Co-Pilot 350 Assist+ – Minneapolis test areas
    - Tesla Autopilot – Minneapolis test areas
    - Toyota Safety Sense 2.0 – Minneapolis test areas
  - Drive test systems through test areas (MN 336, Minneapolis and Texas) and collect data to determine how the cameras observed the marking (quantitative data) or how vehicles operated through the test areas
  - Day and night evaluations
  - Vehicles operated with little driver input to allow the ADAS to guide the vehicles through the test areas

Mobileye 8 EyeQ4 System and Ford Co-Pilot



Tesla Autopilot

Toyota Safety Sense 2.0

TTI/TAMU Camera System

Minneapolis ADAS Vehicle Operation Results

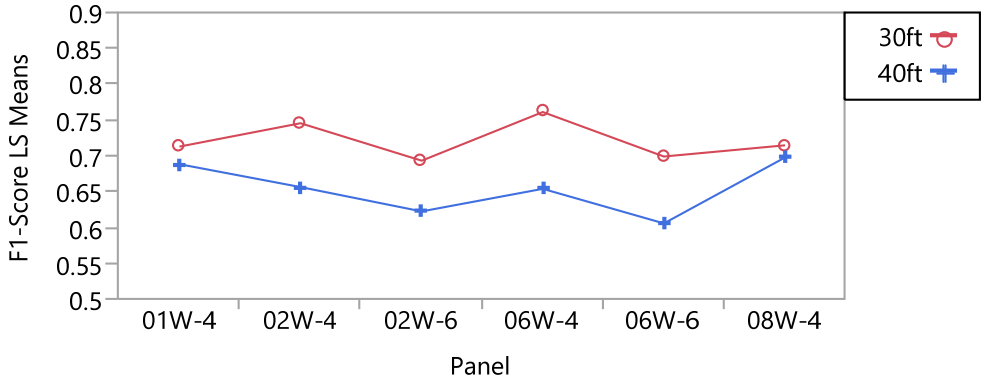
- Observations did not find any evidence that lane line configuration (skip to gap ratio), line width, or contrast pattern affected the results.
- In areas with lower quality markings there was some loss of tracking.
- Areas with turn bays or ramps had the biggest issues.
  - Areas without dotted line extensions often caused undesirable lane shifts or movements out of the intended lane.
  - Areas with roadway curvature had more issues than tangent areas.
  - When dotted line extensions were present the amount of undesirable movement was reduced.
- Proper delineation at gore areas should keep vehicles out of them. Chevrons may be advisable at long gores where incursions are more frequent.

TX Closed Course Evaluation Results

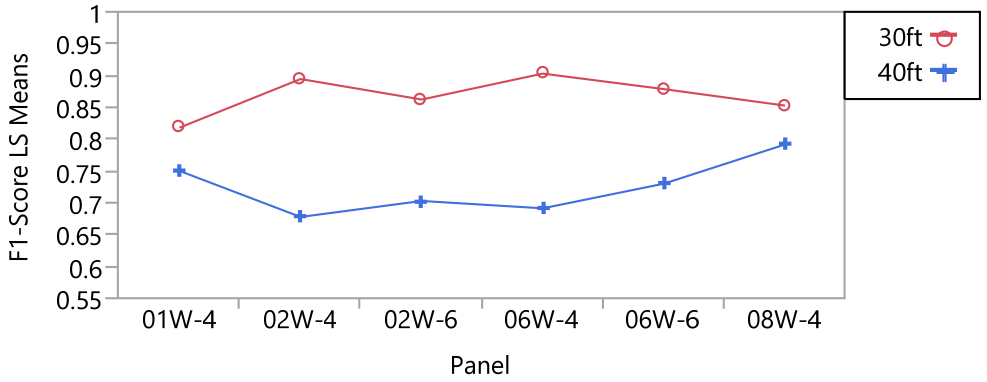
Day and night comparison of 10-30 and 10-40 skip line spacing

TX Closed Course Evaluation Results

Day and night comparison of 10-30 and 10-40 skip line spacing by marking width/quality



DAY



NIGHT

TX Open Road Contrast Evaluation Results

Marking	Driving Direction	Precision (P)	Recall (R)	F1 - Measure
BWB	East	0.56824	0.63833	0.601249226
BWB	West	0.59065	0.648249	0.618110551
WB	East	0.576458	0.785637	0.6649855310
WB	West	0.849475	0.917485	0.882171153
White	West	0.506709	0.521368	0.513933991

BWB = bordered contrast
WB = white followed by black contrast
White = no contrast

Higher values = better line tracking

East data collected toward rising sun
West White only collected with sun glare

Machine Vision Findings

- Better quality markings can be detected further down the road, but most are detected adequately. (results from Mobileye and camera system testing)
  - Nighttime detection typically better than daytime.
  - More stripe with less gap (than current MnDOT practice) for lane lines aided detection.
  - White followed by black contrast had slightly better performance, than bordered, both better than none.
- Vehicle operation observations did not find any evidence that lane line configuration (skip to gap ratio), line width, or contrast pattern affected the results.
- Vehicle operation observations found that areas with lower quality markings that had some loss of tracking.
- Vehicle operation observations found that areas with turn bays or ramps had the biggest issues.
  - Areas without dotted line extensions often caused undesirable lane shifts or movements out of the intended lane.
  - Areas with roadway curvature had more issues than tangent areas.
  - When dotted line extensions were present the amount of undesirable movement was reduced.
- Proper delineation at gore areas should keep vehicles out of them. Chevrons may be advisable at long gores where incursions are more frequent.

Recommendations from Machine Vision Study

- Implement dotted line extensions:
  - At all off ramps (now required by 11th edition MUTCD)
  - At on ramp areas but to leave an opening that is as small as feasible, so that entering traffic does not have to cross the dotted line
  - At turn bay openings on roadways where it is expected that drivers will utilize lane keep assist systems
- Maintain markings in good condition at gore areas in combination with dotted line extensions to keep traffic out of the gore. At areas where incursions are common and the gore area is long, application of chevron markings may be needed.
- Implementing broken lane line contrast markings when the contrast between the combination of pavement surface and white marking material is low.

Resources

MnDOT Provisions for Pavement Marking Operations

Pavement Marking Decision Tree – Project Level

Resources

Pavement Marking Patterns and Widths – Human Factor Study Website

Pavement Markings - Wet Retroreflectivity Standards Study Website

Resources

Assessing Pavement Markings for Automated Vehicle Readiness Study Website

Thank you again!

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