A method for classifying red signal approaches using train operational data

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ABSTRACT

The paper describes a novel technique to reliably classify whether or not a train approaching a signal at red actually came to a stand before the signal cleared (red aspect approaches) using the data from conventional signalling systems. This data is limited to the times at which the signal aspect changes and the times at which the train enters and leaves the signalling section ('berth') in advance of the signal. Knowing the percentage of red aspect approaches is potentially important for understanding the likelihood of a signal being passed at danger (SPAD) at individual signals and also for normalisation of SPAD data, both locally and nationally, for trending and benchmarking. The industry currently uses the number of red aspect approaches based on driver surveys as estimates, which are considered to have significant shortcomings. The development of the classification model is described together with the validation procedures. The techniques presented in this paper allow red approach rates to be reliably determined without the need for complex integration of signalling system and on-train data recorder data. The initial study of 94 million train approaches shows that 5% of them stopped at red aspects. It is also highlighted that there is a large variation in the red aspect approach rates between signalling areas and between individual signals. SPAD risk assessment at individual signals could be significantly enhanced by the ability to estimate red aspect approach rates using the techniques described.

KEYWORD

INTRODUCTION

An event where a train passes a signal showing a red aspect without authorisation is known as a 'signal passed at danger' (SPAD). SPADs can range from minor incidents where a signal is passed by only a few metres to serious incidents where longer overruns give rise to the chance of collision with other trains. The causes of SPADs can vary widely from driver error to degraded braking performance as a result of low adhesion [1]. Driver error is frequently cited as a primary cause, often described in terms of the failure to take sufficient action at preceding warning signals ('misread') or failure to control the train on the approach to the red signal ('misjudgement') [2]. However, it is recognised that there are many underlying technical, organisational and human factors related causes which can contribute to the eventual failure of a driver to stop at a red signal [3, 4]. An example of this is the accident at Ladbroke Grove, UK, in 1999 in which there were 31 fatalities. The accident report [5] identified key failings in the design of the signalling system, signal sighting and driver training as causes of the accident.

The essential precursor for a SPAD is that the train approached a signal showing a red aspect and that the signal did not clear before the train was required to stop. Knowing the number of red aspect approaches is fundamentally important to understand and analyse the SPAD risk of an individual signal, a route, a signalling area or the whole country. The number of red aspect approach could be used to offer a much more meaningful way to calculate SPAD risk, comparing to the currently used normaliser of train mileage [6]. This improved SPAD risk measure can then be used to further guide research in human factors, which could lead to better management of train operations and less number of SPADs.

SPAD risk has been studied by many researchers across the world [2, 6-10]. Though [6,9,10] suggest that the best normaliser for SPAD risk analysis is the number of red aspect approaches, most studies do not normalise SPAD incidents or use train mileage as the normaliser. This is due to the lack of sufficient and reliable red aspect approach data. It is discussed in [6] that with the knowledge of red aspect approach data, which is effectively the SPAD opportunities for drivers, can be used to greatly improve the understanding of human error. Consequently, this could lead to developments in specific mitigations for common infrastructure or operational designs, and reduce the number of SPADs. The knowledge of red aspect approach data could also improve the current safety risk model used by the industry, to link SPAD risks with underlying causes [6].

The UK railway industry currently estimates the red aspect approach rate based on driver surveys for various classes of train (suburban, inter-city, freight etc.) [11]. However, the number of surveys is very limited and only covers a small area during a short period of time. The resulting error could be large when extrapolating the survey results to the entire GB railway network. The other limitation is that both the number and the probability of red aspect approaches at individual signals can be significantly different.

Background

Network Rail, the GB infrastructure manager, provides publicly available live data feeds which give various information on the movement of trains [12]. At the most fundamental level, the source of the information used in this paper is Train Describer (TD) data. A TD is an electronic device connected to each signalling panel which provides a description of each train (its 'headcode') and which section of track (or 'berth') it currently occupies. The TD is responsible for correctly displaying the train movements from berth-to-berth to the signaller and for ensuring that the train's identity is correctly passed to the next signaller's panel when it leaves the current signalling area. Although this paper is based on UK specific data, the principles can be applied equally to the majority of modern fixed block track circuit based signalling systems.

The TD messages include two classes, termed C-class and S-class messages. TD C-class messages record train movements between individual berths. A C-class message will be sent out each time a train moves from one berth to another, and includes the train headcode, the TD area in which the train movement occurred, the two relevant berth IDs (i.e. the 'from' and 'to' berths) and the time of the movement.

S-class messages record the changes of signal aspects, and includes the signal IDs, their TD areas and status. The S-class data only shows whether a signal is 'on', showing a red aspect or 'off' showing a proceed aspect (typically single or double yellow, or green). The signal IDs and status in S-class messages are represented using hard coded address-bits combinations, which can only be decoded using a map provided by Network Rail.

C-class messages and S-class messages can be processed and combined together to form a database of train approach records, details of this process can be found in [13]. During the research over 74 million train approaches to 9,386 signals in 83 TD areas (out of 160 in the entire country) were

collected dated from 2014-03-25 to 2015-04-09 (244 days) and these forms the basis of the analysis presented in this paper. There are dates without messages due to sever or receiver failures. The number of TD areas and signal IDs are limited by the coverage of S-class messages and the decoding map. However, the data still provides a good representation of the entire network, covering different types of routes and areas. The SPAD incidents are also available during this period and will be used in further research.

These 74 million train approaches were initially separated into these following classes in [13]:

- **NRA**

The signal aspect at the end of the berth is showing a proceed aspect when the train enters the berth. Train approaches in this category would not stop at red aspects, as it would not approach such aspects.

- **RED**:

The signal aspect at the end of the berth is showing a red aspect when the train enters the berth. Train approaches in this category could be red aspect approaches if the signal cleared after the train stopped. However, they are not necessarily red approaches as it is common for the signal to clear whilst the train is occupying that berth. Developing a method to distinguish between trains which do and do not stop at a red signal, based on limited data, presents significant challenges. The approach taken is described in the following sections of this paper.

- **ERR**:

Events do not satisfy the definitions above or data is missing preventing the analysis from being carried out.

Train approaches are classified as ERR if the train passes a red signal or the signal fails to switch to red after being passed, caused by errors in the TD messages. Train approaches are classified as NRA if the signal clears before the train enters the berth. These separations are described in [13].

Identifying red aspect approaches

As discussed previously, being able to identify red aspect approaches can significantly improve the understanding and analysis of SPAD risks. However, it is very difficult to achieve due to the very limited information provided by a conventional signalling system. The data available for this research includes the TD C and S class messages which only provide timings of train moving between berths and signal status changes; and limited information of the length of some berths and whether a berth is at a platform. There is no data about the exact position or speed of trains from on-board devices such as GPS.

One of the previous attempts to identify red aspect approaches is included in [14], and this method is based on a set of thresholds configured using railway signalling experience and knowledge. However, this method is not accurate and requires further refinements.

A refined model is proposed in this paper, using an idealised speed profile method to further classify the RED approaches into the following sub-groups:

- **CAS** (Cleared Approaching Signal):

Signal is red when train enters berth but it clears before the train comes to a stand. It is important to distinguish such approaches from CSS approaches as they represent events where a SPAD cannot occur because the signal clears before the train reaches it.

- **CSS** (Cleared Stopped (at) Signal):

Signal clears after train has come to a stand and train departs immediately. CSS approaches are the essential precursor to a SPAD as the train has to come to a stand.

- **CBD** (Cleared Before Departure):

Train enters platform and stops at a red signal. The signal then clears but the train may not depart immediately due to completing station work. Whilst essentially the same as CSS events, a separate category was provided in an attempt to aid normalisation of incidents related to platform specific events. These include incorrect despatch against a red signal and permissive working.

- **PSS** (Possibly Stopped (at) Signal):

Signal possibly clears after train has come to a stand and train departs immediately. This class is the 'grey area' between the CSS and CAS classes and holds train approaches which cannot be confidently classified as CSS or CAS using the currently available data.

METHODOLOGY

A typical sequence of events when a train approaches a signal is shown in Figure 1. In this example, the train enters berth 1 from berth 0 at time t_{in} while signal 1 at the end of berth 1 shows red.. Signal 0 must switch from yellow to red shortly after the train enter berth 1. Signal 1 clears at time t_{clear} before the train passes signal 1 and leaves berth 1 at time t_{out}.
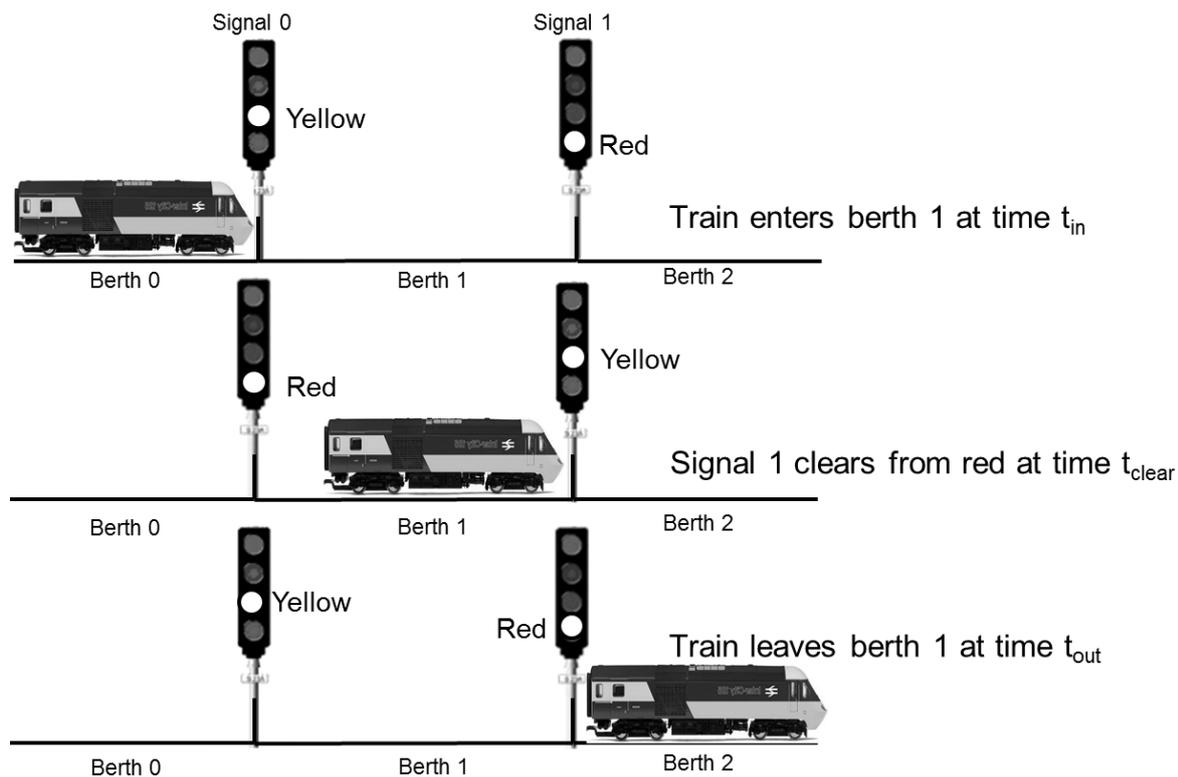

Figure 1 Red Aspect Approach Sequence

Speed profile model

When a train approaches a red aspect, it will slow down and prepare to stop at distance in front of the signal, unless the signal clears before the train stops. A generic speed profile for red aspect approaches can be assumed to be comprised of the following stages, as shown in Figure 2:

1. In the first stage, the train will continue to travel at a constant speed (berth entrance speed V_1) before the train starts braking. The duration of the stage is denoted as t_1.
2. In the second stage, the train will start decelerating until it comes to stop. The duration of the stage is denoted as t_2.
3. In the third stage, the train will stop at the signal until it clears. The duration of the stage is denoted as t_{stop}.
4. In the fourth stage, the train will start accelerating shortly after the signal clears. This stage includes a brief lag to account for the driver's reaction time. The duration of the stage is denoted as t_3.
5. In the fifth stage, the train stops accelerating and keep travelling at a constant speed (V_2). The duration of the stage is denoted as t_4.

Note a red aspect approach may not have all these 5 stages, for example the train may have already started decelerating at the beginning of the berth thus does not have the first stage.

The time between train entered the berth and signal cleared is t_a, and $t_a = t_1 + t_2 + t_{stop}$. The time between signal cleared and train left the berth is t_b, and $t_b = t_{react} + t_3 + t_4$. The total time the train spent in the berth is denoted as T, where $T = t_a + t_b$.

The distance the train travelled before the signal clears (during t_a) is the key parameter to estimate whether a train stopped at red aspect, therefore the following analysis will focus on the period between the train entering the berth and the signal clearing.
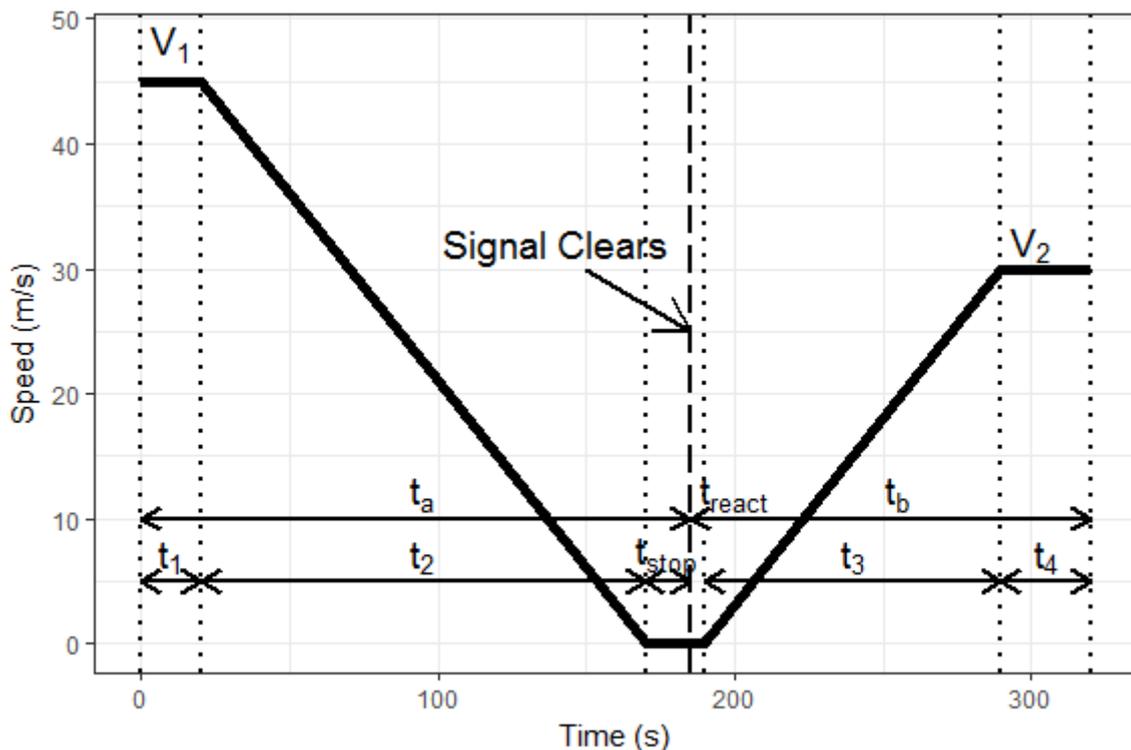

Figure 2 Example Speed Profile for CSS Signal Approach

Among the parameters used in the model, only the time points when trains entered or left berths, and signal status changed are available from the TD data. The lengths of some berths are also available.

Some assumptions are required based on industrial knowledge, such as:

- Previous work by RSSB [14] suggested that the average deceleration rate for passenger trains approaching red signals was 3%g, thus the deceleration rate $a = 3\%g$.

- Trains normally stop about 12 metres ($\Delta d = 12$) in the advance of the red aspect in accordance with typical GB train driving practice) [15].

Estimation of berth entrance speed

The berth entrance speed (V_1) can be estimated statistically using all the train approaches to the berth in question from the TD data.

The red aspect approach rates for individual signals vary significantly depending on the routes and train class [12]. Therefore, all train approaches for the berth are separated into train approach groups using the following parameters:

- TD area: The TD area the train travels in.

- Train Type: The first digit of the train head code represents the class of train.

- Signal IDs: The signal ID the train approaches and its preceding signal ID (Signal 0 and Signal 1 as shown in Figure 1).

- Three berth IDs: The berths the train steps from and to when passing Signal 0 and Signal 1 (Berth 0, Berth1 and Berth2 as shown in Figure 1).

If a train approach group had more than 200 RED approaches, then V_1 was estimated using the fastest 20% of RED approaches, as in these cases, the signal was likely to have cleared before the trains stopped. Otherwise, V_1 was estimated using the slowest 20% NRA approaches, as these trains were likely to be proceeding under a caution aspect.

For red aspect approaches, the train must enter the berth slow enough to stop 12 meters in rear of the red aspect at an average of 3%g. Thus, the maximum entrance speed for each berth can be worked out as: $V_{max} = \sqrt{2a(d_0 - \Delta d)}$, where d_0 is the length of the berth. Therefore, if a trains speed V_1 was found to exceed V_{max} it would be set to V_{max}.

Identification of red aspect approaches

The first half the speed profile between the train entering the berth and signal clearing (t_a) can be used to identify if the train stopped at the red aspect, with the parameters known, assumed and estimated in the above sections.

The first step is to examine if the signal cleared late enough so the train could have come to a stop. The minimum time needed to stop from entrance speed V_1 at a deceleration rate a is V_1/a. Therefore, if $t_a < V_1/a$ then the train is unlikely to have stopped at the signal and the train approach would be classified as CAS. It is still possible that the train did stop but this would require a much higher average brake rate than the norm and this would represent more 'aggressive' driving than found in normal train operation.

Otherwise the train could stop at the red aspect, and the time it stopped t_{stop} can be worked using Equation 1 and Equation 2

$$d_0 - \Delta d = V_1 t_a - \frac{V_1^2}{2a} - V_1 t_{stop} \qquad \text{Equation 1}$$

Thus the time stopped at the signal t_{stop} can be worked out using Equation 2:

$$t_{stop} = t_a - \frac{V_1}{2a} - \frac{d_0 - \Delta d}{V_1}$$
Equation 2

$t_{stop} < 0$ means that the train approach does not fit the assumed speed profile well and possibly stopped at the red aspect with low confidence. Therefore, such train approaches are classified as PSS.

Among the train approaches with $t_{stop} \geq 0$, the ones departing from platforms are identified as CBD approaches and the rest are CSS approaches. Train approaches can be separated by whether the train stopped at the red aspect using the formulae above, however knowledge of train entrance speed and the berth length is essential. Approaches without such information are classified as N/A.

It was found that 38% of the RED approaches fell into the N/A category, i.e. they could not be classified using the approach speed profile method. 93% of the N/A approaches did not have berth length information because their preceding signal IDs could not be found, due to missing preceding berth IDs or lack of signal decoding map coverage. The rest of these train approaches do not have berth entry speed information because the number of train approaches to the signal is too small.

Identification of red aspect approaches with less information

To classify the N/A approaches, a classification tree algorithm was used to optimise the rules to separate CAS approaches from CSS approaches. No efforts were made to separate PSS and CSS as they cannot be separated with high confidence based on the statistical approach. This method is one of the most commonly used methods in data mining to predict the classification results based on several input variables. 80% of train approaches were used for training the classification tree and 20% of them were used for subsequent testing. Using this model, 84% of the testing approaches resulted in a classification consistent with the results of the approach speed profile model described above.
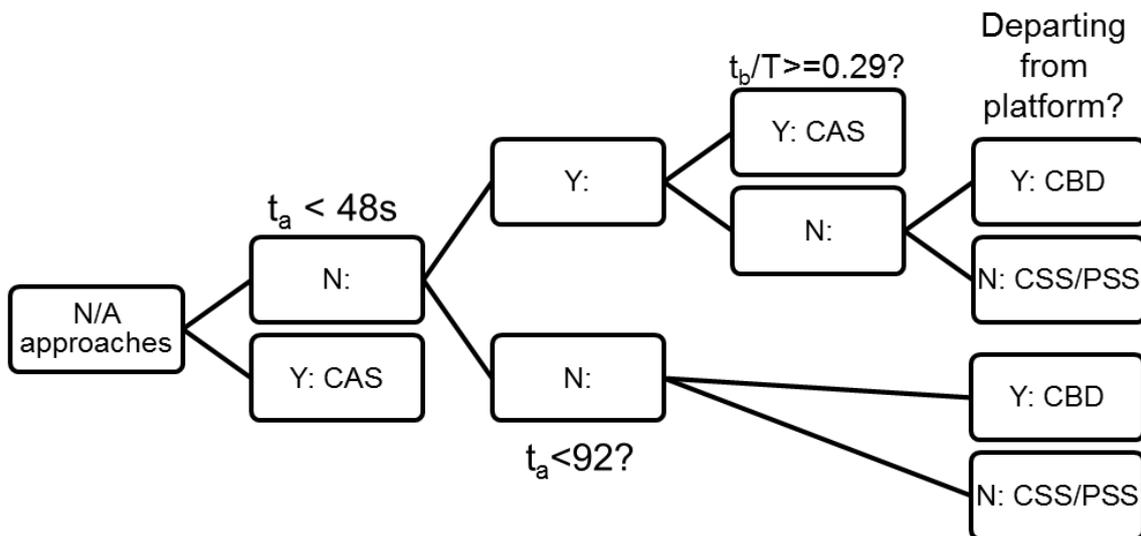

Figure 3 Red approach classification tree

The model shows that:

- Primarily, CAS events are characterised by relatively small t_a, (48 seconds) whereas red aspect approaches are characterised by a larger t_a (92 seconds). This is because a larger t_a suggests the train has travelled further within the berth before the signal clears thus has higher chance of stopping at the signal.

- When t_a is between 48 and 92 seconds, CAS events are characterised by $t_b/T \geq 0.29$ because a larger t_b/T ratio means train travels further after the signal clears, which suggests the train was further away from the signal when it cleared and thus did not stop.

The red aspect approaches identified with this classification tree model can be further divided into CBD and CSS/PSS classes depending on whether the train is departing from a platform.

Summary

A speed profile method was developed to identify if a train stopped at a red aspect based on the timings of trains entering and leaving each signalling berth, the timings of signal, berth lengths and berth-platform association. The deceleration rate and distance trains stop in rear of signals were assumed based on industry knowledge. The berth entrance speed was estimated using the information for other train approaches.

For train approaches at berths with known lengths and entrance speed values, the red aspect approaches can be measured using the speed profile method. For train approaches where the berth length was unknown an alternative approach was developed using a classification tree.

VALIDATION

The separation of non-red approaches (trains that entered the berth while signal being not red at the end) has been successfully validated in [12] via manual calculations and comparing to the Network Rail's Control Centre of the Future (CCF) software. However, as the messages are used in CCF and this work, it cannot be used to validate the separation between train approaching signals showing red.

A log of signal aspects approached and the related timings with several days of cab riding in Merseyrail Electrics signalling area were used to validate the speed profile model proposed in this paper. 118 signals were passed and the model correctly classified 100% of these approaches.

On-Train Monitoring Recorders (OTMR) are devices used on trains to record data about the operation of train controls and performance in response to those controls, including the speed of the trains. GB train operator Virgin Trains provided some OTMR data from 2015-01-06 to 2015-01-10 only containing instances when their trains stopped at red signals. This data was used to validate the identification method described above. 35 OTMR records of red aspect approaches were examined, and all of them are correctly classified as red aspect approaches incidents (CSS, PSS or CBD).

The future plan includes to access more OTMR data to carry out further validations, nevertheless, it will only ever be practical to carry out such a validation for a very small sample of the many millions of signal approaches in the database.

RESULTS

The method described above was applied to the 74 million train approaches and results of some typical signal-train combinations (train approach groups) as well as the overall results are presented in this section.

Case Study Results

Three train approach groups with the highest number of RED approaches within their TD areas were selected for this case study as listed in Table 1. These three train approach groups represent three different scenarios: group 1 for trains approaching a large mainline station; group 2 for low-speed

local stopping passenger services; group 3 for local passenger trains (on the UK West Coast Mainline). All of these three approach groups are identified using the red aspect approaches classification model as described in the Methodology Section. Note the berth length and entry speed information are available for all of these three groups and therefore the analysis is carried out using the detailed rather than the simplified classification model described above.

Group	TD	TD Area	Train Type	Berth0	Berth1	Berth2	Signal0	Signal1
1	MP	Manchester Piccadilly	Express Passenger	0064	0305	0345	MP64	MP305
2	SS	Merseyrail	Local Passenger	0104	0102	0100	ML104	ML102
3	R1	Rugby	Local Passenger	5231	5233	9737	TK5231	TK5233

Table 1 Train Approach Groups for Case Study

The red aspect approach classification results for the three case study groups are shown in Figure 4, Figure 5 and Figure 6.

In these three graphs, the vertical axis shows the ratio between t_b and T, which represents the proportion of the total berth time which each train spent in the berth after the signal cleared. When t_b/T is larger than 1, the signal clears before the train enters the berth, thus it is no longer a red aspect approach. The horizontal axis shows the average speed of the train approaches (Berth length d_0 divided by berth time T).

The dashed line was derived using the condition where $t_a \geq V_1/a$ and the line can be expressed as:

$$\begin{cases} y = k_1 x + 1 \\ k_1 = -\dfrac{V_1}{a d_0} \end{cases}$$
Equation 3

The dash-dotted line was derived according to Equation 1 and can be expressed as:

$$\begin{cases} y = k_2 x + 1 \\ k_2 = -\dfrac{\dfrac{V_1}{2a} + \dfrac{d_0 - 25}{V_1}}{d_0} \end{cases}$$
Equation 4

As discussed in the Methodology section, points above this line are all CAS approaches. For points below the dashed line, they are classified as CSS approaches if they are below the dash-dotted line, otherwise they are classified as PSS approaches. In cases where a train approach group has $V_1 < \sqrt{2a(d_0 - \Delta d)}$, thus $k_1 < k_2$, no approaches in this group will be classified into the PSS group

Figure 4 shows the classification results for train approach group 1. For this group, signal MP64 and MP305 are both on the down fast line approaching Manchester Piccadilly station and the line speed is 65 mph. The entrance speed V_1 is worked out as 56 mph. The distance between these two signals is 963 metres. Figure 4 shows an example the case where the dash-dotted line is above the dashed line, thus no train approaches are classified as PSS.
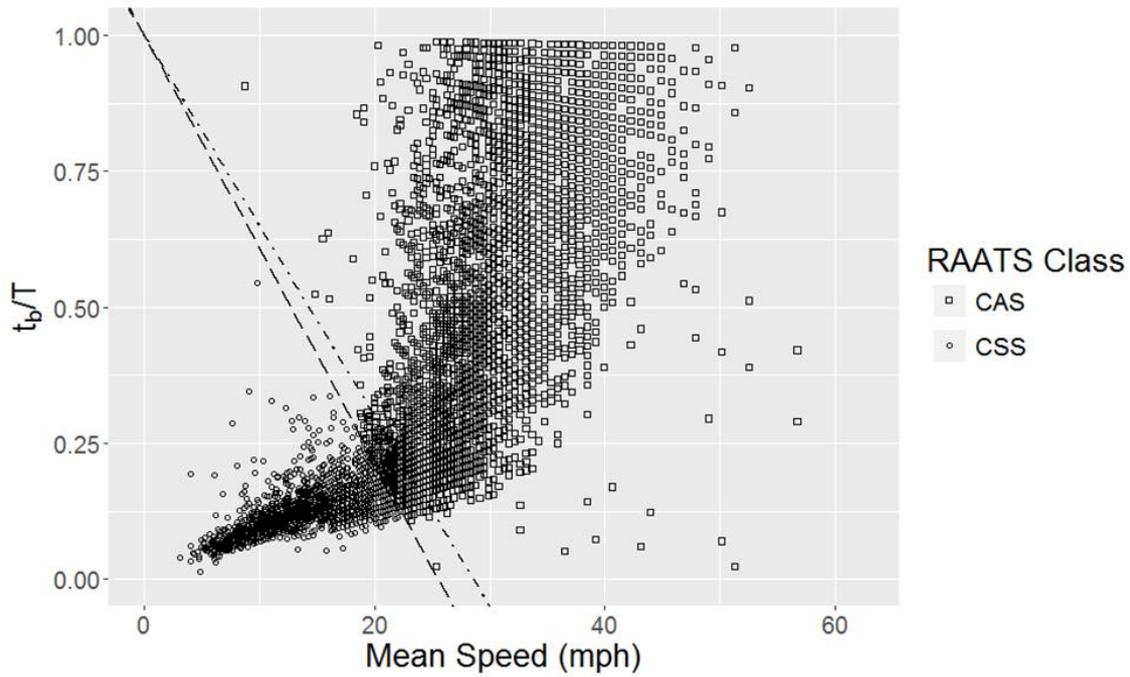
Figure 4 Red Aspect Approach Classification: Train Approach Group 1

Figure 5 shows the classification results for train approach group 2. Signal ML104 is the departure signal from Hillside station and ML102 is the approach signal for Ainsdale station. The berth entrance speed V_1 for signal ML34 is worked out as 50 mph. The distance between these two signals is 1600 metres.
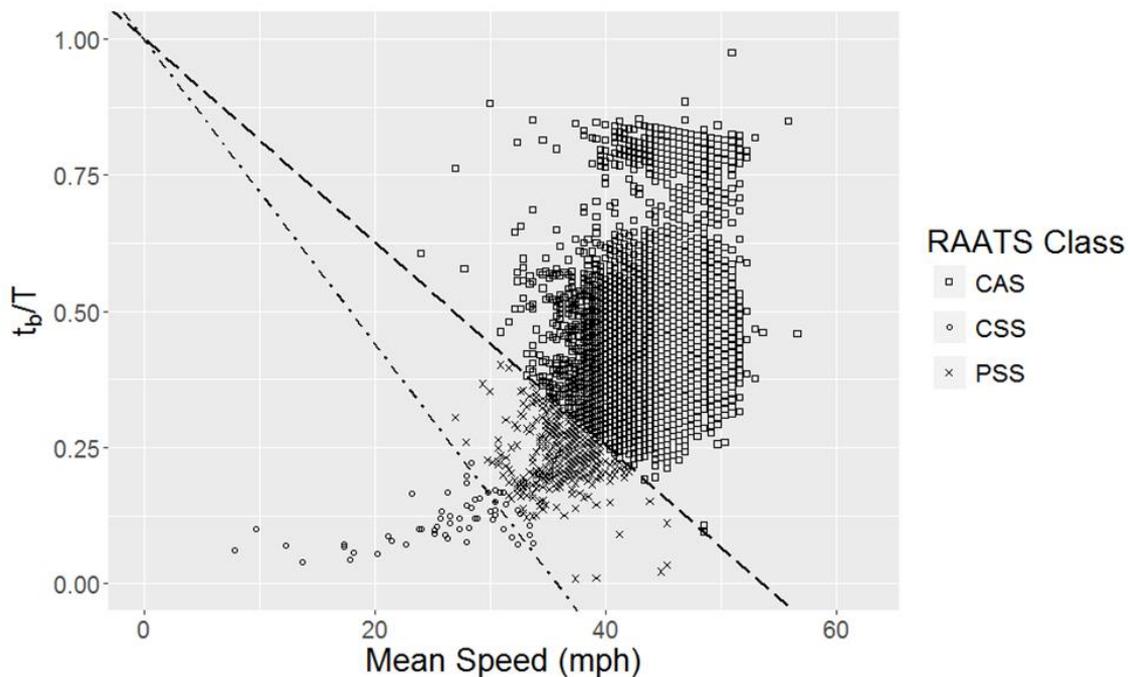

Figure 5 Red Aspect Approach Classification: Train Approach Group 2

Figure 6 shows the classification results for train approach group 3. Signal MP5231 and MP5233 are both on the down slow line at Denbigh Hall North Junction. The line speed is 100 mph and the berth entrance speed V_1 for signal MP5231 is worked out as 49 mph. The distance between these two signals is 1363 metres.
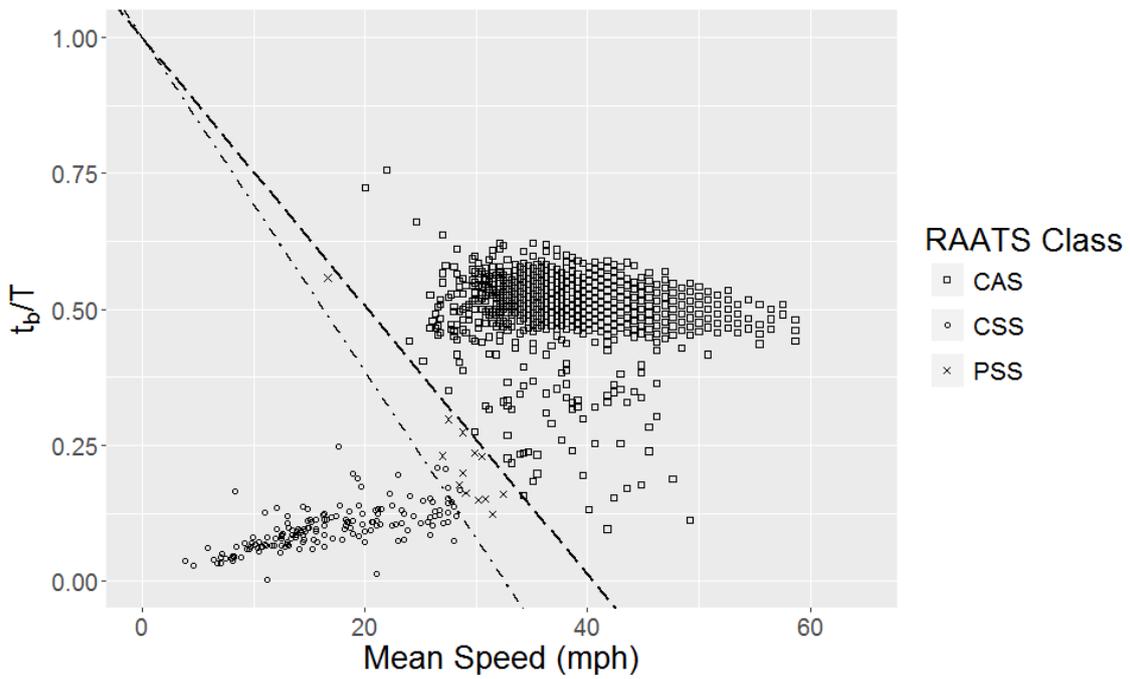
Figure 6 Red Aspect Approach Classification: Train Approach Group 3

Overall Results

The left pie chart of Figure 7 shows the classification results for 74 million train approaches, where 5% of them are red aspect approaches and 5% of them are CAS. The 7.3 million red aspect approaches are further broken down on the right bar. The approaches identified by the classification tree model are tagged with N/A as this method is deemed to give results with a lower confidence than the approach speed method.
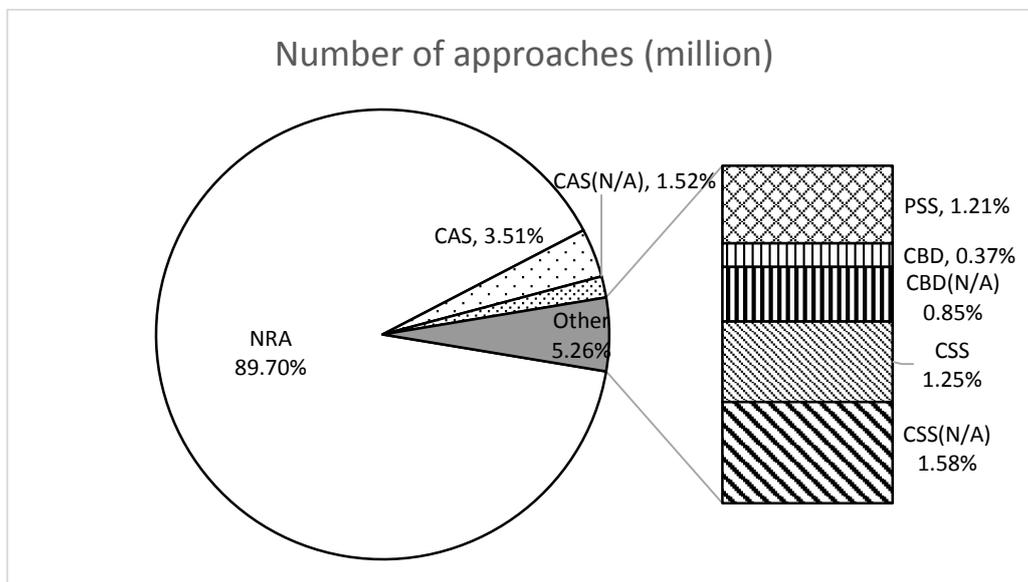

Figure 7 Red Aspect Approaches Classification Results

Figure 8 shows the distribution of CAS and red aspect approaches rates between TD areas and Signal IDs, the shaded area under the box plot represents the distribution density of train approaches. The CAS and red aspect approaches rates between TD areas are densely distributed, and half of the TD areas have red aspect approaches rates between 3% and 12% and the median red aspect approaches rate is 6%. There are areas with high red aspect approaches rates but their train approach numbers

are very small, due to the limited berth signal mapping information. For example, WH (West Hampstead Signal Box) TD area has the highest percentage of red aspect approaches at 96% but it only has six signals available in the database due to the coverage of the decoding information. These six signals are approached less than 5000 times.

In contrast, the red aspect approaches rates by individual signal ID are more evenly distributed with the most of signals having red aspect approaches rates between 0% and 5%, which represent the most common type of signals i.e. those that are rarely approached at red. The signals with high red aspect approaches rate (90-100%) are probably approach control signals, platform starter signals, or depot exit signals which are always approached at red.
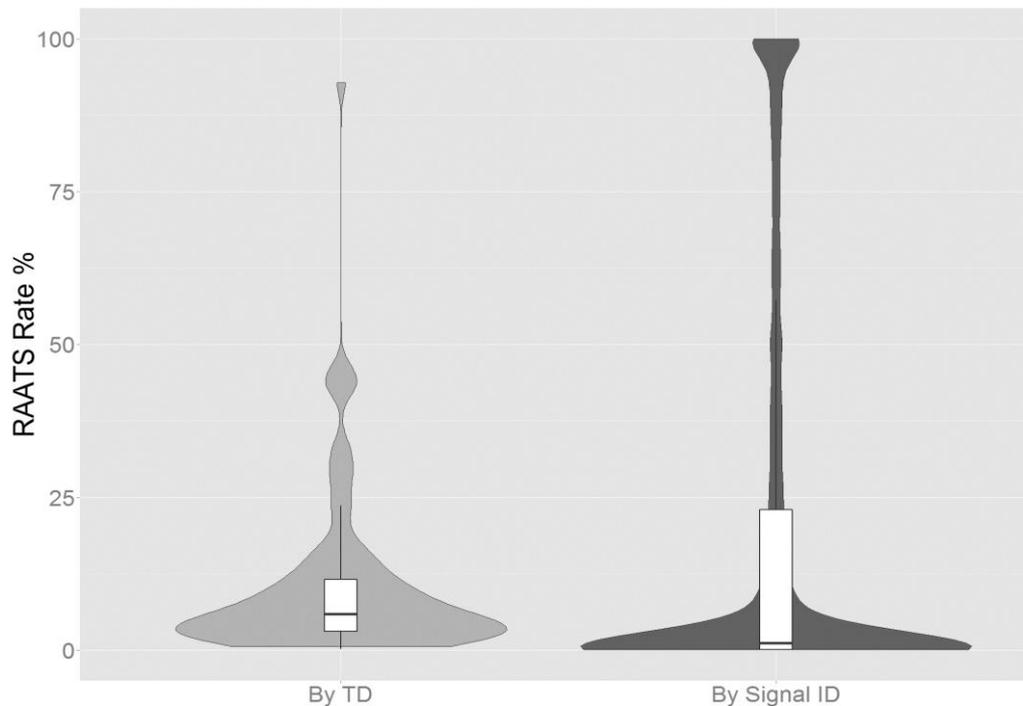

Figure 8 Red Aspect Approaches Distribution by TD Area and Signal IDs

CONCLUSION

Trains stopping at red aspect (red aspect approaches) is a precursor for SPADs. Therefor by identifying red aspect approaches, this method provides the basis for a better understanding of SPAD risk at individual signals and for improved normalisation of SPAD data for trending and benchmarking nationally. A model was developed to classify red aspect approaches based on limited data available from the signalling system using timings of train movement, signal changes, and some lengths of berths etc. Though this method is developed for the UK railway signalling system, it can be modified and applied for all modern fixed block track circuit based signalling system around the world.

The model was applied to 74 million train approaches in 83 TD areas. Three signals in different areas were used as examples demonstrating how train approaches are separated into different categories. The overall results showed that approximately 5% of all train approaches are red aspect approaches. Another 5% of trains entered the berth while the signals were showing red but did not stop because the signals cleared early enough. It also highlighted that there is a large variation in the red aspect approaches rates between individual signals and TD areas.

The identification results were validated with a limited number of red approaches from the OTMR system. All of the 35 red aspect approaches incidents were correctly identified by the proposed

method. More OTMR data will be acquired in the future to carry out further validations and improvements.

Besides SPAD risk analysis, there are a number of other potential uses of the data. The analysis has the potential to assist with understanding performance and capacity constraints on the network. This could be achieved by comparing the theoretical timetable against what actually occurs and assessing if there are areas where operations could be optimised or designed better.

A further use could be in understanding the routing of trains and the frequency of each route being used. Better knowledge of these would improve the estimates of parameters in risk models that account for these in their algorithms.

The methods described in this report have been used to develop an online tool to analyse red approach rates at individual signals, groups of signals or all signals in the database. The tool is being made available to the GB railway industry through the Rail Safety and Standards Board's (RSSB) website.

ACKNOWLEDGMENTS

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