Calculating Train Braking Distance

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Abstract

The paper discusses the development of an IBM PC®[1] based tool, for calculating train braking distances for various train classes on a rail network. There is discussion on current industry practice and the limitations of that practice, the concept of the tool itself, including the assumptions made, the strategy adopted to minimise the risk of incorrect calculations, and the results of adopting that strategy.

Keywords: train, braking, distance, calculation, railway.

1 Introduction

For trains to safely travel on a railway, trains must be provided with sufficient distance in which to stop. Allowing too long a distance reduces the capacity of the line and hence the return on rail infrastructure investment. Too short a distance and collisions would occur, because the train would not be able to stop within the available distance and would therefore occupy a section of track that could be allocated to another train. Consequently it is important that the distance be adequate, but not overly so. Figure 1 shows the relationship between braking distance and "headway" which is a measure of capacity.

Traditionally, the calculation of the required braking distance is on a per Limit of Authority basis. The task is further complicated if there are many trains with different braking and ride performance characteristics operating on the same section of track, because for safety, the distance needs to be the longest of all the different trains. The calculation needs to be repeated for every train type and every approach path to that Limit of Authority.

Within Queensland Rail (QR), there are currently some 40 different train types defined and some 7000 locations where trains may be required to stop. For some of those 7000 locations, there are many different approach paths. Every time there is a change involving an increase in train speed or a reduction in the train braking performance, the calculation must be repeated for every signal involved for that train type. This often means thousands of calculations.

[1] Registered trademark of International Business Machines Corporation

Despite the obvious criticality of the required braking distance, the calculation process traditionally used within QR, and for that matter most other railways, is not as robust as it perhaps should be.

The purpose of this IBM PC® based tool is to:

- assist the signal designer to provide an adequate distance for the safe stopping of trains operating on a given line whilst at the same time maximising line capacity;
- put in place controls to ensure that the data used for the calculation is verified and traceable, and any changes controlled;
- allow the ready evaluation of a new train by performing multiple calculations in one execution;
- readily highlight those Limits of Authority that need to be relocated to allow for changes in speed or train braking performance.

In Section 3 we describe common industry practices and the limitations of those practices. In Section 4 we provide an overview of the tool requirements and implementation strategy. In Section 5 we conclude by discussing the effectiveness of that strategy.

2 Definitions

ATP – (Automatic Train Protection) is a predictive enforcement system which continuously monitors the speed of a train in relation to either a target speed, which for a Limit of Authority would be zero, or a target distance, and intervenes such that the train is prevented from passing a Limit of Authority or exceeding a speed limit.

Braking Distance – is the distance the train travels from when the train driver makes a full-service brake application to when the train stops (Fig 1).

COTS – (Commercial Off the Shelf) – it is a phrase used to refer to commercially available products being used "as is".

Full-Service Brake – is the maximum deceleration rate deceleration so as to minimise the risk of injury to passengers or damage to goods or cause damage to the train.

Limit of Authority – is a location along the railway where a train's current authority to move ends. It is usually delineated by a signal, passive sign, or track kilometrage.

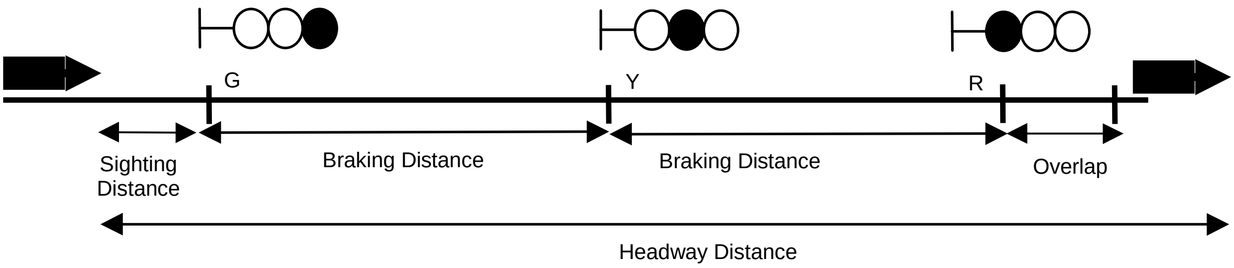

Figure 1: – Standard 3 Aspect Sequencing used in QR
(The paper relates to the calculation of the distances labelled "Braking Distance")

Train Type – a train is characterised by its maximum permissible speed, its deceleration rate, the time delay for the deceleration rate to become effective, its length and its permission to exceed certain classes of track speed restrictions. Passenger trains and bulk commodity trains e.g. coal, mineral, grain have certain nominal lengths depending on where they operate. General freight trains can be of any length up to a specified maximum for a particular line. To cater for this variation 'long' and 'short' types are defined. Note: The brake delay time varies with train length – the longer the train, the longer the delay.

3 Calculating Braking Distance

3.1 Influencing Factors

Braking distance depends on:

- the speed of the train when the brakes are applied;
- the deceleration rate available with a full-service brake application, which varies according to the coefficient of friction between wheel and rail;
- the delay from when the brakes are commanded by the train driver to when they are actually become effective (brake delay time);
- the state of the wear of the brake pads and the air pressure available in the brake cylinders;
- the geography of the track, in particular the track gradient the train travels over from when the brakes are commanded to where the front of the train stops;
- the mass distribution of the train.

3.2 The Effect of Train Mass

Stopping a train requires work. This work equals the change in the train's kinetic energy plus the change in its potential energy (change in height due to the gradient of the track).

The 'work' is the energy in decelerating the train over the stopping distance, i.e. the product of the train's mass (m), the train's acceleration rate (a) (deceleration is negative acceleration) and the stopping distance (S).

The change in 'kinetic' energy relates to the change in the train's speed i.e. the difference of the speed at which deceleration began (U) and the 'at stop' speed i.e. 0.

The change in 'potential' energy relates to the change in height of the train's centre of mass due to the gradient of the track i.e. the difference in height at which deceleration began (h_1) and the its height at the stopping point (h_2).

Mathematically this can be expressed as:

$$m*(a)*S + ½*m*(U^2) + m*g*(h_1-h_2) = 0 \qquad (1),$$

where 'g' is the acceleration due to gravity and $h_2 \geq h_1$.

Mass is common in all the terms in the equation, and therefore can be cancelled out. This suggests that mass has no direct effect on the stopping distance. However, mass has an effect on the stopping distance as the location of the train's centre of mass varies with the mass distribution. Mass also affects the deceleration rate of a particular item of rolling stock. For freight wagons, where the mass can vary from no load to full load, there are two levels of brake force used i.e. "empty" and "loaded". The design of the brake system is such that as the load increases, there is a point where the force changes from "empty" to "loaded". For braking distance calculations the lowest deceleration rate is used to calculate the deceleration rate for the complete train.

The change in height relates to the track gradient. The track gradient is the change of vertical height over the corresponding change in horizontal distance i.e. tan α where α is the angle of slope. For small α, which is the case for railways (mountain rack railways aside), tan α equals sin α. Sin α is the change in height (h_2-h_1) over the stopping distance (S):

$$(h_2-h_1) = S*\sin\alpha = S*\tan\alpha \qquad (2)$$

Substituting (2) into (1) and rearranging:

$$S = (-U^2)/2(a-g*\tan\alpha), \text{ for } a < 0 \qquad (3)$$

The term "-g*tan α" is the gravitational acceleration. For uphill track gradients i.e. $h_2 \geq h_1$, gravity assists deceleration.

3.3 Calculation Method

It is impossible to calculate the precise stopping distance as this distance can vary significantly due to the condition of the train and the environmental conditions at the time. To take the conservative approach, i.e. allow for the worst case conditions would grossly impact on track asset utilisation. The industry approach is to assume that the train's brake system is healthy and that the specified adhesion for that class of train is available when the brakes are required to be applied.

Most railways do not take into account the brake delay time, and further simplify the calculation by using the average gradient of the track on the approach side of the Limit of Authority.

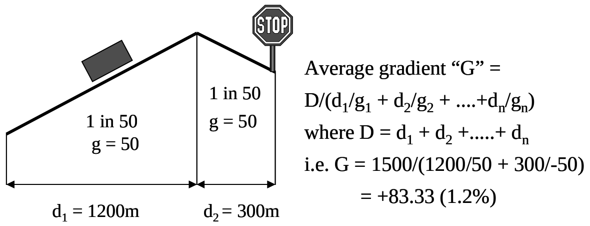

Figure 2 – Average gradient concept

To calculate braking distances it is therefore a matter of knowing the train braking parameters for each type of train and the gradient of the track and apply Newtonian physics (see equation (3)).

However to compensate for these simplifications and the variable factors, an allowance of 15-20% is usually added.

This distance is the minimum distance that needs to be provided. Other factors that will further increase this distance are:

- other design constraints e.g. the track layout arrangement, level crossings etc;
- the sighting distance to the first warning for the Limit of Authority ahead;
- access to the physical location for installation and future maintenance;
- suitability of the site to erect its supporting structure.

There is of course the "last ditch" compensatory factor, in that the train driver is required to "know the road".

In the UK, metros and light rail systems aside, signal designers rely on braking distance speed graphs as published by Railtrack (1996). These graphs provide the braking distance required for a particular train speed over a range of track gradients. These graphs are based on specified train brake performance parameters provided by rolling stock engineers. The signal designer merely needs to determine the "average" gradient of the track on the approach side of the Limit of Authority. Using this gradient average value and the maximum speed the train is allowed to travel on the track approaching the Limit of Authority, the braking distance required can be directly read from these graphs.

3.4 Limitations

3.4.1 Gradient averaging

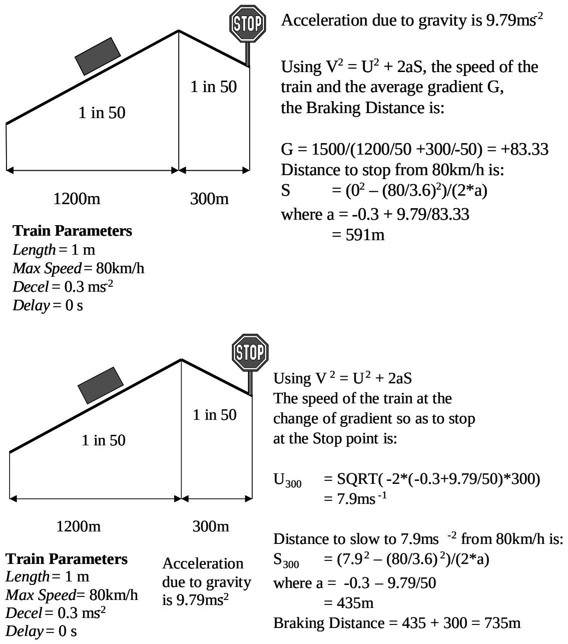

Figure 3 – Average gradient concept limitations

From the two diagrams in Figure 3, the braking distance calculated using the average gradient approach is some 144 metres short. It can also be easily demonstrated where gradient averaging can lead to much larger braking distances than necessary.

3.4.2 Brake delay time

Allowing 15-20% does not compensate for ignoring the brake delay time. For example, consider a train that has a brake deceleration rate of $1ms^{-2}$, and a brake delay time of 5s. Assuming an initial speed of 100km/h and level track, the required braking distance is 524m. Ignoring the brake delay time, the braking distance would be 385m. Adding 20%, increases this to 462m, i.e. some 62m short. This is much worse for long trains where the brake delay time is much longer. A brake delay time of 28s is typical for QR's coal trains.

For "shortish" brake delay times the error is not that significant as there are other factors which compensate:

- the train driver would normally initiate a brake application on sighting the first warning to the Limit of Authority ahead, which is well before the calculated full-service braking distance location (a full-service brake is a fairly severe brake application and train driver's drive more conservatively);
- there is also retardation due to track curvature and viscous drag which is ignored in the calculations.

3.4.3 Introducing a new train

If it can be demonstrated that each of the new train's parameters are on the "safer" side when compared to any other train for which the signalling was designed then the new train can be introduced. "Safer" in this case means:

- the maximum train speed is equal to or less; ***and***
- the full-service deceleration rate is equal to or greater; ***and***
- the brake delay time is equal to or shorter; ***and***
- train length is equal.

If any of the parameters are not "safer" e.g. the maximum speed is higher or the brake delay time is longer, then a re-calculation of all braking distances is required. Depending on the intended operating routes, this could involve thousands of calculations.

QR has previously not kept records of the data used braking distance calculations (only the physical location of the Limit of Authorities and the warning to those authorities are documented on drawings). This meant that all the data has to be regathered if calculations needed to be repeated. QR now has procedures to retain these calculation records.

3.5 QR

Prior to the late 1980's, braking distances were calculated as described in Section 3.3, and like most railways ignored the brake delay time.

QR is however somewhat unique, in that, trains with grossly different performance characteristics operate on the same section of track. In general railways, particularly those in Europe, tend to limit the variability of train characteristics on a particular line and therefore can maximise the capacity of that line.

The introduction of ATP in the late 1980's, forced QR to reconsider the method of determining braking distances, because it was now necessary to provide sufficient distance for the ATP system to stop the train. Actually train testing highlighted the inadequacy of previous practices. Since then, QR has refined the calculation method to take into account the brake delay time, mass distribution and the actual track gradients (as opposed to averaging track gradients).

Assuming constant gradient track, the braking distance can be calculated using:

$$S = -(U + b*t_d)^2/2(a + b) - U*t_d - b*t_d^2/2$$

"U" is the speed of the train when the brake command was issued
"a" is the acceleration provided by the braking system
"b" is the acceleration provided by gravity
"t_d" is the train's brake delay time
The terms in *italics* allow for gravity effects during the brake delay.

Figure 4 – Braking distance equation with delay

Separate calculations, solving for "S" or "U" as necessary, are done for each gradient working backwards from the Limit of Authority, taking into consideration the location of the train's centre of mass and its length.

The method of calculating braking distance had been used in a somewhat primitive tool for many years. Whilst this method relies on some simplifying assumptions, in particular a uniform train mass distribution, the extensive experience to date has demonstrated that the results can be trusted. This calculation method is fully specified in the requirements specification for the PC tool.

3.5.1 Calculation Assumptions

The method of calculation assumes the following:-

- Gravitational acceleration is $9.79ms^{-2}$ for the entire QR network.
- The mass of the train is uniformly distributed throughout the length of the train i.e. the centre of mass is longitudinally in the centre of the train. (There has been some research to support this assumption. This has also been supported through experience.)
- The braking coefficient is not a function of speed and is a constant for a specific train type.
- For the period of the brake delay, there is no "acceleration" force from either gravity or the train's brake acting on the train, and after this time has elapsed there is full train braking force applied.
- Retardation due to track curvature and viscous drag can be ignored.

4 Braking Distance Calculation Tool

4.1 Implementation Concept

The tool is used in the design process for a railway signalling application. It is only used when required to calculate train braking distances.

The tool is intended to run on the IMB PC® platform, the platform used by QR. Due the potential safety consequences of an incorrect result, specifically a distance that is too short, some diversity has been used as a means of defence against the risk of such errors due to factors outside of the tool's application. The extent of the diversity is:

- There are two versions of the tool; one for the Microsoft Windows®[2] environment, the other for the IBM OS/2®[3] environment.
- Both versions are written using the C^{++} language. However C^{++} compilers from different suppliers are used.

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[2] Windows is a registered trademark of Microsoft Corporation.

[3] Operating System/2 and OS/2 are registered trademarks of International Business Machines Corporation.

- The development of the each version was undertaken by different organisations, albeit to a common detailed and specific requirements specification.

The two versions have been designated as "ISAAC" and "NEWTON".

From the user's perspective, each version of the tool operates in the same way:

- Input data files (ASCII text) are prepared specifying the train performance ("Train" file) and the track configuration ("Track" file).
- A "Selection" file (ASCII text) is prepared nominating the specific train types from the Train file and the specific Limits of Authority from the Track file for which the calculations are required, and the name of the "Output" file.
- Assuming that the input files exist, they are syntactically and logically checked for correctness, and provided there were no errors, the tool will perform the required calculations for the nominated train types and limits of authority.
- The tool will create the output file with the specified name containing the source listing of the input files and the results.

Both ISAAC and NEWTON versions of the tool need to be used before any calculated result can be accepted. The process requires formal review of the input source data and the results from both tools. This review also includes a 'reasonableness' test of the calculated result.

4.2 Implementation Experience

The project began with the production of the requirements specification. This largely involved documenting the essential features of the latest evolved prototype and introducing features to overcome the severe limitations of this prototype. Formal reviews were held involving appropriate subject matter experts. Issue 1.0 of the requirements specification was issued February, 1998. The requirements specification, did not specify the safety requirements, but did specify the requirement for two diverse tools and the language C^{++}. At that stage no formal safety analysis had been done, however based on the engineering judgement of those involved with reviewing the requirements specification at the time, it was clear that diversity was the only practicable defence against the COTS products for the development and eventual use of the tool.

Due to resource constraints the development of the tool was deferred, although there was an ever-increasing need to progress it. This development was put forward and accepted as an undergraduate software engineering student project. Two students were engaged to develop, independently, the two diverse tools. The development process was managed under a Quality Management System (Certified to AS 9001). Whilst this did not lead to the creation of the tool, it did highlight some errors and inconsistencies in the requirements specification. Fourteen formal "Change Requests" (CR's) were raised. These were actioned under a formal review and approval process. It should be noted that not all requests for change were accepted. In all those changes raised, there were no adverse safety issues.

Issue 2.0 of the requirements specification was issued July 1998. The development by the undergraduate students ceased in July 1998.

Given the progress at the time, it was clear that professional resources were required if the tool was ever to become a reality in the near future.

Coincidentally, QR had introduced a process for undertaking research and development projects. A formal research and development submission was prepared. This submission was based on the fact that no such tool was known to exist in the railway industry and the safety issues associated with such a tool. Suffice to say that the submission was accepted.

Formal contracts were let to two different organisations. The organisations were 'different' in more than ownership; one was a specialist software research organisation with limited railway domain knowledge; the other was railway domain research organisation, with some software engineering ability.

Whilst the tool requirements specification specified the key requirements, the contract also specified key standards, which the developers were expected to observe. Specifically EN 50128 was specified. The contract also included the follow clause:

> *"The C^{++} language contains some features and practices which should not be used for safety-related applications. One such reference is the publication C^{++} in Safety Critical Systems by Binkley, David W., NISTIR 5769, November 1995. Such features and practices should not be used for this development."*

From the contractor's perspective the compliance requirement with EN 50128 was very much limited to the detailed design and coding phases. The safety case and acceptance testing were excluded from the contracts.

Acceptance testing was undertaken by QR. Tests were devised to check each feature specified in the requirements specification. In addition, simple scenarios were devised to verify the correctness of the calculation. The tool output was compared with hand calculated results.

During this phase of the project six further Change Requests were raised which resulted in Issues 3.0, 4.0 and 5.0 of the requirements specification being issued. The changes arose during acceptance testing:

- CR15 – this change related to the parameter range of a user definable parameter.
- CR16 – this change related to the method of calculation where there were track related speed changes within braking distance to a target. (The specification was too conservative in this instance.)

- CR17, 18, 19 & 20 – change to correct inconsistency and some ambiguity in relation to “errors” and “warnings”.

Whilst there have been no adverse safety errors identified, the identification of the error corrected by Change Request CR16, did highlight the ease in which errors in interpreting requirements specifications can arise. One version of the tool agreed with the hand calculated result; the other version of the tool did not. On investigation, the tool which did not agree, had interpreted the requirements specification as had been intended, although in doing so failed to satisfy another (conflicting) requirement. The other tool did not. The hand calculation was based on the tester’s opinion as to what should be the correct result. In this case, the requirements specification was incorrect.

4.3 Language Selection

The choice of C^{++} was largely a matter of practicality. QR has considerable in-house expertise as the language is used for other applications. Its widespread use within the Information Technology community also meant that there would be a reasonable pool or resources available at least for the foreseeable future.

The language ‘C’ is listed in standards such as CENELEC EN 50128 as a useable language, albeit with limitations. Whilst ‘C’ is very much a procedural language, C^{++}, being an object-orientated language, allows for well-structured software.

Because of the popularity of C^{++}, there was a choice of sources available for the intended operating systems. This provided some confidence that the language compilers would be somewhat diverse.

It was for these reasons that C^{++} was selected.

4.4 The Hazards

Applying the calculated braking distances on a railway provides the potential for hazards to exist. There are essentially two “hazards”; one is safety related, the other commercial. The safety-related hazard is a calculation of a braking distance which is shorter than required, whereas the commercial hazard occurs in a calculation of a braking distance which is much longer than required. In essence a wrong braking distance is the common “hazard”.

4.5 Causal Analysis

Causal Analysis was performed for the hazard “Braking distance wrong” using the Fault Tree Analysis technique, to identify the causes that have the greatest impact and to provide some measure of the level of trust that one could place on the tool’s results.

The tool used was FaultTree+ for Windows®. The modelling attempted to consider all plausible causes, including those external to the tool e.g. the accuracy of the raw input data, and the roles of the designer and design checker.

The analysis shows (Figure 5) that the diversity in the tool virtually eliminates those results which are not the same from each tool. The major cause of the hazard stems from when the results are the same.

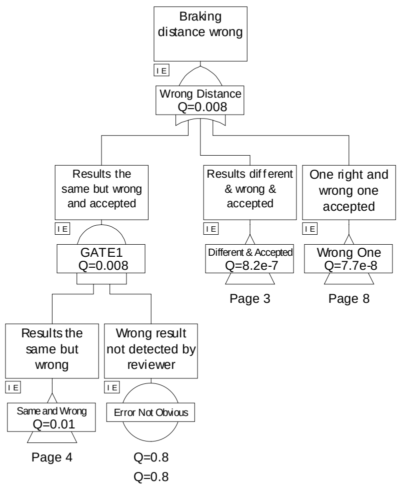

Figure 5 – Top Event – Braking distance wrong.

Figure 6 shows that the major cause of the hazard stems from the accuracy of the raw track and train data. This is outside the scope of the tool, but it highlights the importance of having the correct raw data. The tool provides little defence against incorrect raw data.

Figure 6 also shows that it is unlikely that identical results would occur due to different tool implementation errors.

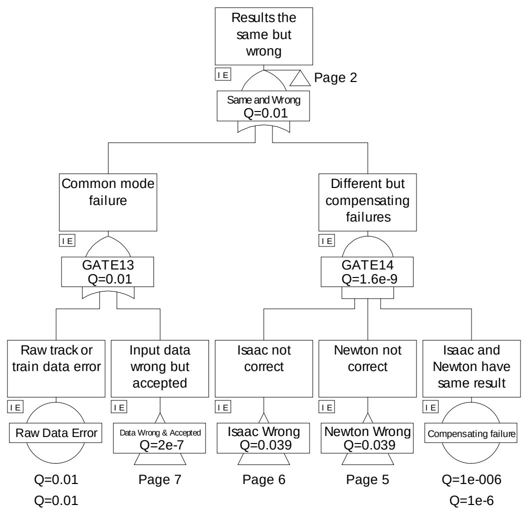

Figure 6 – Gate “Results the same but wrong”.

Figure 7 shows the impact of having a common requirements specification and the roles of the designer and design checker.

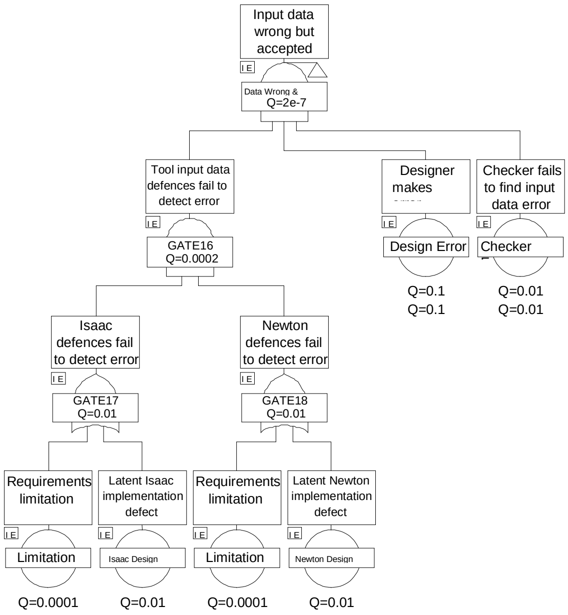

Figure 7 – Gate "Input data wrong and accepted"

Figure 8 is included to show the "non-common" mode causes of failure for a tool version considered in the analysis.

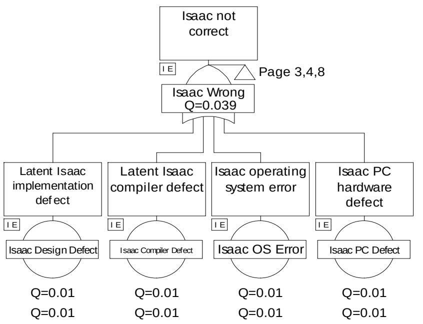

Figure 8 – Gate "Isaac not correct".

The quantification of basic events, particularly those that relate specifically to each version of the tool e.g. Figure 8, was not based on any robust analysis process. Whilst these are potential sources of tool to 'failure', the quantification relates only to those errors which actually allow the tool to execute to completion and produce erroneous results. These erroneous results would only manifest themselves when the input data evokes the defect. Whilst each tool function was tested, the combinational variation of train and track features made it impossible to test exhaustively. The quantifications were determined through peer discussion.

Ignoring the issue of the accuracy of the raw data, the probability of the hazard occurring increase by some 4 orders of magnitude if there were no diversity. In fact the tool itself becomes the greatest cause contributor.

The analysis clearly shows that without diversity, it would be difficult to trust the results of the tool.

5 Conclusion

Calculating train braking distance is not without some uncertainty. The complex nature of the many and varied factors necessitates the making of simplifying assumptions. However the limitations of those assumptions need to be catered for.

The use of computers to perform design calculations is not new. Their limitations, other than perhaps their numerical accuracy, is often not recognised.

There was significant effort in the formulation of the requirements specification. The process of formal reviews and change management were effective. However, this still resulted in a number of inconsistency errors. The evolutionary process through numerous prototypes was a major influence on the definition of the requirements. Without that process, it would not have been possible for the requirements specification to be as comprehensive.

The Causal Analysis re-affirmed the need for diversity.

The implementation strategy in contracting out the development of the two diverse tools to different organisations was justified. Acceptance testing was made much easier due to the fact that the same input data is used for both versions, and that the error handling and output requirements were specified comprehensively.

Some implementation errors have been found in both tools. However none were found to be exactly the same. The fact that none of these errors were the same gives some confidence in the degree of diversity of the tools.

The project timescales were much longer than envisaged. This was largely due to there being no "formal" project and hence no funding until late in the tool's evolution. The evolutionary process was essentially a "spare time" activity.

6 References

RAILTRACK PLC (Safety & Standards Directorate), Railway Group Standard (May 1996), Lineside Signal Spacing, GK/RT0034, Issue 1.0, May 1996, London.

CENELEC (European Committee for Electrotechnical Standization EN 50128, Railway Applications – Software for Control and Protection Systems