An Evaluation of Conspicuity Tape on Trailers & Trucker Behaviors

An expansive study based on data from 194 trailers from 40 states and counting

By

Jeffrey W. Muttart, Swaroop Dinakar, Arnold G. Wheat, David W. Lohf, Jeffrey Suway, P.E., Timothy Maloney, Michael Kuzel
Background

• ~50% of all crashes take place after dark
• ~20% of all fatalities in large trucks are from Side-Impact and Rear-Enders
• Medium and heavy trucks were eight times more likely to be struck in the rear at night than in daylight

Regulations
  – 1993: FMVSS No. 108 (S5.7.1): All Trucks manufactured from 1993 should be fitted with retroreflective tape
  – 2009: All trucks wider than 80” required to have all conspicuity markings
  – Minimum Standard: FMCSR 393.11
The Issues

• Currently only a “when new” standard for retroreflective tape
  – Retroreflective tape degrades over time
• No relevant regulations for law enforcement vehicle inspectors to deem vehicles unsafe
  – Except for if tape is present/not present
• No measurement protocol for law enforcement vehicle inspectors
Trailer markings
About our Study

• Develop a minimum standard for safe on-road operation
• Development of a fast and standard protocol for inspection of retroreflective tape
• Determine the level of retroreflectivity is observed on trucks today
• Effect of dirt on retroreflectivity of tape
The Data

- No. of Trailers measured = 194
- States Represented = 40
- Test Locations: Colorado, Connecticut, California (Southern), Georgia, Pennsylvania and Massachusetts
- Trailers: Box Type (65%); Flatbed (12%); Tanker (8%); Lowboy, Intermodal, Grain, Car Carrier, Livestock (15%)
- Year of Manufacture: Median 2007; Range 1969-2013
Results

• As is vs. Clean
  – White: As is = 75% Clean
  – Red: As is = 76% Clean

• Meeting “when new” minimum standard
  – White: 33% failed to meet minimum standard
  – Red: 20.2% failed to meet minimum standard
Influence of Age

% Meeting Minimum Standards

- Pre-1993
- 1994 - 1999
- 2000-2005
- 2006-2010
- 2011 - 2016

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Future Direction

• Expand on the current study
  – Data collection from more states across the country
• Determine a minimum recognition threshold for retro reflective tape
  – Recognizable from minimum safe maneuver distance
• Develop published standards and protocol
DRIVERS’ ABILITIES TO RECOGNIZE CLOSING
- DRIVER RESPONSE BEHAVIORS
- COULD PATTERN & CONSPICUITY HELP?
Why do this research?: Stopped Vehicles on Highways Get Hit
Drivers are Ill-Suited to estimate...

- Longitudinal Distance,
- Velocity, Or
- Acceleration


Decelerating LV: Not a clear story
LV Stopped: As Speed increased, so did crashes

SHRP-2 Crashes: Decelerating LV versus Stopped LV

Less exposure when > 60 mph
70% of LVs are stopped or traveling less than 14 mph

Detection of Relative Velocity

• Trucks 8 times more likely to be rear-ended at night (Sullivan et al, UMTRI, 2003)
  – “Discernible” width
  – Reflections of street lights and vehicle lights off hood & roof not available.

• Higher objects are perceived as further away (Myers 7th Ed. Psychology)

• Farm tractors rear end crash risk (Gerberich, 1998)
  – Day – 24%
  – Night – 65%
When within 500’ (150 m) drivers recognize closing
ROUTINE PASSING MIRROR GLANCE TIMES
Passenger Cars & SUVs
Average 2.5 head turns - 3 to 7 sec. depending on traffic


Lane Change - Right  - Average driver 2.5 head turns

2 glances (including shoulder check) in 7 seconds (w/ 1 car) - No LV

Consistent with:
CDL driver in a large box truck

• Process took 9 seconds – 3 mirror glances – 1 over the shoulder glance

• truck 5 -Lane change.ogv

• 5 seconds - 2 mirror glances

• Truck 8 - Lane change.ogv

Truck drivers can look in only one place at a time
Mirror glance?
Next – Drivers closer before starting a lane change

• Close to within 124 feet (Mean or 96 ft. median)
  – Lee, Olsen, Weirwille, 2002, 2005

• Within 150 feet

• Drivers do not slow when coming upon slower moving lead vehicle
  – Fitch et al (2009) – average acceleration = 0.0 g
Drivers Do Not Slow in Response to Routine Closing Instead they close to within 100-150 feet (31-46m)

Straight unchanging multi-lane road
0.0 Seconds

Noticeably closing on the lead vehicle
1.0 Seconds
2.0 Seconds
3.0 Seconds
4.0 Seconds
5.0 Seconds
6.0 Seconds
7.0 Seconds
9.0 Seconds
11.0 Seconds
After 12 seconds following this unsuspecting driver starts to move left
Also note the distance is consistent with Lee, et al (X = 124’)

12.0 Seconds
13.0 Seconds

~ 124 ft.
14.0 Seconds
Factors Associated with Recognition of Closing Speed

- The factors that influence a driver’s response include:
  - Angular velocity (Michaels, 1963)
  - \( W \) – width
  - \( \Delta V \) (relative velocity)
  - \( S \) – displacement

\[
\frac{d}{dt} \theta_n t = -w \frac{\Delta V_n t}{(S_n(t))^2}
\]

\[
S_n = (8' \times \frac{(100 \text{ ft/sec} - 0)}{0.006 \text{ rad/sec}})^2 = 365'
\]

Or 3.6 seconds before impact

Fig. 12. An evidence accumulation account of brake timing. The rate of change of a quantity \( A \) depends on various sources of evidence for or against the need for braking, and braking is initiated once \( A \) exceeds a threshold. (Adapted from Markkula, 2014.)
When within 500’ (150 m) drivers recognize closing
Solutions?

• Collision Avoidance/Mitigation Systems – in following vehicle

• Brighter, more defined, “lower” trailers – in stopped truck
Very Little Context:
Lacks Clarity
Depth
& Size information
Context:
More Clarity
But Lacks Depth & Size Detail
Better Perspective Offered
Lighting, Clarity, & Brightness

We are now capable of accurately judging size and relative Position which tells us the distance
Total extra cost = $55.60 if the best quality (10-year) Orafol
= $26.40 if purchased from ULINE
Questions

• **Automacy:** Are you concerned about the following?
  – Driver adaptation
  – Driver trust – what if system says 0.7 g and driver only accepts < 0.3 g
  – Driver fatigue / vigilance
  – Do safety features get to truck drivers last?

• **Conspicuity**
  – When is retroreflective sheeting of no value
  – Lighting and lighting laws – no good deed goes unpunished
  – What benefits are there for my trucking company to spend $50/truck?

• **Response**
  – Steering willingness
  – Braking willingness (jackknife?)
  – Are CDL drivers’ glances the same as passenger car drivers? Should it be better?
Thank you

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• Jeff Muttart, Ph.D.
• Swaroop Dinakar, M.S.
<table>
<thead>
<tr>
<th>Issue</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Following within 2 seconds</td>
<td>Chisholm S. L., Caird, J. K., Lockhart, J. A., Teteris, L. E., &amp; Smiley, A. (2006); Sivak &amp; Olson, 1981; Chang, Lin, Fung, Hwang, &amp; Doong, 2008; Fitch el al., 2009 (100-car study)</td>
<td></td>
</tr>
<tr>
<td>Approaching a stopped vehicle at an intersection</td>
<td>Muttart, 2003</td>
<td></td>
</tr>
<tr>
<td>Approaching slower moving traffic</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Recognize closing

- Yes: Routine lane change
  - Here we assume the response is to steer. Braking is also an option.
  - Yes: Emergency swerve
  - No: Fail to recognize
    - No: Crash
- No: Recognize dangerous closing speed
  - Yes: Emergency swerve
  - No: Fail to recognize
    - No: Crash

Stage 2

Stage 3
Assumption: No typical cues associated with recognition of speed

Sudden slowing by car ahead – Cues include:
- Pitch of the LV --
- Immediate change in following distance
- Taillights flashing on --

Car sideways
- Cars do not travel 70 mph sideways!
  (Assumes car is recognizable)

Can see car ahead is not moving against immediate background
- Curves
- Pedestrian standing next to car
- Red traffic signal (Muttart, Messerschmidt, Gillen, 2005)

Yikes....
Closing Speed is not at issue at intersections

Exception To Additivity

Muttart, Messerschmidt & Gillen, 2005
Context: Closing speed analysis is not applicable

(Muttart, Messerschmidt, Gillen, 2005)
Adjacent vehicles
(same PRT – fewer fail to respond)
Crash Rate on a Bridge Incline
Crash History for this Site

- 42 reported crashes within 0.1 mile between 1/1/1999 and 12/31/2005.

- **92%** of 26 WB (in direction we are looking) crashes were rear end collisions.

- Only 18.8% of 16 EB (coming toward us in photo) crashes were rear end collisions.

- Most occurred during nice weather and in daylight.

- 70% of rear end crashes (18/26) involved a stopped LV.

- 49 – 67% of crashes are rear enders on elevated expressways and tunnels (Deng, et al., 2011)

OTHERWISE: Closing speed is not applicable at intersections or when following close behind

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chisholm S. L., Caird, J. K., Lockhart, J. A., Teteris, L. E., &amp; Smiley, A. (2006); Sivak &amp; Olson, 1981; Chang, Lin, Fung, Hwang, &amp; Doong, 2008; Fitch et al., 2009 (100-car study)</td>
<td>LV Decelerates suddenly 1.01 – 1.48 sec</td>
</tr>
<tr>
<td>Muttart, 2003</td>
<td>Sudden Stop Intersections 0.98 sec (SD = 0.3)</td>
</tr>
</tbody>
</table>

Olson & Sivak did not control for following distance
Almost ½ the drivers did not respond
Hence, they reported times up to 1.48 s
Everyone else is near 1 s.
Looming isn’t only cue

- Distance (closer is better)
- Closing speed (faster is better... to recognize)
- Width (larger is better)
  - Exception: Height – objects higher look farther away
- Exceptions:
  - Background information such as curves, intersections, standing pedestrians, and standing traffic.
Not Only Speed – Difference in Speed

- Decrease in speed variance leads to a lower crash rate.
- The largest crash rate is for vehicles traveling furthest from the average speed (higher or lower).

- Soloman (1964)

III. Closing versus Separating

All vehicles are doing one or the other... What causes a response?
Lane Change- Left  - Longer glance time when traffic is present

2 glances (including shoulder check) in 12 seconds (w/ 1 car) - Moves left ~ 240 feet – 75mph

Consistent with:
Lane Change- Left - Some drivers might make a longer single glance with no traffic

1 longer glance in 3.5 seconds (no traffic) -

Consistent with:
Progression of Events with Markkula’s 3 stages

Stage 1: CLOSING?
Stage 2: CLOSING RATE
Stage 3: LANE CHG PREP
Analysis of a Response to a Lead Vehicle

Cues to know LV is stopped or slow? [LV stopped on a curve or at signal]

Yes – Start PRT when LV becomes discernable immediate hazard
(You may use Chart for PRT)

No – Calculate the visual expansion rate of LV [when is LV an immediate hazard?]
(able to recognize that they are closing dangerously fast)

$\theta = \text{Threshold for detecting closing or Closing Rate (Larger number)}$

Michaels, 1963; Hoffman & Mortimer, 1996; Muttart, Messerschmidt, & Gillen, 2005; Markkula et al., 2016
WHERE TO START AN ANALYSIS OF A DRIVER’S PERCEPTION RESPONSE TIME: RESPONSE TO LEAD VEHICLES
1. Go back in time
2. Start stopwatch as red car crosses “A” – stop clock as yellow car starts to skid
3. Start stopwatch as red car crosses “B” – stop clock as yellow car starts to skid
4. Start stopwatch as red car crosses “C” – stop clock as yellow car starts to skid

Will all “Perception-response times” be the same?
Similarly, will all PRTs be the same?
If… $A = 0.003$ radians / sec;
$B = 0.006$ radians / sec;
$C = 0.01$ radians / sec;
$D = 0.02$ radians/sec
… can you apply the same PRT to all locations?
Measuring subtended angle “Looming”
If you believe Hoffman & Mortimer’s 0.003 radian/second threshold is best, the Perception-Response Time that best fits would be 3.5 – 4.5 seconds. (A)
If you believe Muttart, Messerschmidt & Gillen’s or Fisher, Knodler & Muttart’s 0.006 radian/second threshold is best, the Perception-Response Time that best fits would be 2.1 – 2.5 seconds. (B)
If you believe Maddox et al’s 0.01 radian/second threshold is best, the Perception-Response Time that best fits would be a much faster response (C)

Method: Using the EDR results from M & K (2012) and their crash data (that they shared), steering distances were calculated using IDRR (STEER). Next the maximum maneuver distance (steer or brake) was compared to the results calculated by IDRR (LV).

Assumptions:
• 0.006 radians/second detection threshold and PRT adjusted (by program) to that threshold,
• At nighttime, M&K used width, not recognizable width which is typically 1.5 feet less than the overall width
• Drivers were looking ahead (0 degree eccentricity)
• Road experiment
• Response to one object (the LV)

<table>
<thead>
<tr>
<th>FV Speed (fps)</th>
<th>LV Speed (fps)</th>
<th>Closing Speed (fps)</th>
<th>Discern Width (ft.)</th>
<th>FLASH / BRAKE LTS</th>
<th>DAY/ NITE</th>
<th>Lateral Motion (ft.)</th>
<th>Avg Gs</th>
<th>Steer Time (s.)</th>
<th>Max Steer/ Brake (ft.)</th>
<th>AVG (ft.)</th>
<th>85th %</th>
<th>DISCRIPT</th>
<th>PCT’ILE</th>
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<tr>
<td>80.7</td>
<td>0.0</td>
<td>80.7</td>
<td>5.83</td>
<td>YES</td>
<td>DAY</td>
<td>6</td>
<td>0.16</td>
<td>1.53</td>
<td>100</td>
<td>106</td>
<td>46</td>
<td>NORMAL</td>
<td>46%</td>
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<tr>
<td>66.0</td>
<td>4.4</td>
<td>61.6</td>
<td>8.5</td>
<td>NO</td>
<td>DAY</td>
<td>5</td>
<td>0.17</td>
<td>1.35</td>
<td>65</td>
<td>140</td>
<td>80</td>
<td>Below AVG.</td>
<td>11%</td>
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<tr>
<td>95.4</td>
<td>0.0</td>
<td>95.4</td>
<td>8.5</td>
<td>YES</td>
<td>DAY</td>
<td>0</td>
<td>0.13</td>
<td>2.15</td>
<td>49</td>
<td>223</td>
<td>168</td>
<td>Below AVG.</td>
<td>11%</td>
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<tr>
<td>80.7</td>
<td>36.7</td>
<td>44.0</td>
<td>6.0</td>
<td>NO</td>
<td>DAY</td>
<td>10</td>
<td>0.13</td>
<td>2.15</td>
<td>49</td>
<td>223</td>
<td>168</td>
<td>Below AVG.</td>
<td>0%</td>
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<tr>
<td>80.7</td>
<td>0.0</td>
<td>80.7</td>
<td>4.16</td>
<td>NO</td>
<td>DARK</td>
<td>0</td>
<td>0.13</td>
<td>2.15</td>
<td>49</td>
<td>223</td>
<td>168</td>
<td>Below AVG.</td>
<td>0%</td>
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<tr>
<td>80.7</td>
<td>3.7</td>
<td>77.0</td>
<td>6.5</td>
<td>NO</td>
<td>DARK</td>
<td>4.15</td>
<td>0.18</td>
<td>1.19</td>
<td>82</td>
<td>110</td>
<td>43</td>
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<td>34%</td>
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<tr>
<td>92.4</td>
<td>4.4</td>
<td>88.0</td>
<td>4.66</td>
<td>NO</td>
<td>DARK</td>
<td>6</td>
<td>0.16</td>
<td>1.53</td>
<td>111</td>
<td>79</td>
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<td>68%</td>
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<tr>
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<td>66.0</td>
<td>6.5</td>
<td>YES</td>
<td>DUSK</td>
<td>0</td>
<td>0.13</td>
<td>2.00</td>
<td>151</td>
<td>139</td>
<td>63</td>
<td>NORMAL</td>
<td>24%</td>
</tr>
<tr>
<td>107.1</td>
<td>14.7</td>
<td>92.4</td>
<td>8.0</td>
<td>YES</td>
<td>DAY</td>
<td>5</td>
<td>0.17</td>
<td>1.35</td>
<td>107</td>
<td>158</td>
<td>85</td>
<td>NORMAL</td>
<td>24%</td>
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<tr>
<td>95.4</td>
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<td>95.4</td>
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<td>YES</td>
<td>DARK</td>
<td>9</td>
<td>0.14</td>
<td>2.00</td>
<td>151</td>
<td>139</td>
<td>63</td>
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<td>56%</td>
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<tr>
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<td>66.0</td>
<td>8.5</td>
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<td>DAY</td>
<td>6</td>
<td>0.16</td>
<td>1.53</td>
<td>78</td>
<td>126</td>
<td>64</td>
<td>NORMAL</td>
<td>22%</td>
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<tr>
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<td>0.0</td>
<td>95.4</td>
<td>6.5</td>
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<td>DAY</td>
<td>9</td>
<td>0.14</td>
<td>2.00</td>
<td>151</td>
<td>139</td>
<td>63</td>
<td>NORMAL</td>
<td>66%</td>
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<tr>
<td>73.4</td>
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<td>73.4</td>
<td>6.5</td>
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<td>DARK</td>
<td>8</td>
<td>0.14</td>
<td>1.85</td>
<td>143</td>
<td>116</td>
<td>45</td>
<td>NORMAL</td>
<td>65%</td>
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<tr>
<td>80.7</td>
<td>3.7</td>
<td>77.0</td>
<td>6.5</td>
<td>YES</td>
<td>DARK</td>
<td>8</td>
<td>0.14</td>
<td>1.85</td>
<td>88</td>
<td>143</td>
<td>78</td>
<td>NORMAL</td>
<td>20%</td>
</tr>
</tbody>
</table>

Overall, most likely due to having drivers who crashed only (none who avoided), these data represent an average of a 38th percentile response.

Yet, 71.4% of these real life drivers fall within the normal range offered by IDRR (the most normal 2/3rds of drivers).

Long Headway Situations

17 of 21 within 41' (assumed impact occurred at 0.5 sec – C. Wilkinson, 2006)
Including Maddox & Kiefer: 27 of 35 (77%) within range offered by IDRR

Overall LV 41 of 50 (82%) fall within range estimated by IDRR

Short Headway Situations
14 of 15 have been 0.98 ± 0.4

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If you believe Markkula’s Brake threshold 0.02 radian/second (D) threshold is best,

Trucks and cars were similar responses
LV brake lights on 93%

<table>
<thead>
<tr>
<th>Table D</th>
<th>Response Time relative to (1/\tau \geq 0.2 \text{ s}^{-1} ) (~0.02 r/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N = 141 eyes-off-threat</td>
<td>0.42 s.</td>
</tr>
<tr>
<td>N = 80 eyes-on-threat</td>
<td>&lt; 1.0 s.</td>
</tr>
<tr>
<td>N = 20 eyes-on-threat</td>
<td>&lt; 0.0 s. (before threshold)</td>
</tr>
<tr>
<td>N = 22 eyes-on-threat</td>
<td>&gt; 1.0 s.</td>
</tr>
</tbody>
</table>

Brake onset most often occurred within a second after the driver first saw visual looming above the approximate threshold of 0.2 s−1 for \(-1/(0.02 \text{ rad/s}) \) for \(\theta \). Markkula et al. 2016 p. 221 Accident Analysis and Prevention, 95 (2016) 209-226. (SHRP-2)
Compare Muttart et al to Markkula et al

When does PRT end and Maneuver start?
Both methods yield distances within 8 feet (2.4 m)

<table>
<thead>
<tr>
<th>Closing Speed</th>
<th>Recog. Thres. 0.006 r/s</th>
<th>Minus PRT</th>
<th>Recog. Thres. 0.02 r/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPH</td>
<td>KPH</td>
<td>Feet</td>
<td>Meters</td>
</tr>
<tr>
<td>55</td>
<td>88.5</td>
<td>284</td>
<td>87</td>
</tr>
<tr>
<td>60</td>
<td>96.5</td>
<td>297</td>
<td>90</td>
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<td>65</td>
<td>104.6</td>
<td>309</td>
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<td>70</td>
<td>112.6</td>
<td>320</td>
<td>98</td>
</tr>
<tr>
<td>75</td>
<td>120.7</td>
<td>332</td>
<td>101</td>
</tr>
</tbody>
</table>

Assumption that LV was stopped and 6 feet (1.8 m) wide
Summary

• We do not know when or where a driver perceived.
• Our goal:
  – Compare this driver’s response (based upon the physical evidence)
  – With the response of others (Based from research).
• To do that –
  – Compare pre-impact maneuvers...
  – How long before impact did the maneuver start?
• Closing speed threshold is only a starting point (a landmark) from which we can apply how drivers have responded in research (both simulator & naturalistic).
• Ultimate goal is to compare maneuver distance of the crash driver with the maneuver distance of reasonable drivers.
Variables that Influence RT

- **Subtended angle**
  - The angle formed by the size of an object at a given distance.

- **Subtended angular velocity (Looming Rate)**
  - The rate change of the subtended angle over time.

Van shown at 0, 100, 300, 600 feet

Visual Expansion Rate [VER] is the *CHANGE* in the angle

Figure 1.3.3 Above, an example of subtended angle and below, how subtended angle changes, which is subtended angular velocity (or visual expansion rate)
<table>
<thead>
<tr>
<th>AUTHORS</th>
<th>Vis Expan r/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michaels &amp; Cozan 1963</td>
<td>0.0006</td>
</tr>
<tr>
<td>Brown 1960</td>
<td>0.00003 - 0.0061</td>
</tr>
<tr>
<td>Braunstein &amp; Laughery 1964</td>
<td>0.0014 – 0.0024</td>
</tr>
<tr>
<td>Summala, Lamble &amp; Laakso (1998)</td>
<td>0.0020 – 0.0045</td>
</tr>
<tr>
<td>Mortimer 1990</td>
<td>0.0021</td>
</tr>
<tr>
<td>Lamble, Laakso &amp; Summala (1999) Ahead</td>
<td>0.0022 – 0.0038</td>
</tr>
<tr>
<td>Mortimer 1994</td>
<td>0.0027</td>
</tr>
<tr>
<td>Mortimer 1988</td>
<td>0.0028 – 0.0035</td>
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<tr>
<td>Farber &amp; Silver 1967 (head on)</td>
<td>0.0030</td>
</tr>
<tr>
<td>Duckstein, Unwin &amp; Boyd 1970</td>
<td>0.003 - 0.004</td>
</tr>
<tr>
<td>Mortimer &amp; Hoffman 1996</td>
<td>0.0022 – 0.0052</td>
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<tr>
<td>Bierly 1963</td>
<td>0.0035</td>
</tr>
<tr>
<td>Terry, Charlton &amp; Perrone, 2008</td>
<td>0.004 – 0.005</td>
</tr>
<tr>
<td>Muttart, Fisher, Knodler, 2007</td>
<td>0.0045 – 0.007</td>
</tr>
<tr>
<td>Muttart, Messerschmidt, &amp; Gillen, 2005</td>
<td>0.0063 - 0.0068</td>
</tr>
<tr>
<td>Lamble, Laakso &amp; Summala (1999) 45 Deg.</td>
<td>0.0017 – 0.0095</td>
</tr>
<tr>
<td>Lamble, Laakso &amp; Summala (1999) 90 Deg.</td>
<td>0.013 – 0.015</td>
</tr>
<tr>
<td>Plotkin, 1974</td>
<td>0.0275</td>
</tr>
<tr>
<td>Maddox &amp; Kiefer, 2012</td>
<td>0.007 – 0.05</td>
</tr>
<tr>
<td>Markkula et al, 2016</td>
<td>0.02</td>
</tr>
<tr>
<td>Caro, et al., 2007 (fog)</td>
<td>0.050 (only used)</td>
</tr>
</tbody>
</table>

---

**Distance from LV**

Further

1 radian = 57.3 degrees

2Pi radians in a circle = 2 x 3.14 x 57.3 = 360 degrees

Closer
# Ability to Recognize Closing Rate

<table>
<thead>
<tr>
<th>Authors</th>
<th>Methodology</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summala, Lamble, Laasko, (1998)</td>
<td>Responded to LV at various eccentricities, two headways, brake lights on or off</td>
<td>Results - 0.0045 rad/sec</td>
</tr>
<tr>
<td>Muttart, Messerschmidt &amp; Gillen (2005)</td>
<td>Part 1 – meta-analysis Part 2 – very low fidelity simulator</td>
<td>PRT remains high – levels off after 0.0063 rad/sec</td>
</tr>
<tr>
<td>Plotkin (1968-1974)</td>
<td>“Reconstructed” 5 crashes – applied “known” PRT = 0.75 sec</td>
<td>0.0275 radians/sec</td>
</tr>
<tr>
<td>Fisher, Knodler &amp; Muttart, 2007</td>
<td>Part 1 – Fixed base -High fidelity simulator Part 2 – Field Part 3 – Simulator again</td>
<td>0.0045 to 0.006 rad/sec</td>
</tr>
<tr>
<td>Lamble, Laakso &amp; Summala (1999)</td>
<td>45 degree eccentricity 90 degree eccentricity</td>
<td>0.007 – 0.0095 0.013 – 0.015</td>
</tr>
<tr>
<td>Caro, et al., 2007 (fog)</td>
<td>Simulator – in fog – threshold was up to braking (Do not add PRT)</td>
<td>0.050 (includes PRT)</td>
</tr>
<tr>
<td>Markkula et al, 2016</td>
<td>SHRP-2 Naturalistic data</td>
<td>0.02 radians/second (0.46 second “offset”)</td>
</tr>
</tbody>
</table>
Break...

Contrast gradient
Progression of Events with Markkula’s 3 stages
Starting Point for PRT

- **Recognize**
  - Categorize object
  - 1st reaction to a stimulus
  - 1st hand movement
  - Foot off accelerator pedal

- **Perception-Reaction**
  - Turning steering wheel
  - Moving foot from accelerator to brake pedal

- **Limb Movement**
  - Time from completion of steering to first lateral movement
  - Time from brake application to start of slowing

- **Vehicle latency**
  - Swerve
  - Skid or hard brake

- **Pre-Impact Maneuver**

- **Brake-Response Time**

- **Perception-Response Time**

- **Driver Response Time (generic term – any or all phases)**
Perception-Response Time (PRT)

• Inherent in the term *perception*-response time is that a driver is PERCEIVING an immediate hazard that requires an emergency response.

• Perceive
  – Something more than vision, perception is vision plus categorization, such as good or bad, hazardous or not, shoot or don't shoot; hazardous or non-hazardous.
Four Studies

• Study 1 – Meta-analysis
  – Compared RT to Subtended angular velocity at start of RT.
  – Other variables – topography, pRT, BRT, or PRT?, eccentricity, day or night, flashing lights, brake lights.

• Study 2 – Low fidelity laptop simulation
• Study 3 – High fidelity simulator
• Study 4 – Field study
Two-Part Study (SAE 2005-01-0427)

- 1<sup>st</sup> – Compared subtended angular velocity and reported response time in published research (Must compare like events).

- 2<sup>nd</sup> – A laptop simulator.

- Hypothesis:
  1. Response times remain high until...
  2. A lead vehicle is easily perceivable as an immediate hazard when...
  3. At which time the driver response times level off and remain constant.
Study II: Simulated Screen

- Screen 1a represents the size (subtended) of a ‘car’ at 0.002 radians per second,

- 1b shows a 2 m by 2 m ‘box’ at 0.01 radians per second.

- Also examined the influence of a object the size of a semi-trailer
Part I Meta-analysis
Part II Laptop Simulator

At 62 mph & 0.006 r/s = 301 ft. = (6 x 91 / 0.002) ^ 0.5
Need to determine when a driver starts a maneuver.

Thus, a combination of threshold (i.e. – start line) and RT.

Table 4. Results of meta-analysis comparison of driver response times at various radians/second

<table>
<thead>
<tr>
<th>Radians per second</th>
<th>Reported BRT</th>
<th>Adjusted PRT</th>
<th>Percent &lt; 2 s.</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.0035</td>
<td>3.52 s</td>
<td>4.28 s</td>
<td>0%</td>
</tr>
<tr>
<td>0.0035 to 0.007</td>
<td>2.14 s</td>
<td>2.47 s</td>
<td>46%</td>
</tr>
<tr>
<td>&gt; 0.007</td>
<td>1.16 s</td>
<td>1.29 s</td>
<td>94%</td>
</tr>
</tbody>
</table>

Markkula et al, 2016 (incl. braking ramp-up)

0.02 r/s 0.46 s ~0.75 ~99%
When > 70 mph drivers leave their lanes earlier – Problem at 55-70 mph


© J Muttart 2016
Visual Expansion Rate

- If Visual Expansion rate is small –
  - We are starting the stopwatch early
  - Approaching driver is further away
  - Approaching driver PRT will be longer
- If Visual Expansion rate is large—
  - We are starting the stopwatch late
  - Approaching driver is closer to impact
  - Approaching driver PRT will be shorter
- PRT must FIT with visual expansion rate

Figure 1.3.4 Theoretical progression of a drivers response and how detection of closing speed and PRT fit with one another.
Progression of Events with Markkula’s 3 stages

Stage 1
Stage 2
Stage 3

CLOSING?
CLOSING RATE
LANE CHG PREP
PRT
Maneuver
Low Probability Event

• Tijerina et al. (UMTRI)
  – 95% maintained a safety envelope of \( < 20 \) feet per second (6.1 m/s) relative velocity in each direction.

  – Closure rates of greater than 44 feet per second (13.4 m/s) \( \rightarrow \) low probability event.

Problem: When Closing Speed Recognition Distance is Less Than Stopping Distance
Closing at High Speeds is Rare

- Lee, Olsen, & Weirwille, 2002
- Probability
- **Average closing speed** 5.9 ft./sec $\pm$ 12.55 ft./sec
- 95th percentile $= 5.9 + 1.645 \times 12.55 = 26.5$ ft./sec

- Closing at 60 mph would be 1 in 33 billion
- 3 of 434 were closing at speeds between 40 and 50.5 mph (none closing at faster speeds)
- Median lane change start 96 ft. (Mean = 124 ft.)

- Francher, 1999
- Average closing speed is 4.1 ft./sec (SD = 10.0)
- Range 153.3 ft. (SD = 103.6 ft.)
Closing? Speed of LV?
### Expected Pre-Impact Maneuver

**Average Pre-Impact Maneuver:** 108 feet

<table>
<thead>
<tr>
<th>Equation</th>
<th>Min Avg</th>
<th>Max Avg</th>
<th>Studied Adjtd</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 sec</td>
<td>2.4 sec</td>
<td>3.2 sec</td>
<td>2.6 sec</td>
</tr>
</tbody>
</table>

- **Visual Expanse Threshold (ft):** 306.8
- **Distance to Impact at Vis Exp Thres (ft):** 298.8

### Response to Lead Vehicle

**Init. Speed Appr Veh (mph):** 55

- **Eyes-2-F. Bump (ft):** 8
- **LV Initial Speed (mph):** 0
- **Speed of LV at Imp (mph):** 0
- **Discernable Width (ft):** 7

### Expected Pre-Impact Maneuver

<table>
<thead>
<tr>
<th>Init. Speed Appr Veh (mph)</th>
<th>55</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyes-2-F. Bump (ft)</td>
<td>8</td>
</tr>
<tr>
<td>LV Initial Speed (mph)</td>
<td>0</td>
</tr>
<tr>
<td>Speed of LV at Imp (mph)</td>
<td>0</td>
</tr>
<tr>
<td>Discernable Width (ft)</td>
<td>7</td>
</tr>
</tbody>
</table>

#### Time to Steer

- **Total Steering Distance = 190 feet + 47 feet = 237 feet**
- **Time to steer = d/V = 0.58 sec**

#### Eye Movement Time

**Check if Hovering brake:**
- **Follow closer:**
- **Check Box if mobile phone usage:**

### Closing Speed Detection Threshold

**Hv**

### Average Per-Resp Time

<table>
<thead>
<tr>
<th>85th %ile</th>
<th>39 feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4 sec</td>
<td>3.2 sec</td>
</tr>
</tbody>
</table>

### Visual Expanse Threshold (ft)

- **306.8 ft**

### Distance to Impact

- **3.80 sec**
- **93.2%**

### Avg. Lateral Friction (gs)

- **0.55**

### Response Dist. = ~ 2.4 x 55 x 1.467 = 190 feet

- **Avg. Response Dist. = 2.4 x 55 x 1.467 = 190 feet**
- **Distance to Steer = 0.366 x 55 x 1.467 = 306.8 ft**
- **Total Steering Distance = 190 feet + 47 feet = 237 feet**
- **Time to steer = d/V = 0.58 sec**

### Tot. Steering Dist. = 237 feet

- **85th %ile STEER. DIST. = 306 feet**
The Entire Event
Are you Closing or Separating?...
– 12% rule when applied too far away
12% rule when applied too close
My Related Research


Headway

- Response time increases as headway increases & deceleration rate (LV) decreases.
  - Boer, 1999
  - Duckstein, Unwin, Boyd, 1970
  - Caro, Cavallo, Marendaz, Boer, Vienne, 2007
  - Muttart, 2003

- Smaller deceleration may not be associated with an emergency response event initially.
Flashing Lights?

- **Presence lights** - Fisher and Hall
  - Insignificant difference when detecting a change in headway.

- **Brake lights** - Summala et al
  - 0.3 second faster than without brake lights (Adjusted for Eccentricity – otherwise ~ 0.6 s)
  - Only one LV in the driver’s forward field
  - Markkula et al., 2016
    - 59% had brake lights on all 6 seconds
    - 34% had brake lights on at some time

- **Strobe lights** – Schriener
  - Insignificant effect in Response to Lead Vehicles situations

- **Flashing lights** - Crawford, Boff & Lincoln
  - More difficult to detect if among other flashing lights (like transient brake lights)
  - flashing lights increase the likelihood of detection if there were no other flashing lights.
Eccentricity if Looking into Driver’s Side Mirror
Relative Velocity Detection

Detect...

Detect Closing...

Detect RATE of Closing...

0.34 deg/sec
Subtended Angular Velocity
(Visual Expansion Rate)

• Hoffman & Mortimer (1996)
  – 50% of observers were capable of detecting a relative velocity greater than 0.003 radians/sec.
  – Allowed 4 second observations in laboratory setting.
  – Just noticeable difference for alerted subjects with “binary” choice was 0.002 rad/sec.
  – Alerted subjects with binary choice = drivers stopped at a stop sign!
• Plotkin (1968) – 0.0275 r/s based upon reconstruction.
  – Estimated vehicle speed
  – Assumed several factors including PRT.
Subtended Angular Velocity
(Visual Expansion Rate)

• Lamble et al
  – 0.007 rad/sec with 45 degree eccentricity
• Muttart, Messerschmidt & Gillen (2005)
  – 0.006 r/s is when PRT levels off
  – 0.0045 r/s is threshold that best fits with PRT research
• Summala, Lamble & Laakso (1998)
  – Reported 0.002 to 0.003 rad/sec threshold
  – Findings support 0.0045 r/s
• Markkula et al 2016
  – 0.02 rad/sec threshold
  – Time after 0.02 r/s threshold where braking began = 0.46 s
  – Did not account for braking time but addressed “ramp up” deceleration
Hoffman & Mortimer (1996) calculated the subtended angular velocity [SAV] as follows:

- Perceive relative speed:
  - \( \frac{d\theta}{dt} = \frac{WV_r}{D^2} \)

Sixteen comparisons were presented twice to each of the subjects;

- The relative speeds of 0.54, 1.20, 3.25 and 5.43 m/s were compared with the 0.95, 2.21, 4.38 and 7.23 m/s conditions (P. 418).

- Eight film segments were shown, each with a mean headway of 28 m and having a 4 s exposure.

- Corresponding subtended angular velocities ranging from 0.0013 to 0.017 rad/s.

- Stationary observers, no driving task, no other glance location was necessary, did not address the added difficulty of a stopped LV from more than 300 feet (100 m) away.
Subtended angle threshold gets smaller

Lamble et al 1999

Figure 4. Angular velocity of expansion of the image of the vehicle ahead on the retina at the moment of detection for each position of the foveal in-car task.
Equation:
See Letters & Numbers Above

**Expected Pre-Impact Manoeuvre**

Average Pre-Impact manoeuvre: 0 feet 85th %ile: 0 feet

**Equation**

393 x H + 509 x O + 26 x E – 703 x Tp + (Tr & constant) + Brake adj + Adj to VER

**Studies Adjtd**

3.4 Sec 3.1 Sec 3.8 Sec

**Visual Exp Thresh (ft)**

155.6

**Distance to Impact at Visual Exp Thresh (ft)**

152.6

Distance to Impact

**EXPECTED PRE-IMPACT MANEUVER**

<table>
<thead>
<tr>
<th></th>
<th>85th %ile</th>
<th>85th %ile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Pre-Impact maneuver 0 feet</td>
<td>3.1 sec</td>
<td>4.3 sec</td>
</tr>
<tr>
<td>Equation</td>
<td>2.9 sec</td>
<td>Min Avg</td>
</tr>
<tr>
<td>Studies Adjtd</td>
<td>3.4 Sec</td>
<td>Max Avg</td>
</tr>
</tbody>
</table>

- **Visual Expan Threshold (ft)**: 155.6
- **Distance to Impact at Vis Exp Thres (ft)**: 152.6

**Distance to impact at Visual Expansion Threshold (DTI):**
- **Vis. Exp Threshold Dist** = (LV width x \(V_{rel}/DTI\) = Visual Exp. Rate\(^{1/2}\)
- **DTI** = **Vis. Exp Threshold** x \((V_f/V_{rel})\)
  - **Where:**
    - **Visual Expansion Threshold**, 0.006 rads/sec
    - **\(V_f\)** is the Velocity of the following vehicle
    - **\(V_{rel}\)** is the relative velocity, calculated by \(V_{rel} = V_{ApprHV} - V_{LV}\)
    - Adjusts for distance from eyes to front bumper.

393 x H + 509 x O + 26 x E – 703 x Tp + (Tr & constant) + Brake adj + Adj to VER

393 x 3.2 + 509 x 1 + 26 x 35 – 703 x 1 + 1335 + 125 + -527
Influence of Size of Lead Vehicle on Response
Train Crashes

• “Leibowitz hypothesis,”
• Large objects seem to move slower
  – Two subsystems influence eye movement
    • Reflexive: without thought —
      – Triggered by seeing contours. Allows us to see things while we move
    • Pursuit eye movements. How we view moving objects. How we est. speed.
      – Effort necessary
      – The larger, the less our voluntary systems have to work, and the slower the object seems.

Large Objects – Slower?

- Verified Leibowitz’ hypothesis

- Subjects estimated speed of spheres coming toward them in computer simulation.
- Static posts and lines on the ground as helpful cues
- Observers reported smaller sphere was moving faster — even when the larger sphere was moving 20 mph faster.
- Not until the large sphere was 2 x faster were observers convinced the smaller sphere was moving faster.


Accessed May 14, 2012
Which is closing fastest?
DEPTH PERCEPTION:
ESTIMATING DISTANCE & SPEED
OF OBJECTS MOVING IN-LINE

If you do not know what it is (specifically its size, clarity or brightness), then you do not know where it is.
Very Little Context:
Lacks Clarity
Depth
& Size information
Context:
More Clarity
But Lacks Depth & Size Detail
Better Perspective Offered
Lighting, Clarity, & Brightness

We are now capable of accurately judging size and relative
Position which tells us the distance
Depth Perception Evaluation

- 2”, 4” & 6” squares
- Red C2, White C2 and aluminum sheeting
- At various heights
- Two trailer marker lights at approximately same distance
  - One powered by 6 volt battery
  - One powered by 12 volts
Height, Size & Perceived Brightness – Without Context

Photo by Gregory Vandenberg
View from Within Vehicle

Photo by Gregory Vandenberg
Perception: Brighter is Closer; Dim is Further Away
Higher Objects Viewed as Further Away

ANOVA

<table>
<thead>
<tr>
<th></th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>0.982</td>
<td>12</td>
<td>0.082</td>
<td>2.628</td>
<td>.003</td>
</tr>
<tr>
<td>Within Groups</td>
<td>6.199</td>
<td>199</td>
<td>0.031</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7.181</td>
<td>211</td>
<td>0.031</td>
<td>2.628</td>
<td>.003</td>
</tr>
</tbody>
</table>

Mean Estimated (ft) vs. Height (ft)
Side Marker Light

6 v left & 12 v right

Photo by Gregory Vandenberg
## Trailer Marker Lamps

<table>
<thead>
<tr>
<th></th>
<th>Actual</th>
<th>Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side Trailer Marker Light 6v</td>
<td>205</td>
<td>185.0</td>
</tr>
<tr>
<td>power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side Trailer Marker Light 12v</td>
<td>203</td>
<td>160.0</td>
</tr>
<tr>
<td>power</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Brighter light viewed as Closer
Discussion

• Features That Influence Depth Perception
  – Interposition
  – Linear perspective (vanishing lines of a road)
  – Clarity
  – Height
  – Size
  – Brightness (intensity)
  – TEXTURE
THE PROBLEM

Poor Context + Low Probability + Poor Grasp of Closing Speeds
IN THE NEXT SLIDES, I SHOW THE VIEW WHEN CLOSING AT VARIOUS SPEEDS AND FROM VARIOUS DISTANCES

UNDERSTAND – YOU KNOW WHERE TO LOOK AND WHAT TO LOOK FOR

IF YOU WERE DRIVING SCANNING LOOKING AWAY... HOW WELL WOULD YOU DO?

YOU WILL BE SHOWN A SERIES OF PHOTOGRAPHS OF CLOSING ON A LEAD VEHICLE. YOU WILL BE ASKED QUESTIONS LATER?
# Closing or Separating?

**What is the distance**

- 900’
- 800’
- **700’**
- 600’
- 500’

**Relative speed**

- **Closing at 25**
- **Closing at 45**
- **Closing at 65**
- Not closing
- Gaining at 20 MPH

Taillights 5.5 feet apart
TAILLIGHTS 5.5 FEET APART

What is the distance
- 900'
- 800'
- 700'
- 600'
- 500'

Relative speed
- Not closing
- Closing at 25
- Closing at 45
- Closing at 65
- Gaining at 20 mph
TEST 3
TAILLIGHTS 5.5 FEET APART

What is the distance
- 900'
- 800'
- 700'
- 600'

A – 1 62

Relative speed
- Not closing
- Closing at 25
- Closing at 45
- Closing at 65
- Gaining at 20 mph
TEST 4
TAILLIGHTS 2.5 FEET APART

What is the distance

900'
800'
700'
600'

A – 1 62

Relative speed

Not closing
Closing at 25
Closing at 45
Closing at 65
Gaining at 20 mph
VISION VERSUS PERCEPTION

JEFFREY W MUTTART

