REVIEW OF TRAFFIC SIGNALS ON HIGH SPEED ROADS

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1. SUMMARY

This paper reviews the driver ‘dilemma zone’ (whether to stop or continue at the end of green) on higher speed approaches to traffic signals, policy and practice used to mitigate the safety consequences of this, and the classification of a ‘high-speed’ approach.

2. BACKGROUND AND OBJECTIVES

At the end of green drivers approaching traffic signals can be faced with a decision of whether to stop or continue. Depending upon the vehicle speed and the distance from the junction this decision can be marginal and different drivers would make different decisions. At higher speeds some drivers may be caught in a position where they must choose to either brake hard to stop or continue and risk entering the intersection during the red.

The distance from the intersection over which there can be some uncertainty of the appropriate action at the end of green is called the ‘dilemma zone’. This can have safety implications as there is the potential for conflicts with other road users. A driver who chooses to stop can be at risk from a rear-end collision with a following driver, while a driver who decides to continue may be at risk of running the red, which is a prosecutable offence, and a collision within the junction.

Various strategies are used around the world, with the aim of reducing the instance of drivers being caught in the ‘dilemma zone’, and the safety consequences if caught in it.

In the UK, dilemma zone protection traffic signal control strategies are required on approaches where the 85th percentile speed exceeds 35 mph (where 15% of free-flow approach speeds exceed 35 mph (56 km/h)). Current strategies used are ‘Speed Assessment’, ‘Speed Discrimination’ and ‘MOVA’ (DfT, 2003). All the strategies use loop detection, and the detectors can be in excess of 150 metres from the stop line.

There is notable capital cost in installing this detection equipment. Probably of even greater importance is the revenue cost of maintaining these comparatively complex control systems in full working order.

Much of the current UK advice is based on work undertaken in the early 1960’s (Webster and Ellson, 1965). A lot has changed in vehicle characteristics. An increase in the 35 mph threshold could produce substantial
savings in installation and maintenance cost, if it was found to be safe to do so. As such the UK Department for Transport commissioned TRL to reassess the size and position of the dilemma zone and the speed at which traffic signal approaches should be classified as ‘high-speed’.

Note that, any views expressed are not necessarily those of the Department for Transport.

3. METHODOLOGY

The main strands of the research were:

- An international literature review of traffic signals on high-speed roads
- Site studies using video recordings at five UK traffic signal junctions on high-speed roads, with regards to driver behaviour after the onset of amber.

The findings were used to make an assessment as to whether, with current vehicle technology and driver behaviour, the size and the position of dilemma zone has changed since the last two major pieces of research, ‘Webster and Ellson (1965)’ in the UK, and ‘Zeeger (1971)’ in the US, and if it has, whether the high-speed road criterion of 35 mph could be raised, and/or traffic signal control requirements amended. Further methodology details are given in the relevant sections.

4. MEASURES OF THE DILEMMA ZONE

Two main measures of the dilemma zone have been used by previous researchers:

- The ‘critical section’ based upon vehicle speed, the distance that can be covered without running the red and ‘acceptable’ stopping distance.
- Observed probability of stopping over a range of speed categories; usually defined as the distance from the stop line at the onset of amber between where 10% and 90% of drivers stop.

In the US the probability of stopping measure (recorded on-street by Zeeger (1977)) tends to be used in the design of control strategies/ detector locations; and driver reaction time and maximum acceptable braking in the calculation of amber periods to negate the theoretical critical section, however as noted by Smith et al (2001) there is still a ‘decision zone’ as defined by the probability of stopping dilemma zone measure, and control strategies are widely used in addition to the longer amber to attempt to reduce the number of drivers in the ‘decision zone’.

The UK Speed Assessment (SA) and Speed Discrimination (SD) control strategies are based upon a critical section measure recorded by Webster
and Ellson (1965), which uses the distance at which 90% of drivers can stop comfortably, based upon a test track experiment.

5. OVERVIEW OF DILEMMA ZONE STRATEGIES AND BENEFITS

SA and SD provide a green extension to vehicles travelling over a threshold speed with the aim of avoiding drivers being caught in the dilemma zone. If maximum green is reached then an all-red extension is given to allow extra junction clearance time for possible red running.

The third UK strategy, MOVA, does not implicitly seek to avoid vehicles being caught in the dilemma zone, but its delay minimisation logic tends to avoid ending the green when vehicles are in this zone. It has been shown to reduce delays and red running compared with SA/SD and to be as safe (Crabtree and Kennedy, 2005).

Dilemma zone protection control strategies have been proven to be effective at reducing accidents on high-speed roads in the US. ‘Green extension’ control strategies, similar to SA and SD, have shown accident rate reductions between 35 and 55%, when compared to strategies without dilemma protection (Wu et al (1982), and Zeeger (1977)). However the effectiveness of these strategies is reduced at higher flows where there is a tendency for the green to run to maximum, and a maximum green change can place drivers in the dilemma zone.

Recent developments in traffic control include ‘optimisation’ strategies, akin to MOVA, but specifically addressing dilemma zone issues: D-CS in the US (see Section 8); and SOS combined with LHOVRA in Sweden. They allow green to end for single vehicles in the dilemma zone as the maximum green time approaches i.e. negating the chance of a rear-end collision but not a right angled collision; and specifically providing extensions for large vehicles.

The employment of dilemma zone strategies with linked signals has so far been limited. Research indicates that combining Urban Traffic Control with SA or SD could bring potential safety benefits, while an investigation into a dilemma zone event minimisation strategy has indicated that significant reductions in dilemma zone events can be achieved, without significantly modifying the network timings (Pant and Cheng, 2001).

Alternative methods to address the dilemma zone issue include: speed reduction; longer amber periods; and advanced warning of the amber period.

Reducing speeds on the approaches to traffic signals would reduce the size and potential consequences of being caught in the dilemma zone. Finland for instance has a maximum speed limit on the approach to traffic signals of 70kmh (43mph).

Longer amber periods based upon approach speeds have been shown to be effective at reducing red running, and appear to reduce accident rates marginally (e.g. see ITE (2003), FHWA (2004)). Concerns have been
expressed about the use of a non-uniform amber period (e.g. Webster and Ellison (1965), York and Al-Katib (2000)), and studies have indicated that drivers facing a shorter amber than expected are more likely to run the red. There are also concerns that the use of a longer uniform amber period could affect junction capacity and driver behaviour, especially at lower speed sites. A four second amber period would increase the start of the Webster and Ellison critical section to about 47 mph, which in theory could increase the high-speed criterion beyond 35 mph, to around 45 mph. However, there is still a section where drivers’ decisions vary, which can lead to rear-end accidents, and this may still warrant the use of dilemma zone protection control strategies.

The results of advanced warning of amber studies tend to show that red running and overall vehicle approach speeds reduce and more drivers stop. This leads to a reduction in accidents within the junction, and accident severity. Drivers of large vehicles particularly favour the signs. However, advanced warning of the amber can lead to an increase in approach accidents because drivers react differently to the warning, e.g. some begin to slow early, while others accelerate to beat the lights (e.g. see FHWA (2004), Mahalel and Zaidel (1985), York and Al-Katib (2000)). Also advanced warning of amber can affect the efficiency of the control strategy because it is required to start before the end of green. Partly for these reasons its usage worldwide has been limited, and its use in the UK has not been recommended.

Red light running cameras are used at some traffic signals. They can significantly reduce the number of red running events, and reduce the number of personal injury accidents involving a red running vehicle. However, they can lead to an increase in shunt accidents on the approach, which occasionally has offset the reduction of collision accidents, although the overall accident severity tends to reduce. Results from a number of studies is given in TRB (2003).

6. SITE STUDIES

6.1 Data collection

Driver response to the end of green was recorded and analysed at five high-speed sites between the hours of 08:00 and 18:00. Table 6.1 gives an overview of the site details.

The video recording was undertaken using three cameras at each site mounted on telescopic masts fastened to lamp columns. One with a view of the stop line and traffic signal indication, and the others covering approach views from about 100 and 150 metres. The size and position of the cameras and mountings made it difficult for drivers to spot them and thus had little or no effect on driver behaviour.

Both the 150 and 100 metre cameras pictures had synchronised inserts of the stop line camera. This was done on-site at the time. The insert allowed
accurate analysis of the stop line cross time while showing the approach on
the main picture.

The cameras were mounted at about 5 metres, which was sufficiently high to
get a good view of the traffic with minimal blocking by other vehicles and to be
able to determine distances from the stop line with accuracy, while low
enough so that brake light and traffic signal indications could clearly be seen,
and reduce any sway from wind. The sites were surveyed to provide
indicators every 10m from the stop line for the analysis, which were further
delineated in the office on the video screen with a Perspex overlay to five
metres or less where possible using geometric rules.

A time frame video recorder was used that recorded timings to an accuracy of
0.04 seconds (25 frames per second). Cycles where there was queuing traffic
at the start of amber were excluded from the analysis. The data recorders
recorded:

- The start of amber
- Checked the accuracy of the start of amber time – by the onset of red time
  (3 seconds, +/- 3 frames) – and reset if not accurate.
- Recorded the vehicles in view from 150 metres at the onset of amber –
  lane, classification, distance from the stop line (rear wheel), and
  wheelbase length (if not conforming with the typical values given for the
  vehicle classification)
- Approach speed – by recording the time taken to cover 30 metres just
  before the onset of amber or any braking
- Brake on time
- Cross the stop line time
- Direction taken at junction (i.e. ahead, left, right) – only vehicles going
  ahead were included in the dilemma zone analysis
- Any lane changing
- Comments on any ‘conflicts’ or unusual events

6.3 Main results

6.3.1 Approach speed and sample size

The sample sizes in 10 mph bands and 85th percentile approach speed for
each site are given in Table 6.1.
### Table 6.1: Sample sizes

<table>
<thead>
<tr>
<th>Location</th>
<th>Approach speed (mph)</th>
<th>Total</th>
<th>Mean speed (mph)</th>
<th>85th %ile speed (mph)</th>
<th>Speed limit</th>
<th>Mode of control</th>
<th>Red light running camera</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bagshot</td>
<td>110</td>
<td>348</td>
<td>347</td>
<td>105</td>
<td>910</td>
<td>45</td>
<td>54</td>
</tr>
<tr>
<td>Basingstoke</td>
<td>120</td>
<td>172</td>
<td>48</td>
<td>2</td>
<td>342</td>
<td>38</td>
<td>44</td>
</tr>
<tr>
<td>Camberley</td>
<td>8</td>
<td>116</td>
<td>257</td>
<td>77</td>
<td>458</td>
<td>49</td>
<td>56</td>
</tr>
<tr>
<td>Guildford</td>
<td>161</td>
<td>119</td>
<td>8</td>
<td>1</td>
<td>289</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>Leicester</td>
<td>417</td>
<td>521</td>
<td>124</td>
<td>14</td>
<td>1076</td>
<td>37</td>
<td>44</td>
</tr>
<tr>
<td>Total</td>
<td>816</td>
<td>1276</td>
<td>784</td>
<td>199</td>
<td>3075</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

85th percentile approach speeds were somewhat lower than the speed limit at the three highest speed sites. This perhaps indicates some caution shown by drivers approaching traffic signals on the highest speed roads.

### 6.3.2 Dilemma zone based upon the probability of stopping (10 to 90%)

The data were divided according to approach speed into 5 mph bands. In order to draw general conclusions, the data from all sites were pooled and logit functions fitted to the data as defined by the equation:

\[
p = \frac{1}{1 + e^{-ax + bx}}
\]

Where \( p \) = the proportion stopping  
\( x \) = the distance from the stop line at the start of amber  
\( a \) and \( b \) are coefficients fitted by the regression.

The results are shown in Figure 6.1. A general behaviour can be seen, effectively no drivers stop when they are very close (less than 25 m) to the stop line at the start of amber, the distance at which any drivers are willing to stop increases with approach speed and above that distance the proportion that stops increases rapidly with distance from the stop line at the start of amber.

The exception is for the fastest drivers where the proportion stopping increases noticeably less rapidly with distance. It should be noted that the sample size is less for these fastest drivers and so the results should be treated with some caution, but there is a warning that drivers are less inclined to stop from the highest speeds than might be expected by extrapolating from lower approach speeds.
Converting the above figures into the distance at which a given proportion of drivers will stop when approaching at a specified speed gives the results shown in Table 6.2 and Figure 6.2.

Table 6.2: Observed dilemma zone with the stop line used as the clearance reference

<table>
<thead>
<tr>
<th>Approach speed</th>
<th>Distance from stop line (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mph</td>
<td>m/s</td>
</tr>
<tr>
<td>------</td>
<td>-----</td>
</tr>
<tr>
<td>30</td>
<td>13</td>
</tr>
<tr>
<td>35</td>
<td>16</td>
</tr>
<tr>
<td>40</td>
<td>18</td>
</tr>
<tr>
<td>45</td>
<td>20</td>
</tr>
<tr>
<td>50</td>
<td>22</td>
</tr>
<tr>
<td>55</td>
<td>25</td>
</tr>
</tbody>
</table>

It can be seen that the distances from which 10% and 90% of drivers are prepared to stop increase approximately linearly with speed, although the braking distance at a fixed deceleration increases quadratically with speed. Defining the dilemma zone by drivers’ behaviour results in an appreciable ‘dilemma zone’ (over 30m) even at an approach speed of 30 mph.

An alternative way of looking at the dilemma zone is to convert the distance from the stop line at the start of green to the time to the stop line assuming that the vehicle continues at a constant speed.
Figure 6.2: Dilemma zone from proportion of drivers stopping

Figure 6.3 shows the result of the transformation. The figure implies a high level of red-running, given that the UK amber period is fixed at three seconds, and this was confirmed during the analysis, see Section 6.3.6.

Fifteen percent of drivers were found to have accelerated to avoid red running. Almost all of these, 92%, would have crossed the stop line less than 0.5 seconds after the start of red if they had continued at their measured approach speeds.

Figure 6.3: Dilemma zone as time to the stop line from proportion of drivers stopping

Less than 10% of drivers stopped when they were less than about 2.5 seconds from the stop line at the start of amber. It appears that drivers are considering whether they will cross the stop line without notably running the red, rather than whether they can reasonably stop.

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6.3.3 Large goods vehicles

About 6.5% of the observed vehicles were large goods vehicles (LGVs). Logit curves were fitted with approach speeds divided into 10 mph bands because of the small number of observations. Only the regressions for speeds in the ranges 35 to 45 and 45 to 55 mph converged, the sample sizes were too small in the other ranges. Figure 6.4 shows the fitted curves together with the equivalent ones for all vehicles.

The results imply a broadly similar stopping behaviour by drivers of LGVs to that of general drivers at approach speeds around 40 mph. At higher speeds however they are considerably more reluctant to stop. This reluctance to stop is counterbalanced to some extent by slower approach speeds as shown in Figure 6.5.

![Figure 6.4: Stopping probability for LGVs](image1)

![Figure 6.5: Approach speeds of LGVs and of all vehicles](image2)
6.3.4 Brake reaction time

The brake on time of those drivers who started to brake within 2 seconds of the start of amber were analysed. The upper limit of 2 seconds was chosen to include drivers with slow brake reaction times. However, it will also include some drivers who did not need to make an instant decision, but chose to start braking soon after the onset of amber.

Table 6.3: Brake on times of drivers who started braking within 2 seconds of start of amber

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Median</th>
<th>Mode</th>
<th>85th Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.98 s</td>
<td>0.92 s</td>
<td>0.84 s</td>
<td>1.44</td>
</tr>
</tbody>
</table>

The results are shown in Table 6.3 and Figure 6.6. Of the three measures the arithmetic mean is the highest as the longest brake on times have most influence on this measure and the sample will include some drivers who did not need to brake instantly. The mode time is probably the best estimate of average brake reaction time.

Figure 6.6: Brake on times of drivers who started braking within 2 seconds of start of amber

6.3.5 Acceptable deceleration

The deceleration that a driver would have required in order to stop was calculated and compared with whether the vehicle did stop. For drivers stopping the actual brake on time was used, for drivers not stopping the mode brake reaction of 0.84 seconds was used to calculate the required deceleration.

The resulting proportions of drivers stopping versus required deceleration are shown in Figure 6.7 and Table 6.4 with a logit curve fitted to the data.
The observations suggest that there is considerable variation in the deceleration that drivers will accept. Of the 23 drivers who crossed the stop line when they could have stopped with a modest deceleration of 1.5 m/s² or less, only 5 did not cross during the red. Eleven of the 23 ran the red by more than 1 second. Conversely a few drivers were prepared to brake hard, over 5.0 m/s².

![Predicted proportion stopping](image)

**Figure 6.7: Predicted proportion of drivers stopping versus required deceleration**

**Table 6.4: Deceleration rates for selected stopping percentiles**

<table>
<thead>
<tr>
<th>Percentile</th>
<th>10th</th>
<th>15th</th>
<th>50th</th>
<th>85th</th>
<th>90th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deceleration m/s²</td>
<td>1.8</td>
<td>2.1</td>
<td>3.5</td>
<td>4.9</td>
<td>5.3</td>
</tr>
</tbody>
</table>

### 6.3.6 Red running

The number of red running vehicles and proportion of red running vehicles to number of signal cycles is given in Table 6.5. For LGVs it was the number of cycles in which an LGV driver was in a position to continue or stop at the start of amber unconstrained by stopping vehicles ahead.

On average a vehicle ran the red in a fifth of the signal cycles analysed. The numbers of LGVs observed was small and so the results are subject to statistical uncertainty, but the over representation of LGVs in the red-runners, particularly of those who ran the red by an appreciable amount is worrying.
Table 6.5: Red-running

<table>
<thead>
<tr>
<th></th>
<th>All Vehicles</th>
<th></th>
<th>LGV (6.5% of all vehicles)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>Proportion of cycles</td>
<td>Number (proportion of all red runners)</td>
<td>Proportion of cycles</td>
</tr>
<tr>
<td>Red-runners</td>
<td>301</td>
<td>20.6%</td>
<td>31 (10%)</td>
<td>15%</td>
</tr>
<tr>
<td>&gt;1s into red</td>
<td>52</td>
<td>3.6%</td>
<td>7 (13%)</td>
<td>3.4%</td>
</tr>
<tr>
<td>&gt;2s into red</td>
<td>13</td>
<td>0.9%</td>
<td>2 (15%)</td>
<td>1.0%</td>
</tr>
<tr>
<td>&gt;3s into red</td>
<td>5</td>
<td>0.3%</td>
<td>1 (20%)</td>
<td>0.5%</td>
</tr>
<tr>
<td>&gt;4s into red</td>
<td>2</td>
<td>0.1%</td>
<td>1 (50%)</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

Section 6.3.5 considered the required deceleration for drivers to stop at the stop line. This analysis was repeated for red-running vehicles. The results are shown in Figure 6.8.

![Figure 6.8: Required deceleration to avoid red-running](image)

It is interesting to note that almost all of the red-runners who ran more than 1 second into the red could have stopped with a deceleration of less than 4 m/s². The mean and 85th percentiles are given in Table 6.6.

Table 6.6: Mean and 15th and 85th percentile required deceleration

<table>
<thead>
<tr>
<th></th>
<th>15th percentile m/s²</th>
<th>Mean m/s²</th>
<th>85th percentile m/s²</th>
</tr>
</thead>
<tbody>
<tr>
<td>All red-runners</td>
<td>1.6</td>
<td>3.1</td>
<td>4.0</td>
</tr>
<tr>
<td>Over 1s into red</td>
<td>1.2</td>
<td>2.2</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Figure 6.9 shows the number of red-runners broken down by the time it would have taken them to reach the stop line from the start of amber at the measured approach speed versus the deceleration that they would have needed to stop.

Overall 8% of the red-runners would have cleared the stop line before the start of red if they had continued at their measured approach speeds, rather than slowing. They all ran the red by less than 1 second.

There were a few cases (5%) where red-running could not have been avoided without decelerations of over 5 m/s². About half of these were drivers that slowed on the approach which led to the red running, probably indicating the driver dilemma of whether to continue or not. The other drivers were of a journey time away which would have run the red by only one second. The potentially more serious red running, with a journey time greater than four seconds to the stop line at the onset of amber, occurred by drivers who required braking of less than 4 m/s².

Overall, if drivers had been able both to judge well when to continue and to accept a moderately hard deceleration when required little red-running would have been observed.
7. COMPARISON WITH OTHER STUDIES

7.1 Probability of stopping zone

Table 7.1 compares the results of this study with that found in the Webster and Ellson (1965) track trial and the US dilemma zone boundaries from an on-street study by Zeeger (1977). Figure 7.1 shows the 90% stopping distances diagrammatically.

The sample size for the 55 mph category in this study is lower than other categories shown and as such there is less confidence in the 55 mph result.

Table 7.1: Comparison with Webster and Ellson and Zeeger Dilemma Zone

<table>
<thead>
<tr>
<th>Approach speed</th>
<th>Distance from stop line (m)</th>
<th>Webster and Ellson</th>
<th>Zeeger</th>
<th>This study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mph m/s</td>
<td>10% 90%</td>
<td>10% 90%</td>
<td>10% 90%</td>
<td>10% 90%</td>
</tr>
<tr>
<td>30</td>
<td>13</td>
<td>40</td>
<td>24</td>
<td>41</td>
</tr>
<tr>
<td>35</td>
<td>16</td>
<td>47</td>
<td>31</td>
<td>52</td>
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<td>40</td>
<td>18</td>
<td>54</td>
<td>38</td>
<td>62</td>
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<td>45</td>
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<td>60</td>
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<td>77</td>
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<td>50</td>
<td>22</td>
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<td>55</td>
<td>25</td>
<td>74</td>
<td>70</td>
<td>113</td>
</tr>
<tr>
<td>60</td>
<td>27</td>
<td>80</td>
<td>84</td>
<td>134</td>
</tr>
<tr>
<td>65</td>
<td>29</td>
<td>87</td>
<td>103</td>
<td>160</td>
</tr>
</tbody>
</table>

This study agrees with previous studies, that drivers on-street are less willing to stop than those studied in the test track trial.

Figure 7.1: Distance that 90% of drivers stop with regards to approach speed

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Figure 7.2: Journey time to the stop line at onset of amber that 90% of drivers stop with regards to approach speed

Figure 7.2 shows that:

- In the on-street trials, 10% of drivers choose to continue when the journey time is between 4.5 and 5.0 seconds to stop line for approach speeds between 35 and 55 mph (mostly centred on about 4.5 seconds in this trial and 5.0 seconds in the US trial). Those at lower and moderate speeds in this 10% continuing category should have easily been able to stop, but are proceeding well into the red in this trial (n.b. in the US longer amber periods are used and, therefore, the level of red running will have been less).

- The test track trial showed an increase in red running as approach speed increased, indicating that the drivers tended to try to stop if they could, but the difficulty in stopping increased with speed.

Figure 7.3 shows the 10% stopping distances converted into journey time to the stop line at the onset of amber assuming constant speed.
As can be seen in figure 7.3:

- The Zeeger and Webster and Elson results are very similar at the level where 10% of drivers stop. The drivers stop if they can, and at lower speeds it is easier to stop. At higher speeds the 10% stopping distances are similar to this survey.

- This survey showed a fairly constant relationship over all speeds. At the 10% stopping probability level, these drivers with a comparatively high propensity to stop, only choose to stop if they are close to possibly running the red.

The indication from this survey is that the vast majority of drivers are making their stop-continue decision not on whether they can safely stop, as in The Traffic Signs Regulations and General Directions (The Stationery Office, 2002), but on whether they believe they can safely continue.

Overall this survey shows that the ‘dilemma’ zone, as defined by the probability of stopping, is considerably further away at lower and moderate speeds than that specified by Webster and Elson, and these results align with other on-street surveys. Drivers have a greater propensity to continue on-street compared with the test track, where drivers appeared to be trying to stop if they could. Also at the time UK intergreens tended to be much shorter than current and this would have been likely to increase the propensity to stop. There may also have been a worsening in driver behaviour over time.
7.2 Brake reaction time

Previous studies, which attempted to take account of the potential to delay braking due to distance or time from the stop line, indicated a mean brake reaction time in response to the onset of the starting amber to be 0.8 to 0.9 seconds and 85th percentile to be around 1.0 to 1.2 ((Blackman (1960), Chang et al (1985), Wong and Goh (2000)).

In this study the mode value has been taken as the most representative average value of brake reaction time, and the result of 0.84 seconds aligns with previous studies. The 85th percentile value of 1.44 seconds found in this study is somewhat higher than found previously and will include some drivers who have delayed braking purposely.

The values found here are slightly less than the one second US standard for average brake reaction time at traffic signals, and the Australian standard for 85th percentile brake reaction time of 1.5 seconds.

7.3 Accepted deceleration

The Webster and Ellson (1965) critical section dilemma zone is based on the distance where 90% of drivers chose to stop, in a test track experiment, and did so successfully. Baguley and Ray (1989) calculated that these distances were approximately equivalent to 3.6 m/s² deceleration with a one second brake reaction time. The equivalent 90% accepted deceleration value found in this trial was 1.8 m/s².

Other on-street trials have also shown much lower ‘accepted’ decelerations. Williams (1977) in a US trial found that 85% of drivers stopped when the deceleration required was 2.0 m/s² (1.1 second reaction time). This current study showed a similar result with the 85% stopping deceleration at 2.1 m/s² (0.84 second reaction time).

Olson and Rothery (1972) in a US on-street trial found that stopping decisions varied from between 2.4 m/s² and 3.7 m/s² required deceleration (one second reaction time). This current survey found similar results, showing variation between about 2.5 and 4.5 m/s² for the equivalent range.

The US uses 3.0 m/s² acceptable deceleration (and a one second reaction time) in the calculation of amber periods, this is equivalent to the deceleration that about 65% of drivers accepted in this survey.

This trial as in a number of other previous studies questions the use of a single value for ‘accepted’ deceleration, as the value increases as speed increases. Taking the 90% stopping distances found here and a more conservative one second brake reaction time, the implied accepted decelerations are shown in Table 7.2.
Table 7.2: Implied deceleration from distance where 90% of drivers stop assuming a one second brake reaction time

<table>
<thead>
<tr>
<th>Speed (mph)</th>
<th>30 mph</th>
<th>35 mph</th>
<th>40 mph</th>
<th>45 mph</th>
<th>50 mph</th>
<th>55 mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deceleration (m/s²)</td>
<td>1.5</td>
<td>2.1</td>
<td>2.6</td>
<td>2.8</td>
<td>3.1</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Another way to look at accepted deceleration is to review the level not accepted in red running. This again indicates that accepted deceleration is low. The mean required deceleration to avoid red running was 3.2 m/s², and 15% ran the red when only 1.8 m/s² was required (assuming the mode brake reaction time).

7.4 Red running

Allsop et al (1981) in a previous UK survey found that the braking which would have been required by red runners to avoid running the red (assuming a one second reaction time) to be between 2.9 (25th percentile) and 4.9 m/s² (85th percentile). This study showed a lower range, with the 25th percentile being 2.0 m/s² and the 85th percentile to be 4.0 m/s² (assuming a 0.84 second reaction time).

Out of the total sample of drivers, 150 metres or less from the stop line at the onset of amber, 7% (301/ 4141) ran the red. The level of red running was comparable with that found by Baguley and Ray (1989), excluding drivers who crossed the stop line in amber, they found that by site between 6 and 33% of drivers ran the red when faced with an amber 150 metres or less from the stop line. In this study the overall average was about 20% (301/1534).

Roughly about three quarters of drivers on ‘high-speed’ roads will continue if the journey time to stop line is three seconds at the onset of amber. These results may partly be due to drivers underestimating short journey times as shown by Van der Horst (1990). While this may be the case, the indication is that drivers overall have a greater propensity to continue than to stop when faced with an amber.

As shown in a number of previous studies a proportion of drivers would not have run the red if they had maintained their initial approach speed, 8% in this study. Conversely about 15% of drivers accelerated avoiding red running.

Most red running occurred within the first two seconds of red (96%). Given the UK recommended intergreen times these red runners are unlikely to be a significant safety risk. The remaining four percent do give rise to safety concerns, particularly as LGVs are over represented in these red runners.

7.5 Large goods vehicles

In-service fully laden Large Goods Vehicles generally have much lower braking performance than cars. In-service trials by TRL in 2002 showed average decelerations from between 3.2 and 5.0 m/s², once the brake has
been applied, with a mean of 3.9 m/s². At this level LGV’s travelling at higher speeds could be caught in the situation where they cannot physically stop without running the red. LGV’s are subject to lower speed limits and are specifically advised by the Driver Standards Agency (The Stationery Office, 2003) to approach traffic signals at speeds from which can stop under full control.

This survey did show that LGVs do tend to have lower approach speeds at traffic signals than other vehicle types. However, as in previous studies, LGV drivers are less likely to stop than drivers of other vehicle types travelling at the equivalent speed when faced with an amber, especially when travelling 45 mph plus. While accounting for 6.5% of all vehicles, LGVs accounted for 10% of the red running i.e. LGV drivers were over one-and-a-half times more likely to run the red than other drivers. This aligns with previous surveys, in the US, which showed LGVs 1.8 and 2.3 times more likely to run the red (Farrahar et al (1999) and Bonneson et al (2002)).

8. CONSEQUENCES FOR TRAFFIC SIGNAL CONTROL STRATEGIES

The results from the sites study show that 90% of drivers travelling at between 25 and 55 mph stop when presented with an amber signal 4.5 seconds before they would reach the stopline.

This driver behaviour means that double-SD detection does not fully cover the variation in drivers’ decisions over all its design speeds (up to 45 mph). However, those drivers not covered would be able to stop without undue braking (the largest required at 45mph being 3.4 m/s² with a one second reaction time). Increasing the detector distance from 79 metres to 90 metres, to cover the decision zone at 45mph, while operating the same strategy, would increase the chance of a maximum green change. This would increase the likelihood of drivers being caught in the ‘critical section’ dilemma zone, where drivers can be faced with a genuine dilemma of braking sharply or running the red.

MOVA should fully cover the decision zone with the IN-detector being eight seconds ‘cruise speed’ from the stop line, as should triple-SD and SA, at least up to the recommended 85th percentile maximum approach speed of 65 mph for signal-controlled junctions. It should be noted that MOVA implicitly avoids vehicles being caught in the decision zone and may partly explain why trials have shown significant reductions in red running compared with SA and SD (Vincent and Peirce, 1993), also SA and SD tend to run to the maximum green in moderate and high flows.

In the US, a new control strategy (D-CS) has been devised (Bonneson et al, 2002). Bonneson recognised that the Zeeger dilemma zone equates to around 2.5 to 5.5 seconds journey time from the stop line, and devised a strategy, which measures approach speed, to attempt to avoid green ending with vehicles in this area. The system optimises the green end time based upon vehicle delay, number of vehicles in the dilemma zone, closely following vehicles (a single vehicle should not be involved in a shunt accident), and the
presence of large vehicles. In this way the system tends not to run up to the maximum green, but chooses a reasonable time to end the green, given that complete avoidance of vehicles in the dilemma zone may not be possible. Initial results indicate that the system is able to provide equal or lower vehicle delays and significantly reduce the number of vehicles in the dilemma zone compared with traditional US ‘green extension systems’.

Large Goods Vehicles were over represented in the proportion of red runners. Some control strategies abroad have been developed to specifically address LGV’s in the ‘dilemma zone’, and it may be worthwhile utilising similar strategies in the UK.

9. CONCLUSIONS

The Webster and Ellson (1965) test track trials showed that acceptable stopping distances for the majority of drivers (90%) were found to approximately equate to a one second brake reaction time and an average deceleration of 3.6 m/s² (Baguley and Ray, 1989). The 90% acceptable stopping distances formed the upper boundary of the calculated dilemma zone. The Webster and Ellson (1965) results led to the high-speed road criterion of 35 mph 85th percentile speed for traffic signals.

This study showed that most drivers were not prepared to use decelerations as high as shown by Webster and Ellson, particularly at low approach speeds. Drivers stop-continue decisions were found to be largely based upon their journey time to the stop line at the onset of amber, not upon braking ability as found by Webster and Ellson.

The boundaries of the stop-continue decisions are about 2.5 and 4.5 seconds journey time to the stop line at the onset of amber for all approach speeds between 35 and 55 mph, based on the 10 and 90% stopping probability distances. At 60 mph the 90% of drivers stopping boundary was recorded at just over 5 seconds journey time from the stop line.

This consistent journey time to the stop line relationship over a range of approach speeds indicates that faced with an amber on ‘high-speed’ roads the vast majority of drivers base their stop-continue decision on whether they believe they can safely continue, rather than safely stop, as per the Regulations.

The propensity to red run was found to be high. About three quarters of drivers on high-speed roads continued when their journey time to stop line was three seconds at the onset of amber (i.e. risk running the start of red), and most red runners could have stopped without undue braking. Only one driver observed running the red by more than one second required a deceleration above 3.5 m/s². A small percentage (4%) of red runners ran the red by more than two seconds.

Large Goods Vehicles were about one-and-a-half times more likely to run the red than other vehicle types, and run the red later.
In-service Large Goods Vehicle braking performance is much lower than cars, with some unable to achieve the stopping distances derived by Webster and Ellson.

Three of the five study sites were on 70 mph roads. While there were some site characteristics which could have kept approach speeds down, the relatively few vehicles with approach speeds of 60 mph and greater may well reflect that most drivers approach traffic signals on the highest speed roads with some caution.

There is no indication that improvements in vehicle technology in the last 40 years have made drivers more willing to accept higher average decelerations on the approach to traffic signals. Compared with the Webster and Ellson results, the decelerations that drivers are prepared to accept have decreased at all but the highest speeds, and the distance from the stop line at which drivers decisions vary have got further away from the stop line.

Given driver behaviour and some low in-service LGV braking levels, there appears to be no warrant to relax the UK high-speed road criteria.

**BIBLIOGRAPHY**


Blackman, A. R. (1960) *Driver Behaviour during the amber period of traffic lights (3) Response times*, Road Research Laboratory, Research Note RN/3884/ARB (Unpublished).


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