**Quantitative Modelling in Cognitive Ergonomics: Predicting Signals Passed At Danger**

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**Abstract.** This paper shows how to combine field observations, experimental data, and mathematical modeling to produce  quantitative explanations and predictions of complex events in human-machine interaction. As an example we consider a major railway accident.In 1999 a commuter train passed a red signal near Ladbroke Grove, UK, into the path of an express. We use the Public Inquiry Report, "black box" data, and accident and engineering reports, to construct a case history of the accident. We show how to combine field data with mathematical modelling to estimate the probability that the driver observed and identified the state of the signals, and checked their status. Our methodology can explain the SPAD (“Signal Passed At Danger”), generate recommendations about signal design and placement, and provide quantitative guidance for the design of safer railway systems speed limits and the location of signals.

**Practitioner summary.** Detailed ergonomic analysis of railway signals and rail infrastructure reveal problems of signal identification at this location. A record of driver eye-movements measures attention, from which a quantitative model for out signal placement and permitted speeds can be derived. The paper is an example of how to combine field data, basic research and mathematical modelling to solve ergonomic design problems

**Keywords**

Railway ergonomics, cognitive ergonomics, accidents, attention dynamics, mental models, eye movements, mathematical models

**Introduction**

When we analyse complex human-machine interactions in real life situations such as accidents, the reports are typically narrative accounts together with data from such sources as black boxes. These are related to data from site surveys, task analyses, ergonomics handbooks and data bases. Quantitative measures are usually  statistical means, and we try to explain  events in relation to population statistics. In this paper we show how a much more detailed quantitative methodology is possible. We use the field study and narrative reports to identify cognitive processes that are relevant to the events. We then use empirical observations and experiments to estimate how cognitive activity puts quantitative limits on human performance.  We develop mathematical models for the interaction of cognition and the environment, even in dynamic situations.  By combining field data, empirical data, and mathematical modeling we can account for the events that occurred at the level of real-time performance of an individual worker, and make highly specific design recommendations to improve safety and efficiency in the human-machine systems performance. The approach we recommend can in principle be applied to any “real life” situation, as distinct from mere laboratory studies, but the particular empirical studies needed and the choice of mathematical models will of course vary with the situation investigated.  As an example we consider a major railway accident.

On the 5th October, 1999, a commuter train left Paddington Station, UK, heading west ("down") driven by Michael Hodder, a fully qualified but relatively inexperienced train driver. Less than three minutes later, near Ladbroke Grove station, the train crossed several tracks from right to left, under the control of signals displayed on overhead gantries straddling the tracks. The tracks to be crossed included “up” (towards London) and “down” (away from London) lines for high speed express trains, and on those tracks expresses could be travelling at up to 100 miles per hour (160 kph). Other tracks carried local or commuter trains. Hodder should have stopped his train as he crossed the lines, because a signal associated with his track showed a red aspect ("R"). The record shows that his train initially slowed, but then accelerated through the red light resulting in a Signal Passed At Danger (SPAD). Just over half a minute later an upbound express arrived at high speed and a catastrophic crash occurred.

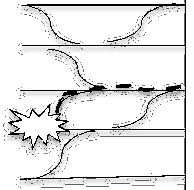
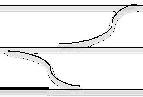
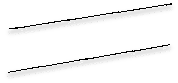
A diagrammatic summary of these events is shown in Figure 1. Note that the figure is not to scale. Further details of the engineered system characteristics and infrastructure are given in the text.

The Public Inquiry (*The Ladbroke Grove Rail Inquiry*, Cullen, 2000) sought input about human factors in order to understand why Hodder had passed the light at red. The first two authors were retained as expert witnesses by the rail Unions. The following paper is based mainly on their investigations at the time of the enquiry and later studies and analysis. The third author was retained as an expert witness by Network Rail and has reported analyses of the incident previously (Stanton and Baber, 2008; Stanton and Walker, 2011).



|  |  |  |
| --- | --- | --- |
| BRAKES! |  | applies power coasts |
| 51 mph | 45 mph | 38 37 36 mph 40 mph! |

Figure 1.



GANTRY 8

GANTRY

UP MAIN

Speed limit 80 mph 

Speed limit 60 mph

Record of Hodder’s train control actions and speeds

Schematic of track layout near Ladbroke Grove, with signal settings and record of speeds reached by Driver Hodder. Not to Scale. Distance between signal gantries is 600 metres. Tracks weave left and right over this distance so visual alignment of signals with tracks changes frequently (see Figure 3). Signals are to the left of the track to which they apply.

Signals at R shown as white stars on gantries. Signal at Y shown as double ring. Dashed line is route of Hodder’s train.

The ‘Black Box’ data from the train were recovered and are displayed in Figure 2. The main events are coded as follows:

a = Speed control notch 1 selected

b = Speed control notch 2 selected

c = Speed control notch 3 selected

d = Speed control notch 4 selected

e = Speed control notch 7 selected

f = SN43 AWS horn activated - green aspect - line 4 indicated

g = SN63 AWS horn activated - double yellow aspect

h = Speed control notch 0 selected + brake level 1 applied

i = brake level 1 released

j = SN87 AWS horn activated - single yellow aspect - position line junction indicator number 1

k = Speed control notch 5 selected

l = SN109 AWS horn activated - red aspect

m = Speed control notch 7 selected

n = Speed control notch 0 selected + emergency brake applied



Figure 2. Speed profile of train with main events denoted

**Considerations of system infrastructure.**

1. *Signal Conventions****.***

Signals are identified as SN*n*, where *n* is a number. The signal at which Hodder should have stopped is SN109, displayed on Gantry 8. Signals on this section of trackcan show one of four states (called ‘aspects’ in the industry), Green (G), Double Yellow (YY), Yellow (Y), or Red (R). The usual geometry of signals, as seen on all the signal gantries between Paddington Station and SN87, (the last signal prior to SN109 at which the SPAD occurred,) is shown in Figure 3. Four lamps are presented in a vertical column, just to the left of the left-hand rail, typically at a height of greater than 3 metres above the rail. A lamp subtends about 6’ of arc at a distance of 275 yards (250 metres). An R aspect has a single red light at the bottom of the column, and requires the driver to stop the train before reaching the light. On a Single Y aspect the driver may proceed, but must be prepared to stop, as the next signal is at that time R. On a Double Yellow aspect, YY, the driver may proceed without slowing, and should expect the next light to show G, YY, or Y. On a G aspect the driver may proceed at full speed. Speed limits are usually shown on trackside signs to the left of and about 1 metre above the rail. Where multiple tracks are present most signals are displayed just to the left of his track as viewed by the approaching driver, on gantries that straddle the whole extent of the tracks. Some are displayed on vertical metal standards, cantilevers or lattice poles.



5

4

33

2

1

6

1

2

3

4

5

6

Figure 3. The tracks approaching SN109, showing the difficulty in identifying the signal aspects and their relation to tracks. The lower numbers identify the tracks. The upper row show the signals that correspond to the tracks with the same numbers. These numbers have been added to the picture by the authors. The gantry on which they are mounted is *well* *beyond* the prominent white road bridge, which is why only SN105 shows all 4 lamps. (See also Figure 1.) Note the difficulty of identifying signal with track, that two of the signals are completely obscured by structures on the gantry, and that one or more of the lamps several signals are also obscured. The lamps have been drawn to make their position clearer. In reality they are much less visually prominent at this point. White stars are red lamps. White circles are yellow and green lamps. The positions, not the aspects of the lamps are shown. The rightmost tracks and signals are masked by the frame of the window.

2**.** *Track Layout*.

The track layout dates from the 19th century, at the time of steam engines and mechanical signalling systems. Main line electrification began in the late 20th century, and the system was electrified using overhead catenaries to supply current. After leaving Paddington station there are up to eight tracks, shared by up and down lines. There are many places where if the points are set appropriately a train will pass from one track to an adjacent track. The points and signals are set and coordinated by the signalling system that functions independently of the driver of the train, who is required to observe and react to signal aspects as the train passes along and across the tracks. A detailed analysis of the signaling control system and its personnel relevant to Hodder’s SPAD is given by Stanton and Baber (2008). On the section of track from Paddington to Ladbroke Grove the lines curve sinuously left and right. (That is, they are not straight as shown in Figure 1.) It is often difficult to tell which signal refers to which track, because the line of sight straight ahead of the cab may be to the right or left of all signals, or towards some point along the gantry.

3. *Supporting Infrastructure*.

Several road bridges carry foot and automobile traffic across the railway. SN109, the signal that resulted in Hodder's SPAD, was one of seven signals on Gantry 8 (numbered from the departure from London’s Paddington station). Other structures carry insulators and support electrical power catenaries, and during the approach to signals some or all signals are sometimes obscured by electrical equipment, bridges or gantries, other structures, foliage, etc. until a train is within one or two hundred metres of the signals. (See Figure 4.) To identify the signal relevant to their track drivers must often "count across" the tracks and signals, pairing them off one against the other.

At the time of the accident most trains were fitted with an Automatic Warning System (AWS) that sounds a horn in the driver's cab if a signal showing a non-G aspect is approached, or if a speed limit is approached. A bell sounds if a G aspect is approached. The AWS therefore distinguishes between a G aspect and any other aspect, but does not distinguish among Y, YY, and R aspects. This auditory signal is driven by contact closure when a train passes over a magnet placed between the rails, some 185 metres (202 yards) before the signal.

**Y**

**Y**

**R**

**G**

**Y**

**Y**

**R**

**G**

(4a) Standard 4-Aspect signal (4b) Geometry of signals on the

gantry carrying SN109

Figure 4. Signal Geometry

**The time line of the SPAD and collision**

The following summary is based on evidence in Cullen (2000) and on reports from the black box recorder as analysed by the engineering consultants WS Atkins (1999, 2000a,b,c,d,e,f) and cited in the Cullen report. It covers events from the moment Hodder passed signal SN87, the last signal relevant to his route prior to SN109, until the moment of the collision.

There were no “trackside distractors” such as pedestrian intruders or maintenance operations , although as figures 5-7 show the signals are masked by a bridge on approach and a speed sign is displayed. The sun was low above the horizon, very bright, and shining onto SN109 from *behind* Hodder.

Hodder's train passed SN87 at a speed of about 40 mph. No speed control notches on the driver’s console were engaged. SN87 was showing a single yellow aspect (Y). Since Hodder was coasting, not accelerating or braking, it is probable that he saw the Y aspect on SN87, since a Y aspect means that the following signal may show a red aspect (R), and requires the driver to prepare to stop the train before that next signal. Hodder shortly afterwards engaged the speed control Notch 1, suggesting that he had decided to accelerate. At about 260 yards (239m) before SN109 he engaged Notch 5 and began to accelerate from a speed of 37 mph. An emergency brake application (a braking rate of 12% *g*) at this point would have stopped the train in approximately 137m (150 yards) but slowing was unlikely to have been his intention. Hodder acknowledged the AWS horn associated with SN109 before reaching the latter, and SN109 was showing a R aspect. Approximately 4 seconds after the horn sounded (see Figure 2), at about 104m (113 yards) before SN109, Hodder engaged Notch 7 and continued to accelerate. Stopping prior to the signal was now impossible. He passed SN109 with power still engaged at a speed of just over 40 mph. He applied the brakes at a speed of 51 mph (82kph) presumably on seeing the HST ahead, but by then the 250m (273 yards) of clear track that would be required for the emergency braking to prevent the accident was no longer available.



Figure 5. Approach to SN109, note that bridge is masking signal gantry



Figure 6. Approach to SN109, note that signal gantry is revealed behind bridge



Figure 7. Approach to SN109, note that signal gantry is completely revealed

**Statement of problem**

1. Did Hodder correctly perceive the aspect of the previous signal SN87, did he forget it, and if so would this account for his SPAD at SN109?
2. Did Hodder fail to see SN109 or did he misidentify the aspect of SN109 on first seeing it? Did he fail to check it again during his approach; and if so, why?
3. Why did Hodder not interpret the AWS alert as indicating a danger aspect that required him to prepare to stop? Why did the signalling system not respond to his SPAD?

The most relevant cognitive and ergonomic factors are:

1. The extent to which the layout of track, infrastructure and signals in the approach to SN109 impeded the visibility and interpretation of the signal state.
2. The role of the driver's mental model of the route and his expectations of the upcoming signals.
3. The high demands on dynamic visual attention.
4. The fact that the AWS gives the driver ambiguous information.

*The role of SN87*

The fact that Hodder coasted past SN87 suggests that he had correctly identified the Y aspect of SN87, and was therefore expecting the next signal to be Y or R. There is a strong belief in the UK railway industry that drivers have almost perfect route knowledge of the routes they drive, and that these mental models (Moray, 1990; Moray, 1997; Revell and Stanton, 2012) are vital components of their skill as drivers. Their long term mental models are thought to include the layout of the track, the times and places at which signals will appear, the location of speed limits, and the probability ofother rail traffic. Short term mental models are thought to include the aspects of signals recently passed, and hence the probable state of upcoming signals, expected switches from track to track, expected occurrence of auditory AWS events and their implications, etc.. Mental models are assumed to be used to predict imminent events and to plan appropriate responses. In theory, drivers could rely on strong mental models to reduce the need to scan the environment for information, thus reducing workload. Railway personnel commonly assert that experienced drivers will anticipate when a signal is due to appear and will be looking in the correct direction to see its aspect as soon as it appears. These claims support a strong belief in the high quality of drivers and imply the use of mental models. Reliance on mental models would also account for how drivers can be fixating the location of a signal before it appears. That drivers use mental models in this way is an assertion of faith, since at the time of the Cullen enquiry no empirical evidence existed about the distribution of train drivers' eye-movements or any other measure of their dynamic attention or working memory. While the explanation for the SPAD in this paper emphasizes overload in the driver’s visual attention, other explanations have been proposed, such as that by Stanton and Walker (2011).

*The dynamcs of visual attention in train driving*

We will estimate the cognitive workload on the driver by measuring eye movements. This is an uncommon technique, but very powerful. In particular it allows us to investigate the moment to moment cognitive load in detail for a single driver. There has been other research into driver mental workload using interviews, subjective ratings, focus groups and similar methods ( Zoer, Sluiter, and Frings-Dresen, 2014; Naweed, Rainbird, and Chapman, 2015). Such studies lead to qualitative models of mean performance at best, and resemble the classical research supported by NASA on pilot workload in the period 1970 – 1990 (see, e.g. Moray, 2008). But those methods do not allow detailed real time modelling of cognition. Balfe, Wilson, Sharples, and Clarke (2012) believe that

“Ethnographic, naturalistic observation

and structured interview methods can provide insights

which may never be achieved with quantitative

methods.”

In this paper we emphasise quantitative methods, because they allow mathematical modelling, since in real tasks visual attention depends on the dynamics of eye movements, and it is well known that people have little or no idea of the patterns of their eyemovements, and are always very surprised when shown eyemovement recordings (Moray, Neil, and Brophy, 1983). Quantitative design recommendations require quantitative analysis of behaviour and performance. We do not deny that qualitative methods can answer qualitative questions (Annett, 2002).

Since the Cullen inquiry there have been two extensive and detailed studies of train drivers' visual attention. Both analysed driver eye movements recorded in the real situation of driving commuter trains on real routes (Groeger, et al 2006; Luke et al., 2006). The quantitative data from these studies agree closely with each other. In this paper we will use the quantitative data from the study by Groeger et al. (2004). The drivers, who took part in the experiment voluntarily and with the agreement of their Union, wore an eye camera that recorded the view in the direction of the driver's line of regard, and superimposed on the video recording a marker that indicated the point of fixation. They drove over a standard route on the Thameslink Bedford to Brighton line between St. Albans and East Croydon that included both rural commuter lines and a route through London, with many stations and signals. The journeys were part of the drivers’ normal duty roster.

Groeger et al. (2004) summarise their qualitative analysis in Table 1 based on 470 approaches to signals, using 10 experienced drivers who were all familiar with the route. Their study did not include the section of track from Paddington to Ladbroke Grove, but enough signals were passed (470), and enough drivers (10) were observed to establish sound statistical estimates of typical behaviour. They were driving commuter trains similar to that driven by Hodder from Paddington. From their data we can reasonably generalize to the Ladbroke Grove situation, although the fact that SN109 is a multi-SPAD signal, that is several drivers had committed a SPAD at the same location, means that there may be something special about it.

Table 1 Distribution of train drivers' eye movements.

|  |  |
| --- | --- |
| Category | Individual objects & object locations |
| Own Signal | Own signal (separately coded for ‘looks’ within 1, 2 and 4 degrees of signal)  Own direction indicator |
| Other Signal | Signals to the left and right of driver’s own signal (on the same gantry)  Upcoming signal on the same line as driver’s own signal Upcoming signal to the left or right of driver’s own signal  Direction indicators to the left or right of the driver’s own signal |
| Own Gantry | Any position on driver’s own gantry, except the signal |
| Other Gantry | Any signals not facing the driver  Any gantries to the right or left of driver's own gantry |
| Signage | All speed restriction signs AWS magnet  TPWS grid CDRA sign  Station TV monitors Station clock  Station electronic train information screen Platforms to the right and left |
| Moving Objects | Travelling trains to the right and left of the driver Station or track crew |
| Off Track | Fields to the right and left Verge between track and fields Trees  Oncoming bridges and city buildings Tunnel wall and ceiling |
| Track Ahead | Driver's own track  Track to the left or right of the driver |
| Sky | The sky |
| In Cab | All objects and controls inside cab Driver's own window  Side windows Instructor |

All the categories in Table 1 are needed to classify the distribution of driver visual attention. It is obvious from Table 1 that the dynamics of driver attention make it very unlikely that drivers will always be looking towards a signal at the moment it appears. Groeger et al. (2004, p.iii). state that:

“The final 15 seconds of the approach to several hundred signals was analysed in detail. Despite the quantity of data collected, considerable variation in viewing behaviour (i.e. differences between drivers at the same signals, differences when the same driver viewed different signals) severely limits the generality of the findings, and the implications that can legitimately be drawn from them.

That acknowledged, the tentative indications are that drivers look at signals for the first time about 8 seconds before they are reached, thereafter signals are looked at on a number of separate occasions. About half of the 15 seconds before a signal is reached is spent ‘fixating’ on objects (i.e. glances lasting at least 0.12 seconds), 20% of the approach time is spent looking at signals. The timing of the first look at a signal and distribution of glances and fixation time across the approach depends on:

the signal aspect — cautionary signals are looked at earlier and for more time overall (i.e. adding duration of all fixations together);

the signal mounting — signals on gantries are looked at earlier and for longer;

the aspect of the signal-in-rear — having passed a SingleYellow or Red, the driver looks at the upcoming signal sooner.”

During the last 15 seconds of a continuous approach to a signal there are some 25 items of the visual environment to which attention may be paid (Table 1), and Groeger et al. reported that,

"substantial numbers of first looks at signals are made *after the AWS has sounded[[4]](#endnote-1)*".

That means that the drivers' attention is often drawn by the Automatic Warning Signal to the appearance of the signal: drivers were not already looking towards the signal when it appeared, contrary to what is widely believed in the industry.

These data on visual attention to signals are relevant to the analysis of the crash in two ways. First, they allow us to estimate the probability that the signal SN109 was observed at least once, twice, etc.. We can estimate the probability that Hodder looked at the signal at all, and that he checked its aspect in the time between its appearance and the arrival of his train at the signal. We will return to this calculation below.

Second, the data show that what is seen interacts with the driver's mental model to affect his or her expectations (Plant and Stanton, 2012; Rafferty et al, 2013; Revell and Stanton, 2012; Salmon et al, 2013). Drivers are taught to drive "defensively", so if a signal has a Y aspect they prepare to stop at the next signal which will probably have an R aspect when they reach it; while a G or YY aspect allows them to assume that they will not have to stop at the next signal (Stanton and Walker, 2011), and can proceed at the current speed or accelerate to their desired running speed.

Long-term expectations become part of the “route knowledge” contained in drivers' mental models. On this route a driver will expect 4–aspect signals to have lights in a vertical column, reading Y–G–Y–R from top to bottom, as in Figure 2a, since all signals between Paddington station and Gantry 8, which carries SN109, have this standard form, as do most other signals. The time of day will also produce expectancies about the density of train traffic en route, and hence the likelihood of conditions where cautionary aspects (Y, R) will predominate on certain sections.. Short-term expectations will depend on perceptions made during the journey. If a driver has almost always driven over a stretch of track in which the signals show a green aspect, his long-term expectations will predict that to be the case again. If however he encounters a Y-aspect instead of the usual green-aspect, his expectation as to what he will see at the next signal should be altered, and that short-term expectation will be held in working memory (WM), and will bias what he expects to see and what he expects to happen next: the predictive nature of railway signaling encourages this. As is well known the contents of WM are volatile and easily disrupted by the arrival of new perceptual information or recall from long-term memory (Reason, 1990). So the association of features in the environment interacting with expectations can lead to strong-but-wrong assumptions about the state of the world (Moray, 1990).

The W.S.Atkins report (1999) shows that Hodder's recent experience would not have led him to expect problems at SN109. A record of 21 recent journeys by Hodder when approaching Gantry 8 was analysed: 17 involved SN113, 2 involved SN111, and 2 involved SN109. Of these, SN109 once showed a G, (onto Down Main), and once showed a R aspect (when the SPAD occurred). All the other approaches showed a G aspect to proceed onto the Down Relief. Nothing in this experience that would have caused Hodder to develop a strong mental model for special attention to SN109, and the overwhelming evidence, with a probability of 19/20, p = 0.95, is to find a signal at Gantry 8 to be showing a G aspect. We may conclude that both Hodder's long and short-term mental models would have primed him to expect a non-R aspect at Gantry 8. The AWS sounding on approaching SN109 would not change this expectation, since that morning all the signals after leaving Paddington had shown G, Y or YY aspect, and the AWS warning sound does not indicate R, but merely a non-G aspect. Hodder acknowledged the AWS within approximately 0.5 seconds suggesting he expected a Y or YY aspect at Gantry 8. Indeed, Stanton and Walker (2011) make a similar case when comparing alternative explanations for the behaviour of the driver. By comparing the driver’s response time to other signals, they show that the driver’s cancellation of the AWS warning at SN87 and SN109 was approximately half of that to SN63 (and earlier signals on the route).

*Empirical data on visual attention*.

In real-world tasks visual attention is allocated by eye movements. See Jones, Milton and Fitts (1949) and Senders (1964) for classic examples. The train drivers' task is made difficult by the visual complexity of the environment, mechanical vibration in the cab, the rapid change in the visual array due to the movement of the train, and the fine detail both in structure and colour of visual information. For example, on a signal sighted at a distance of 250 metres the lamp subtends less than 0.1 degree, (about 6' of arc). For a driver to see accurately the colour and detail of such a signal it must be foveated, that is appear within 2o of the centre of fixation, (Abramov, Gordon, and Chan, 1991; van Esch, Koldenhof, van Doorn, and Koenderink, 1984). Moreover there is some evidence that information is only read into the brain when the image on the retina is static, although eye movements are needed to prevent the fading of the image (Ishida and Ikeda, 1989; Henderson, 1993). In laboratory studies eye movements may occur several times a second, but such values are extremely rare in real-world tasks where fixations of up to several seconds are common (Moray and Rotenberg, 1989; Moray, Neil and Brophy, 1983). When a visual task involves fine discrimination or information of low probability, the duration of fixation increases and the frequency of eye movements decreases (Senders, 1964; Senders, Elkind, Grignetti and Smallwood, 1965).

Groeger et al. (2004) report several statistics of eye movements associated with the different categories of data in Table 1. Tables 2 - 4 are derived from their report. We have added a measure of the range of the data, by showing values associated with +/- 1 standard deviation about the means. Does the design of the railway system impose a cognitive load on a driver that is so unreasonable that he may be led into making errors?

Examine Table 4. On the average when approaching a single yellow signal drivers first looked at that signal when about a quarter of the way to it from the point where it first appeared (mean proportion of distance remaining = 0.76, sd = 0.28). It would not therefore be unusual if a driver did not first look at the signal until he had covered half the distance from where it was first visible, since 68% of the data fall within the range 0.48 to 1.00, that is ± 1.0 sd. The data suggest that about 16% of Groeger’s drivers when approaching a Y aspect did not fixate it until they had traversed nearly 1/2 of the distance to it from where it first could have been seen had they looked at it.

From Tables 2 – 4 we should expect that as a signal is approached drivers will spend more than 78% of the time looking at non-signals on about 16% of occasions, and hence only 22% of the time looking at signals.

When approaching a Red aspect drivers tend to make their first fixation earlier, presumably because of their mental models, but the statistics suggest that on about 2% of approaches drivers do not first fixate the signals until only about one third of the distance to the signal remains (mean = 0.81. sd = 0.25; therefore 2 sd = 0.5, and 0.81– 0.50 = 0.31.) The fact that 2% is a small probability is irrelevant: fortunately SPADS are rare events.

Table 2. Proportion of time spent fixating signals being approached

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Non-signals |  | Signals |  |
| Aspect being approached | Mean (s.d.) | Range +-1sd | Mean (s.d.) | Range +-1sd |
| Green | 0.50 0.28 | 0.22 - 0.78 | 0.16 0.14 | 0.02 - 0.30 |
| Double Yellow | 0.43 0.19 | 0.24 - 0.62 | 0.22 0.12 | 0.10 - 0.34 |
| Single Yellow | 0.41 0.21 | 0.20 - 0.62 | 0.21 0.15 | 0.06 - 0.36 |
| Red | 0.44 0.21 | 0.43 - 0.63 | 0.22 0.19 | 0.03 - 0.42 |

Table 3. Fixation durations in seconds[[5]](#endnote-2).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Non-signals |  | Signals |  |
| Aspect being approached | Mean (s.d.) | Range +1sd | Mean (s.d.) | Range +-1sd |
| Green | 0.91 0.44 | 0.47 - 1.35 | 0.40. 0.31 | 0.09 - 0.71 |
| Double Yellow | 0.79 0.35 | 0.44 - 1.34 | 0.47 0.26 | 0.21 - 0.73 |
| Single Yellow | 0.76 0.37 | 0.39.- 1.13 | 0.46 0.29 | 0.17 - 0.75 |
| Red | 0.75 0.24 | 0.51 - 0.99 | 0.43 0.31 | 0.12 - 0.74 |

Table 4. Mean proportion of time remaining until the signal is reached after the first fixation following the signal first becoming visible

|  |  |  |  |
| --- | --- | --- | --- |
|  | Mean | s.d. | Range +-1sd |
| Green | 0.59 | 0.33 | 0.26 - 0.92 |
| Double Yellow | 0.73 | 0.28 | 0.45 - 1.01 |
| Yellow | 0.76 | 0.28 | 0.48 - 1.04 |
| Red | 0.81 | 0.25 | 0.56 - 1.06 |

(A value of 0.81 means that when the first fixation on the signal occurs, 19% of the time between its first appearance and the moment it will be passed has elapsed. We can use the s.d. to define the Range covered by +-1 sd, but  values greater than 1.0 have no meaning and will not occur in recorded data).

SN109 is mounted on Gantry 8, which carries another 6 signals. (But note an important exception, SN105, to be discussed later.) On approaching Gantry 8 overhead equipment such as electric insulators, catenaries and bridges cause signals to appear in the following sequence. The R aspect of SN105 first becomes visible at a distance of 496 m (542 yards), that of SN107 at 349 m (381 yards), that of SN115 at 327 m (357 yards), that of SN113 at 263 m (287 yards), and that of SN111 at 248 m (271 yards).

“The red aspect of SN109 begins to appear from behind a large OLE insulator (See Figure 3.) when the distance to the gantry is 219 metres.” (Atkins, 1999).

In Figure 3, based on a photograph taken about 250 m (273 yards) from Gantry 8, the first three and the sixth signals are visible, but two are hidden by insulators carrying the catenary cables or by the road bridge. The later the first fixation, the less time there is for a second fixation to check the signal aspect before passing it. At the moment that SN109 became permanently visible at a distance of 168 m (183 yards), Hodder’s train was traveling at 38 mph (61 kph). If on that occasion Hodder did not look at SN109 until half way to it, only 94 m (102 yards) remained, and that distance would be covered in about 5 seconds. If Hodder behaved as Groeger’s drivers did on the average, and spent only 20% of the time looking at the signal, then he would only have about 1 second to examine SN109, (0.2 x 5.0 = 1.0). This would barely allow time even for one fixation on SN109, and would certainly afford no opportunity to recheck the signal, bearing in mind that signals are fixated for about 500msec, to which the time for an eye movement to that fixation would have to be added.

If the aspect of SN109 is so critical, why would not the driver keep his attention on the signal from the first time he fixates it until he passes it? Table 1 shows that he distributes his attention over more than 20 features of the driving environment when driving defensively, and to do so he must switch his attention from one part of the visual environment to another. Furthermore it is known that drivers “count across” to determine which signal refers to which track. Even if counting across can be done without moving the eyes, Trick and Pylyshin (1994) suggest that this may require a subitising time of more than 250 msec. The data in Tables 2 and 3 show that in the last 15 seconds before passing a signal drivers fixate the signal for only about 20% of the time. For another 44% of the time they are fixating other parts of the environment (track side, rails, speed signs, oncoming trains, information and equipment inside the cab, etc). The remaining 36% of the time they are not fixating anything: their eyes are moving, and therefore acuity will be much reduced.

Groeger et al. (2004, p.iii) report

“…20% of the approach time is spent looking at signals”

and,

“On those approaches where the last 15 seconds were coded (a total of 154), an average of 17.05 fixations were made, lasting, on average, for 9.44 seconds. That is, there were 1.14 fixations per second of approach, and 63% of all approach time was spent fixating on various objects, with the remaining time spent scanning the visual scene. Perhaps not surprisingly, these figures vary with the length of the approach, with more fixations being made but the proportion of the approach when drivers were fixating remaining similar throughout.”

(Groeger et al. p. 14.).

The way in which signals are mounted also has a considerable effect. Groeger et al. report that signal fixation, averaged across all signals, irrespective of aspects, signal mounting, preceding signal, etc., is about 520 msecs (sd = 400). Mean signal fixation is dramatically affected by the nature of the mounting. The mean times are approximately 380 msecs for a lone signal on a post, 340 msecs for one of a pair of signals on a cantilever, and 450 msecs for one signal among a group on a gantry. Total duration of fixations are similarly affected by signal mounting: post, 600 msecs; cantilever, 660 msec; gantry, 780 msecs. This suggests that a situation such as SN109 where there are several signals on a gantry will adversely affect rapid scanning.

Table 2 shows that about 22% of time is spent looking at signals, and about 44% of time looking at non-signals. These are equivalent to about 3.3 seconds (out of 15 seconds) and 6.6 seconds (out of 15 seconds) respectively. At 38 mph, it takes only 11 seconds to cover the 198 metres to SN109 from when it first appears. Groeger’s data suggest that there would be an average of fewer than 2 fixations on signals and about 5 fixations on non-signals during the last 15 seconds of an approach to a signal. Taking into account the values of the sds in Table 2, and averaging over all 4 signal aspects during the last 15 seconds of the approach, it seems that on at least 16% of approaches less than 10% of the time (that is less than 1.5 seconds) will be spent looking at signals. There will be as many as 16% of approaches where a driver will not have time for more than one look at the signal that he is approaching. If that look should, for whatever reason, lead to an incorrect identification of the signal aspect, there will not be time for a second look to correct that judgement, and the signal will be passed with the driver having an incorrect judgement of the aspect.

We emphasise that such behavior would not be due to a driver’s incompetence, lack of motivation, or lack of training. Rather it is a mark of well developed driving skills and their associated mental models. It would be caused by the interaction of the design of the rail system (track layout, signals, train schedules, required speed, etc.) with the inherent properties of the human nervous system that limit the rate at which the environment can be visually attended. Even a well–trained, highly motivated, driver will suffer from these limitations (W.S. Atkins, 2000; 99817B).

We may conclude from the quantitative analysis by Groeger et al. (2004) that there is is a very real possibility that Hodder had time only for one visual sample of the aspect of SN109 as he approached it. In addition, because of the electrical hardware, bridges, gantries etc., the signals become visible progressively, and given the curvature of the tracks and the fact that Hodder's train was crossing from right to left, there would be considerable difficulty in identifying which signal was relevant to which track. (See Figure 3.)

*Why would Hodder fail to identify correctly the aspect of SN109?*

The standard design of a 4-aspect signal is a vertical column of four lamps in order from top to bottom Y, G, Y, R. It is standard practice that the heights of the lamps above the rails should be identical for the several signals on a single gantry. If a driver scans laterally across the gantry, the R lamps will all be in a horizontal line, and similarly for the other kinds of lamps. Uniquely on this route at Gantry 8 both these expectations are violated. The leftmost signal is a 4-lamp vertical column, but this signal is not attached to Gantry 8. It is separate from the gantry, and the lamps are lower than any of those on Gantry 8, which are aligned horizontally as would be expected. Moreover, the sets of lamps on Gantry 8 have an abnormal geometry. They all have a unique "Reversed-L" geometry probably because of the spatial constraint on the location of the signals. During the approach the structures of the bridge and of the electrical equipment obscured signals on the gantry from time to time. The R aspect light of SN109 was obscured partially or wholly until the driver was quite close to the signal, at about 168m (183 yards).

Since the normal geometry of signals is a vertical array with red at the bottom, this is what the driver’s mental model would predict and the driver consciously expect. If the red aspect, although illuminated, could not be seen because it was obscured by the bridge or by insulators, then the driver, if paying attention to the vertical YGY lamps, might assume that red was vertically below the visible lights but not illuminated, rather than that it was illuminated, to the left, and obscured. As he neared Gantry 8 the driver could have seen other signals on that gantry, and would have been able, in principle, to note their abnormal geometry, and hence could have realised that an absent red aspect of SN109 might be hidden rather than absent, but this would violate a strong expectation of the signal geometry. This possibility furthermore depends on his having enough time to look at several of the signals, which we have seen is unlikely. Furthermore, a R aspect to the left of a Y but at the same level might be interpreted as being on a different 4-vertical signal beyond that carrying the Y aspect. Hodder may have interpreted what he saw of SN109 during the approach as indicating that SN109 was in a state of “not-R”. It is believed that the backscatter of the bright morning sun from the yellow lamp lenses probably did not "shine" like a Y or YY aspect, (a so-called "phantom" signal,) but in the absence of any visible R aspect, the appearance would have been ambiguous. According to official Sighting Standards the signal controlling a driver’s track should be adjusted such that it is the brightest signal on view. Although the backscatter of the sunlight from the lamp did not produce a “phantom” light, the bright morning sun may have saturated the color information available and may have caused the Y to be the most prominent if the R was not visible or was misinterpreted.

Interpreting a quick glimpse is made even more difficult by the free-standing SN105 vertical-4 aspect signal to the left of Gantry 8. This is the first signal to become visible as Gantry 8 is approached (Wilkins in Atkins 99817A1). If this were the first signal that was fixated by Hodder, it would confirm his expectation that as usual R lamps were located below YGY lamps, thus further biasing his expectations about any other signals he might fixate. Wilkins (Atkins 99817A1) found that SN105 becomes visible at 496 m (542 yards) from Gantry 8, and it is evident from the photographs in the Cullen reports and those we took during a ride in a train cab (Figure 3) that the red aspect lamp of SN105 is substantially lower than those on Gantry 8, including SN109. The height of the red lamp of SN105 is 3353 mm above rail level. SN105 will therefore have appeared earlier because it was not occluded by the structure of the bridge that hid the higher lights on the gantry. The heights of the other R aspects on Gantry 8, including SN109, are all over 5000 mm above rail level. SN109 is at 5085 mm, and the others differ only slightly from that value. Another question concerns the cognitive demands of “counting across”, which was mentioned earlier (Trick and Pylyshyn, 1994). Potential confusion may occur about whether to include the off-gantry signal in any count. If drivers in a dynamic rather than static viewing context tend to rely on enumeration rather than estimation that will complicate the driver’s task further.

As the train passed over the points from Line 4 to Line 3 it would have tended to point towards SN105 which would have been prominent. The default expectation of a driver on seeing one of a set of multiple signals at a single location will be that if one is visible the others should be visible at the same height, because of the design doctrine of “parallel” location of signals. If SN105 was seen by Hodder to be showing a R aspect, and if he were then to look rapidly across the lines at the same height above the ground as the red light of SN105 in order to see the other lights, no R aspects would be visible, since the other R lamps were at a higher level and some at least were concealed by infrastructure. (See Figure 3.) If his default belief was that they were at the same height, and if moreover his mental model was of the standard signal geometry, this would generate a belief that they must be showing a non-R aspect. This belief could have been corrected as the other signals came into view, but the British Railways Sighting Committee Report (1994) says that the R aspect of SN109 becomes unobscured only at 168 metres (183 yards).

*Did Hodder ever look at SN109? The probability of at least one fixation.*

We know from Groeger et al. (2004) that as a driver approaches a signal he spends a mean of about 22% of the final 15 seconds looking at the signal, and that the sd of that mean is about 15, if we change the proportions to percentages. This implies that the mean probability that the driver's first fixation is on the signal just after it first appears is about 0.22. Therefore the probability that the first fixation will *not* be on the signal will be (1.00 - 0.22 = 0.78). Hence the probability that none of the first *n* fixations after the signal comes into view will be on the relevant signal is given by (1.00 - 0.78*n),* and the probability of at least one of the *n* being on the signal is the complement of that number. Hence we can construct Table 5*.* “Own Signal” here means the signal that is relevant to the track on which the driver is travelling.

Table 5. Probability of at least one fixation on Own Signal as a function of the number of fixations.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Number of fixations | 2 | 4 | 6 | 8 | 10 | 12 |
| P that at least one will be on Own Signal | 0.39 | 0.63 | 0.78 | 0.87 | 0.92 | 0.95 |

We have already seen that there would not have been time to examine every signal on Gantry 8. After reaching a point 168 m (183 yards) from Gantry 8 Hodder will have made very few fixations before passing Gantry 8. At 38 mph the time to travel 168 metres would be approximately 9.5 seconds, which would allow for at most two fixations on SN109 if we take Groeger et al.’s mean value. If the train were travelling faster and if the driver were counting across to identify SN109 there would be even fewer fixations on the latter, the identification of SN109 might well be uncertain, and there would be no time to check its aspect by a second fixation.

It may be thought that the driver’s route knowledge would ensure that he would remember that the signals on Gantry 8 were of a “reversed-L” shape, and that if he had kept alert as required by defensive driving he would have been aware of this. But as Wilkins says in Atkins 99817B (20.25),

"Perfect signalling design and perfect sighting arrangements would demand little or no route knowledge on the part of the train driver. Conversely, the ideal in respect of SPAD risk minimisation would require drivers to possess perfect photographic knowledge of the many hundreds of signals along the routes over which they drive. Neither ideal is capable of achievement in the practical world, . . . it would be wholly unreasonable to expect drivers to learn in photographic detail all the complexities of signal viewing in a complex layout affected by significant OLE obstruction.”

The YGY column of lights on the vertical part of SN109, although probably not showing a phantom aspect, (Watt, 2000; Wilkins, Atkins 99817A1, 12.0-12.1), were reflecting very bright sunlight, and may well have been interpreted as a washed out Y or YY, given that SN87 had shown a Y. The colored photos available in Cullen (2000) do not show a phantom aspect, but nonetheless the surface reflection, in the absence of a clear R or G, might well be interpreted as a Y or YY, washed out by the sunlight, since they must be showing *some* aspect. If Hodder had decided that SN109 was “not-Red”, and did not see a bright G, this would further reinforce the memory carried from SN87 that the aspect of SN109 was Y or YY, and the reflected sunlight would reinforce this belief.

To summarise, we have two strong biases due to expectations from the past and current experience of the driver: because SN87 showed a Y aspect, Hodder expects a “not-green” and probably a Y aspect ahead. Groeger et al.’s drivers saw Y followed by R on about 50% of occasions. Data in Atkins 99823A suggest that when approaching SN109 from SN87, the probability of finding SN109 showing a G aspect is 0.70, finding it showing a Y or YY aspect is 0.07, and showing an R aspect is 0.22. The data are not sufficient to decide what the probability of each aspect would be conditional on a Y at SN87, but if we combine those data with Groeger’s, the probability of an R aspect at SN109, given a Y at SN87, would seem to be only about 0.11. A reasonable default expectation on approaching SN109 from SN87 showing Y would be that it would show not-Red with a probability of 0.89. If Hodder expected the red lamp to be below the YGY lamps, he would interpret his “not-R” perception to be due to an unilluminated red lamp below the lower Y lamp, not to a hidden illuminated red lamp to the left of the lower Y lamp. Note also that the reverse-L format at Gantry 8 means that the red aspect of each signal is not as close as possible to the line of sight (as is required by regulations). In fact the red aspect lamp of SN109 was 1505 mm to the left of the left rail running edge further violating default expectations (Atkins 99817A1, 10.5.10).

The Atkins report notes that,

“The fact that Hodder’s eyes apparently did not revisit SN109 should not be regarded as unusual; unlike road traffic lights, railway signals are not in the habit of reverting to red as a driver approaches. There is therefore a tendency for a driver to mentally “put a tick in the box” for a signal once it has been read and not to review the signal thereafter.”

That comment supports the analysis made in the present paper.

After a point about 168 m (183 yards) before Gantry 8~~,~~ the R aspect of SN109 remains permanently unobstructed and is clearly visible until the driver’s cab passes the latter, but it was not fixated again, because the dynamics of eye movements and the tactics of visual attention in this task did not allow it. The fixation times in Table 3 equate to about 0.5 seconds per fixation on signals, and about 0.8 seconds per fixation for non-signal items. Therefore *there would be an average of less than 2 fixations on signals and about 5 fixations on non-signals during the last 10 seconds of an approach to a signal*. From the values of the sds in Table 2, and averaging over all 4 signal aspects, we predict that on at least 16% of approaches less than 10% of the time (that is less than 1.0 second) will be spent looking at signals. That is, there is almost a 16% probability that not even 1 fixation will occur on the required signal during the final 168m approach to the signal, if Groeger et al.’s measurements of driver eye movements are typical. It should be stressed that they and those of Luke et al. (2006) which agree with them, are the only objective data available.

Fixation rates might have been greater (i.e. more fixations per second) had Groeger et al.’s measurements been taken at Ladbroke Grove, but this is rather unlikely given the complexity of the visual array on much of the Paddington–Ladbroke Grove route and that the duration of fixations increases with complexity. There is very little opportunity for a driver to take either several looks at the signal or one prolonged look, if he is also to pay attention to all the other aspects of the environment that are required to maintain situation awareness (Endsley, 1995; Stanton et al, 2006) and drive defensively (Stanton and Walker, 2011). Furthermore the magnitude of the sd means that even if our estimate of the proportion of time spent looking at signals during approach were out by 100%, so that proportion was really about 0.4, there would still be more than 15% of approaches during which signals are fixated for less than 20% of the time. The approach to SN109 when made at a speed around 40 mph (64 kph) is very demanding and places a heavy attentional load on the driver. Because of the unusual geometry of the signal and the way in which the signal is obscured from time to time, there will seldom be time for the driver to correct a misperception of the aspect of the signal.

*The role of the AWS*

Hodder acknowledged the AWS within half a second and then applied maximum acceleration. Why did he not brake? There would have been time for him to switch his gaze in response to the horn at least once; and we know from Groeger et al. (2004) that drivers often direct their attention to signals in response to an auditory signal from the AWS. Any explanation is necessarily speculative, but can be based on ambiguities in the AWS, whose design has two major ergonomic flaws. If a train passes the AWS magnet when approaching a G-aspect signal, a bell sounds in the cab. If the aspect of the signal is not G, a horn sounds. But there is no difference between the sound when approaching an R-aspect, a Y-aspect, or a YY aspect. The horn indicates “Signal aspect is not-G”. It does not indicate “Signal aspect is R”, which indicates immediate danger and a need to stop the train. That is a fundamental design flaw.

There is a second ambiguity in the AWS. It is sometimes used as a Permissible Speed Warning Indication (PSWI) when a driver approaches a speed limit. Wilkins (Atkins 99817B) notes that if Hodder thought the AWS was a warning for the 80 mph limit he would not have perceived it as a warning of the not-G aspect of SN109 and instead would have thought it appropriate to accelerate. The AWS is thus ambiguous in two senses, greatly reducing its effectiveness (Stanton and Walker, 2011).

If Hodder continued to monitor the whole driving environment to maintain situation awareness in accordance with defensive driving, he did not have time to look back at SN109. The AWS horn sounded, indicating that SN109 showed a “not-G” aspect confirming his mental model of YY at SN109. Groeger et al. (2004) found that 250 of the signals approached showed a G aspect (probability = 0.72), 15 a YY aspect (probability = 0.04), 52 a single Y aspect (probability = 0.15), and 29 a R aspect (probability = 0.08), (Groeger et al., 2004, p.18). The probability that any signal will show a R aspect is less than half the probability that it will show Y or YY. Hodder’s recent experience will have led him to expect “not-R” at Gantry 8 with a probability of 0.95. The horn confirmed his belief in the presence of a YY or Y aspect, and his past experience of this route did not lead him to expect an R aspect. He therefore did not direct his attention to the signal, but merely cancelled the horn .as a sign that an 80 mph speed limit was now applicable (Stanton and Walker, 2011). Although the displays in the signalling control centre showed the occurrence of the SPAD, the work of Stanton and Baber (2008) shows that there was not enough time for the signallers to intervene effectively before the crash occurred.

Finally, on the morning of the crash there would have been a powerful reflected glare from a yellow and black track identification panel at the top of the gantry (W. S. Atkins, 99817A1, Photograph 12). This would tend to make Hodder direct his eyes downwards to avoid being temporarily blinded by the glare, making it even less likely that he would look up at the signal at the last moment that it was visible. If he did not lower his gaze he may have been temporarily blinded by the flash from the reflected sun, in which case his visual acuity would have been greatly reduced. Believing the signal to be showing Y or YY, having had this belief “confirmed” by the AWS, or thinking the AWS referred to the speed limit at that point, and not having time to make another fixation, he took his train onto the track in the path of the express arriving at high speed.

**Summary of Factors Affecting Driver Cognition and Perfomance**

A summary of the interaction of system characteristics and the way they affected Hodder’s cognition and behaviour will lead to design recommendations.

1. Previous experience the sequence of signals aspects after leaving Paddington produced a strong expectation that signals ahead would not have an R aspect, so Hodder accelerated progressively from coasting as he approached SN109.

2. The track curvature and the masking of signals on the approach to Gantry 8 created uncertainty as to which signal applied to which track.

3. There was not sufficient time to examine the signals repeatedly due to the constraints on the physiology of eye–movements and the need to foveate selected items.

4. Nonetheless SN109 was visually located, but the mental model of expected signal geometry, plus the fact that other signals had the normal geometry, made the driver expect that an R aspect would be vertically below the YGY of SN109. Moreover an early sighting of the R aspect of SN105 at a visual angle nearer to the ground would increase the expectation that SN109 was not-R, since no light was visible on SN109 or any other signal on Gantry 8 at the same height.

5. No R was visible below the YGY of SN109, and its R lamp was masked by overhead structures until late in the approach.

6. Hodder probably concluded that the state of SN109 was “not-Red”.

7. Since no bright G was visible, he concluded that the state of S N109 was Y or YY, probably the latter because the two Y lamps looked similar in the reflected sunlight.

If he remembered the aspect of SN87 as being Y, he would expect that SN109 would be not-R with a probability of almost 0.9 (see text above) and no R was visible when he fixated the signal.

**From Analysis to Design Recommendations.**

From the above analysis of cognitive ergonomics and applying quantitative modeling of visual attention the following detailed recommendations for changes in systems design are evident.

1. The AWS ambiguity as to whether it is signalling approach to a signal or approach to a speed limit should be removed.
2. The AWS should provide an unambiguous indication of an approach to a R aspect instead of signalling "non-G".
3. The geometry of the signals and gantries should be unambiguously standardised.
4. There should be no ambiguity as to which signal applies to which track even when an approach is made over curving track[[6]](#endnote-3).
5. If it is impossible to relocate the gantries or rebuild the bridges, electrical equipment and other infrastructure, an appropriate speed limit must be set so that there will be adequate time for the drivers to pay attention to the signals and detect their aspects with a high probability of being correct.
6. Appropriate quantitative models should be developed to allow these recommendations to be implemented as follows.

**Conclusions for quantitative modelling.**

Given measures of dynamic visual attention such as that used by Groeger et al. (2004, 2006) et al. and by Luke et al. (2006), the choice of speed limits can be made on the basis of a rational quantitative model (Moray, 1999). We can proceed directly from the data of Groeger et al. (2004) and Luke et al. (2006). Use risk analysis to identify the minimum number of fixations that are required during the approach to any signal, and what probability is acceptable that a driver will make that number of fixations. Using the statistics derived from the data of Groeger et al. (2004) calculate the time required for the occurrence of that number of fixations and the probability of making them. Examine the track layout and determine at what distance the signal of interest becomes unambiguously and continuously visible during the approach. If we divide that distance by the time required we obtain the required speed limit during the approach.

For example, suppose we decide we can accept a probability of p = 0.9 that at least one fixation will be on the relevant signal. Then from Table 5 we find we need time for at least 10 fixations. Suppose that the signal is only visible without interruption for the final 100 metres. Then that in turn requires a speed of not more than 11 mph. If for operational reasons a higher speed is required by the train operating companies, say 22mph, on this section of track, then the signal *must* be made visible for 200 metres, and so on for other speeds and distances. Thus we obtain an ergonomic design decision that satisfies the known constraints on driver cognition and behaviour. This approach could be used to supplement the guidelines on signal viewing time (Railway Group Guidance Note GE/GN8537). Care would need to be taken when using these data in sighting signals, to take account of the context of the driving and signal sighting task and all of the issues that may lead to SPADs (including those identified in the analysis presented in this paper). These include different signal heights on the route, different signal configurations, the influence of the AWS, different mental models built up due to past experience on the route. More data are needed and should be collected on other trains, routes, and with other drivers.

A second method is based on more elaborate modelling. Given enough data, we could represent the dynamics of visual attention as a frequency transition matrix among the set of fixated objects in Table 1. We can then collapse the data to make a transition matrix between fixations on Own Signal and any other selected subsets of Table 1. We could develop a Markov model, and derive statistics such as the Mean First Passage Time (Kemeny and Snell, 1960). These in turn provide a more powerful tool for predicting how often a particular feature of the visual environment will be fixated within a given period (Moray, 2007; Moray, Neil and Brophy, 1983). However the first method will suffice to make a major improvement in safety collecting a more extensive set of data on eye-movements in relation to various patterns of signals, auditory warnings, infrastructure, and cab design. This is particularly important because there are many changes occurring in the technology of train design, including the use of in-cab displays rather than track-side signaling, head-up displays, etc. System design in the face of such extensive evolution requires the use of quantitative predictive modelling where possible (Moray, 1999).

**Note:** Distances and speeds are given both in Imperial and Metric units, since there was no uniformity in the sources on which the paper is based. For the sources of data see the **Acknowledgement** section of this paper. The paper analyses the 1999 Ladbroke Grove accident in detail, but the emphasis is less on the state of the railway infrastructure.at that time than on the methodology used. Considerable changes have been made to the rail infrastructure since 1999.

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4. **Notes**

   Our italics. [↑](#endnote-ref-1)
5. In the original paper by Groeger et al. 2004 this table is mistakenly labeled “ Fixations per second”. The present legend is correct. [↑](#endnote-ref-2)
6. Since the Public Inquiry large boards carrying track numbers have been placed beside each set of lamps. Other changes are planned in the modernisation of the railway. This paper is primarily concerned with the state of the system at the time the Ladbroke Grove accident occurred. [↑](#endnote-ref-3)