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# Evaluating train protection systems

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This paper arose from the work carried out for the Cullen/Uff Joint Inquiry into Train Protection Systems. It is concerned with the problem of evaluating the benefits of safety enhancements in order to avoid rare, but catastrophic accidents, and the role of Operations Research in the process. The problems include both input values and representation of outcomes. A key input is the value of life. This paper briefly discusses why the value of life might vary from incident to incident and reviews alternative estimates before producing a 'best estimate' for rail. When the occurrence of an event is uncertain, the normal method is to apply a single 'expected' value. This paper argues that a more effective method of representing such situations is through Monte-Carlo simulation and demonstrates the use of the methodology on a case study of the decision as to whether or not advanced train protection (ATP) should have been installed on a route to the west of London. This paper suggests that the output is more informative than traditional cost–benefit appraisals or engineering event tree approaches. It also shows that, unlike the results from utilizing the traditional approach, the value of ATP on this route would be positive over 50% of the time.

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## Introduction

Operations Research (OR) is primarily concerned with methods for analysing complex interactive systems. In its early days, the benefits of actions in uncertain and risky situations was an important OR topic. Much of the work in the area of defence, for example, tried to relate the costs of proposals to the very uncertain outcomes. Kirby and Capey[1,2] give numerous examples from World War II of analysis of uncertain and potential losses against uncertain gains.

Following this pioneering work, however, risk analysis largely became the province of engineers and valuation that of economists. The important topic of how best to evaluate risky situations was largely ignored, with a broad acceptance of the 'expected value' approach within a cost–benefit framework. One notable exception was the work of Cook *et al*,[3] who use data envelopment analysis to develop differing weights for benefits such as saving life or limb and inputs such as traffic delay and contract cost.

This is not to say that methodological development has been absent, but rather that OR has been lacking in interdisciplinarity. The engineers have tended to concentrate developing in interdisciplinarity on methods of minimizing risk. Thus, Kornhauser *et al*,[4] in an excellent paper on transporting hazardous materials, write 'there are several key elements (in the decision)… volume, frequency … their quantification requires economic considerations which are not considered as part of the paper'.

Orringer *et al*,[5] consider rail safety procedures in the context of a fixed maintenance budget. Interestingly, they use Monte-Carlo simulation to show that safety benefits can be achieved by ignoring minor faults with limited potential to cause accidents to enable the search vehicle to continue looking for major faults. However, the costs and benefits of another vehicle are not examined.

In a more modern example, Barnet[6] looks at the issue of air safety and its future. The problems of dealing with risks that are extremely rare is highlighted, but the current air safety culture accepted without evaluation. As we discuss later, the implicit extremely high value given to life on an airplane contrasts sharply with that given on the motorway.

This paper is concerned with bridging the gap between risk estimation and risk valuation in the problematic area of catastrophic failure.

## Background to the case

In 1989, Hidden[7] conducted a public inquiry into a major railway accident at Clapham Junction just south of central London. He concluded that British Rail (BR) should introduce automatic train protection (ATP) on a large 'percentage of its network' within 5 years, with a high priority being given to densely trafficked lines. ATP is a complex and expensive system that uses track side transmitters to vary the speed of the train depending upon line conditions. Essentially, ATP would eradicate all accidents

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that occur as a result of a train passing a signal at danger, commonly known by the acronym Signal Passed at Danger (SPAD).

In BR itself, there was considerable unease that the costs of installing the system appeared to exceed the likely benefits. As a consequence of the Government's 1993 decision to privatize BR's operations, ATP installation was postponed. At that time, the BR board informed the Chief Inspecting Officer of the Railways that the 'time factor in installing ATP was adversely affected' by the 'tight financial situation and current uncertainty about future developments'. In 1995, the Director of Safety for the now privatized Railtrack informed the Chief Inspecting Officer that there was no legal basis for Railtrack to provide ATP, if this were not 'reasonably practicable'.

A number of cost–benefit-type studies suggested that ATP was not cost effective, but, in recognition that some further safety measures were required, in 1999 Railtrack[8] elected to adopt the cheaper Train Protection Warning System (TPWS). It estimated that it would prevent around 65% of SPAD-related accidents at around 20% of the cost of ATP.

However, following the Joint Inquiry into the Southall and Ladbroke Grove accidents and in the light of the adoption of European Directives on inter-operability, Cullen[9] recommended that Raitrack

1. install a supplemented TPWS (TPWS+) on all high-speed lines
2. install ERTMS level 2 (ATP plus) on the key East Coast Main Line, West Coast Main Line and Great Western Main Line, and
3. consider the extension of ERTMS level 1 (ATP) where currently installed to cover all trains.

As important Cullen suggested a timetable for implementation.

In April 2002, a cross industry report (ERTMS[10]) considered these recommendations. It concluded that only ERTMS level 2 would be adequate for the UK rail system as a whole or particularly because of capacity constraints associated with level 1. They also argued that the accelerated timetable suggested by Cullen would actually involve more death as passengers transferred to the road. Owing to the implementation of the 'second best' TPWS throughout the system, the cost of an accelerated 'enhanced' scheme was now put at £75 million per life saved. To make any financial sense of the better safety system, the capacity gains from ERTMS level 2 were needed. Thus, despite ERTMS not being available until 2008 at the earliest, the argument not to follow Cullen's recommendations was accepted by the government.

It is not our purpose here to dispute whether this is indeed the 'best' solution for the UK. However, there was a similar confidence in 1995 over not following the recommendations of Hidden and, in particular, that not extending ATP to a stretch of railway to the west of London between Paddington and Didcot was the 'best' decision. Two serious crashes later, that decision looked seriously erroneous.

This paper is primarily concerned with the debate about the use of cost–benefit analysis (COBA) in these situations, the limitations of the analysis and the development of improved analytic methods.

## Problems with former analyses

The formal analyses of safety-related projects have, in general, been uncritically framed within the context of a cost–benefit model. In their simplest form, these models estimate the cost of a project, investment or regulation narrowly to those who undertake it, and contrasts these costs with the benefits that would result in terms of injuries or fatalities avoided, years of life added, etc. The principal problem with simplistic cost–benefit approaches, in the context of rail safety, is that they do not account for a number of issues that arise from the nature of risky events, such as individual and societal risk perception, differences in expert and lay risk assessment or even the often catastrophic nature of accidents. Indeed, the potential cost of catastrophes was explicitly excluded from the cost–benefit calculations of ATP because there was no agreed method of treatment.

What is presented here is an alternative approach to assessing the validity of rail safety projects, which does take into account the often catastrophic nature of rail and transport accidents. In addition, we seek to consider the costs and benefits to society as a whole and to utilize values that more accurately reflect the values of those affected by rail disasters. We illustrate our approach by comparison with previous studies of the extension of ATP on the Paddington–Didcot line, which concluded that investment was not cost effective. Before presenting our model, we will briefly discuss some of the concerns that have driven us to develop an alternative model.

## Risk perception and the framing of risk

Research by Morgan[11] and other comparable studies (eg, Margolis[12] and Carthy[13]) suggest that individuals have a preference for avoiding disastrous outcomes, as well as outcomes that affect those who had to expose themselves to a risk that they could not mitigate. Individuals value a reduction of those risks to which groups of individuals are unavoidably, or involuntarily, exposed more highly than the reduction in risk that occurs to those who deliberately seek or actively contribute to a risk. Thus, risks occurring in mining, offshore oil and gas production and passenger air travel would, by most individuals, be assigned a higher priority than accident reduction in the context of certain sports activities. Meanwhile, the *a priori* willingness of individuals to engage in a risky activity differs widely. As a result, social risk assessments depend largely on framing, which makes risk comparisons inherently difficult. To give an example, the fact that many people engage in far riskier activities than rail travel does not imply that existing risk levels in rail transport are tolerable and/or that society should disinvest in rail safety.

The implication of this is that, if the COBA approach is utilized in a transport safety context of a different, higher than the 'average' value of life should probably be utilized in recognition of both risk aversion of customers and the catastrophic nature of the events.

## Validity of COBA

The fact that, in the context of a privatized rail industry, investments in passenger safety compete directly with the economic interests of the operators as well as other potential consumer interests in speed and value for money makes it essential that the assumptions on which COBA are based mirror both the nature of accidents and that of social preferences as closely as possible. In the past, these concerns have led some academics to oppose the use of COBA in the context of health- or environment-related investments.

Kelman[14] noted three principal objections to the use of COBA. Firstly, that there were areas of environmental and health and safety regulation where a certain course of action is justified, even if benefits do not outweigh its costs. Secondly, that there are often good reasons to oppose efforts to put dollar values on non-marketed benefits and costs. Lastly, that there were occasions where society would explicitly wish not to monetise benefits or costs, because it places a superior importance on other issues.

While Kelman's critique has some validity, it is essentially limiting. In our view, any decision requires bringing together the inputs and outputs, and this requires aggregation on a common scale utilizing some weighting mechanism. Utility-type weights have advocates but, monetary weights, if they can be used, have the major advantage of direct transferability between projects.

The major problems with conventional approaches to COBA is that they have often been applied mechanically (and narrowly) without taking account of the true nature of risky events (such as the occurrence of disasters) nor the different value weights that will arise in different contexts. In this context, however, central to any evaluation is the value of life.

## The value of life

Today, the methodology appropriate for the valuation of a human life, both in terms of its size and derivation, is still a matter of doubt. Conventional methods for the valuation of life range include: a discounted estimate of future earnings; an estimate of the discounted loss accruing to others; and an estimate of society's past valuation of human life implicit in public initiatives aimed at reducing loss of life and a survey estimate of an individual's willingness to pay (WTP) for a reduction in the risk of death.[15]

While the WTP method today enjoys the broadest acceptance, there are different views as to how WTP is best studied. According to Viscusi,[16] these can be grouped into 'labour market studies of the value of life', those based on 'tradeoffs outside the labour market' and 'value of life estimates based on survey evidence'. Although studies continue to be published following all three approaches, labour market-based approaches appear to have gained the widest acceptance, while survey-based approaches have become less popular.

Criticisms of WTP approaches have focused on two points, namely the moral problems underlying the WTP approach, and secondly, the inaccuracy of WTP estimates. As concerns the moral dimension of WTP studies, Kelman[14] has suggested that, in taking guidance for public decisions from private decisions, this approach falsely assumes that there should be no difference between private behaviour and the behaviour we display or desire in public life. Rather, Kelman suggests that should our society provide us the occasion to display a reverence for life that we espouse, but do not always display. In our view, this implies that if a society were to value collectively a certain outcome, such as having profitable, privatized railways invest in, and ensure, safe travel, it may wish to express this in a higher than otherwise detected valuation of human life.

Another significant problem concerns the inaccuracy of WTP estimates. Jones-Lee[17] presents an early meta-analysis of existing studies (labour market-based and others) and revealed preference-based estimates of human life to range from £410 000 to £795 000. (All values in this section have been standardized to 1987 £ Sterling.) Questionnaire-based estimates, meanwhile, showed an even broader divergence from £50 000 to £8 250 000.

In terms of magnitude, the more recent survey of labour market-based WTP by Viccusi[16] essentially supports Jones-Lee's earlier findings. Thus, for studies post-1985, Viscusi identified values of life ranging from £0.96 to £9.72 million, an average valuation of human life of £4.4 million. Given that the studies include a range of countries, a value of £2 million (equivalent to £3.3 million in 2000) suggested earlier by Jones-Lee[17] on the basis of UK studies would appear to represent an appropriate estimate for the value of life.

The more recent WTP estimate of the value of life by Jones-Lee[18] of (£ Sterling, 2000) 1.157 million, presented on behalf of Railtrack at the Paddington Inquiry, was based on a relatively small sample ($n = 150$). The fact that this estimate would tend to contradict the cumulative evidence suggested by other approaches and studies suggests that it is not reliable.

Most recently, Cullen[9] states that on the basis of value for life estimates for road accidents and the *clear measured risk* *aversion* of rail passengers, BR and the HSE now use a current value of life for passengers on railways of £3.22 million, £2 million in 1987 terms. We would also argue that where the result is a 'catastrophe' (such as almost universally applicable to airline accidents or nuclear incidents), this value should be appreciably higher than the £1.34 million suggested by Railtrack.

## Estimation of the risk of an accident

Rail accidents occur for a variety of reasons such as bridge collapses, rail distortion or even suicide. As highlighted earlier, another major cause is when a driver has passed a signal set at danger (a SPAD) and gone on to collide with another train, hit buffers or derail at points.

The estimation of risk of a SPAD-based rail accident can be approached from two directions. Where there are little or no data on past incidents, it makes sense to capture any subjective information that individuals hold about the likelihood of any step that may lead to an accident. In this way, it is possible both to identify the critical factors and to obtain some, albeit subjective, estimate of the risk. In some cases, some statistical probabilities can be attached to these events that can contribute to accidents, but in most cases the very limited observations make such estimates subject to potentially a very wide error. This problem is magnified because each probability is part of a multiplicative chain, and hence the resulting potential error can be extremely large.

Over the years, BR has invested heavily in identifying risk critical elements using this Event Tree approach and has, quite naturally, taken this forward as a forecast of the risk (Modern Railways[19]) but without consideration of the very low reliability of the estimate.

An alternative method of assessing the risk of a rail accident is based on estimating the average number of SPADs per annum for any section of line (from the SPAD records), and then applying an appropriate ratio for SPADs to accidents. This methodological approach follows the suggestion by Rasmussen[20] that where there are substantial recorded experiences with accidents and where individual probabilities of an event or fault tree are difficult to calculate, an 'actuarial method' based on accident probabilities should be used. This approach poses a number of minor problems as regards the applicability of national rates to specific sections and the time period of collection, but does have the significant advantage of being based on a sufficiently large number of observations. While this approach is less precise it has the virtue of consistency. As Kornhauser *et al*[4] put it 'a more reliable measure of risk can be obtained from a less precise yet consistent analysis than an analysis that is very detailed in parts but fraught with data gaps in other parts'.

Concerns with the costing of catastrophic, multi-fatality events in previous studies, were raised by the then nationalized rail industry as early as 1994. Thus, section 6 of the BR ATP report noted that:

> 'The largest number of fatalities… from ATP preventable accidents was seven, at Paisley in 1979. But, it is all too easy to envisage circumstances in which an ATP-preventable accident could have a death toll an order of magnitude greater than that. The analysis considered by the Board recognized this as a crucial issue, but concluded that there seemed no ready way in which it could be quantified' (BR[21] p 27).

However, if a catastrophe is assumed to be simply an extremely unusual event with many fatalities (ie, above seven), then the statement is not strictly accurate; it is possible to obtain some estimate of the impact of a catastrophe on COBA using Monte-Carlo simulation.

## Applying the Monte-Carlo approach

The main feature of the Monte-Carlo approach is the combination of a random number and a probability distribution of an event. The event in this instance, an accident, is assumed to have a Poisson distribution. This distribution is based upon a single parameter, the mean, and accidents generated by this distribution over a number of years will have the same mean. The Poisson describes the distribution of rare events and has been widely applied in the areas of rail safety (eg, see Evans[22]). With the use of a random number generator, the number of accidents in any year can thus be simulated. The average of these will be the mean of the distribution. If the accident rate is say 0.05, then one accident would be expected to occur every 20 years. Over a 25-year period, however, it is possible for there to be no accidents at all or conversely three could occur in 1 year. Monte-Carlo simulation views these as simply samples from the complete range of possible alternatives.

If an accident is projected to occur, then the second question is how serious will it be? A distribution of these occurrences can be estimated from previous research and past observation on the severity of accidents. By generating more random numbers and mapping them to this distribution, casualty rates can be established that, when averaged over many trials, replicate the casualty distribution, including those rare catastrophes.

There is a set of random numbers for each year, and 25 such sets for the whole model (assuming a time horizon of 25 years), which constitute a 'trial'. Since each combination is a random sample, the outcome (eg the cost/benefit ratio) is equally a valid random sample from the range of all possible outcomes. Each 'trial', with new sets of random numbers, is another possible sample from these outcomes. As the results are based on the underlying distributions, if sufficient trials are carried out, the results obtained will replicate the likelihood at which these results occur in reality. The appropriate number of trials is contentious. If the random number generator is poor, then recycling can occur relatively quickly making runs of more than 150 simply repetitive. However if, as in this case, the simulation is simple then any inefficiencies from too many runs are balanced by the possibility of covering a wider range of outcomes. In this case, we chose rather arbitrarily runs of 1000.

An important feature of the approach is that an estimate of the impact of a catastrophic event appears, together with the likelihood of these type of results. By allowing for the possibility of a multi-fatality accident, this model presents a methodological superior alternative to event tree analysis, which typically averages out fatalities over a number of years and assesses their costs on that basis.

Our model is based upon two units of measurement, accidents and resulting casualties. As outlined in the following sections, benefits are associated with the number of casualties avoided. The model then takes the year-by-year cash flows and discounts them back to provide a net present value (NPV) and reports the number of times in 1000 trails benefits exceed costs in addition to the mean, median and standard deviation of these trials.

## Casualty frequencies and rates

BR[21] and WSAtkins[23], with the modifications suggested by Hendy[24], enabled us to identify a mean accident rate. Further data from BR,[21] WSAtkins[23] and AEA[25] provided us with enough data to define the probability distribution for the size of any accident as given in Table 1. Casualties are expressed in the form of fatality equivalents (FATs), where a major injury is defined as counting as 0.1 equivalent fatality and a minor injury counts as 0.005 equivalent fatality (BR[21]).

To summarize, we can estimate the number of accidents in a given year, the severity of which is expressed as a fatality equivalent. This value can then be multiplied by the value of life to obtain the cost of an accident. If ATP was installed, the prevention of these accidents would represent a benefit that can then be offset against the cost of installation of the ATP system. There are, however, a number of other factors to be considered. Specifically, assumptions (or more precisely estimates) have to be made regarding other matters such as the discounting rate, asset life and social costs. These are now briefly discussed.

## Other factors in the cost-benefit study

The first of the modelling assumption concerns the discounting rate, that is, the rate at which future cash flows will be deflated to express them in consistent units of currency. To avoid problems of forecasting inflation, these are taken as real rates (ie, all projections and discount rates assume zero inflation). A real discounting rate of 8% is a well-known, and frequently used rate of return within the rail industry. In the later years of the nationalized British Rail, potential major investment projects were required to show an 8% real rate of financial return before approval could be given.[26] In today's economy, however, there seems little justification for an 8% level and more justification for a 3% real rate of return, slightly higher than real risk-free returns.

A second consideration is the length of time the ATP installation will be offering benefits, the planning horizon. If maintenance costs are included, there is no reason to presuppose that the system should not have a useful life in the order of 25 years. Evans,[27] for example, used a 29-year planning horizon in his assessment of projections of accidents and fatalities avoided by the fitment of the TPWS. Annual maintenance costs were assumed to be 10% of construction costs.

Physical costs are defined as the direct costs to the train operating company and Railtrack of an accident. This will include items such as rolling stock repair, infrastructure renewal and lost revenues from ticket sales. Annex 7 of the 1994 BR ATP study (BR[21]) provides an estimate in 1994 prices of £4.2 million for a major accident (ie, one involving loss of life) and £43 K for a minor accident. As in the approach adopted, both the number of accidents and the severity of each accident are directly estimated, these

**Table 1** Fatality equivalent frequency distribution

| *Class interval* | *Mid point* | *Frequency* | *Probability* | *Cumulative probability* |
|---|---|---|---|---|
| 0 to less than 0.1 | 0.00 | 400 | 0.8333 | 0.8333 |
| 0.1 to less than 1 | 0.55 | 24 | 0.0500 | 0.8833 |
| 1 to less than 2 | 1.5 | 25 | 0.0521 | 0.9354 |
| 2 to less than 3 | 2.5 | 12 | 0.0250 | 0.9604 |
| 3 to less than 4 | 3.5 | 3 | 0.0063 | 0.9667 |
| 4 to less than 5 | 4.5 | 3 | 0.0063 | 0.9730 |
| 5 to less than 10 | 7.5 | 10 | 0.0208 | 0.9938 |
| 10 to less than 25 | 17.5 | 2 | 0.0042 | 0.9980 |
| 25 to less than 50 | 37.5 | 1 | 0.0021 | 1.0000 |
| Total | | 480 | | |

BR figures (adjusted for inflation) can be directly attached to accidents.

In the context of rail safety, any COBA must assess whether the benefits of such a measure would exceed the costs for the public as a whole, not just for the rail operator. Inclusion of these social costs recognizes that a valuation should be placed upon events such as the delay, disruption and the re-routing of journeys. Furthermore, it is important, particularly with the current fragmented railway structure, that an item headed social cost is included to ensure that an appropriate 'public' perspective is adopted in the COBA. Unfortunately, we were unable to find any estimates of such costs in the context of rail accidents. Clearly, therefore, any evaluation of social costs is speculative in the extreme, but examination of the expected delay resulting from minor and major accidents suggested that social costs are likely to be a minimum of some 10% of the physical costs of an accident.

Improvements in rolling stock design have reduced casualties and may continue to do so in the future. Hence, improvements should also be taken into account in any appraisal. Atkins[23] used an annual reduction rate of 0.77%, and this is used in this example. On the other hand, it is also clear that more people are using the railways. If more trains run then the accident rate is likely to increase. If more passengers are loaded on the same number of trains then the casualties per accident will increase; likewise if trains are travelling faster so that collision speeds increase, a greater number of casualties could be expected. These effects are likely to be as significant, if not more significant, than the reduction in casualties via rolling stock improvement and would logically be expected to work in the opposite direction, that is, increase the likelihood of accidents and/or casualties. Growth in passenger numbers has been one of the few successes of privatization of the railways, with figures increasing annually by over 4% nationally for the period 1996/1997 to 1999/2000 and over 6% per year for Thames Trains, operator of the Paddington–Didcot line. Projection of this level of growth over 25 years, however, is contentious, although the Government's 10-year plan projects a national growth of 50% in passenger numbers over the next 10 years (DETR[28]). Nevertheless, it is equally clear that to assume no growth is invalid. Since there is a close relationship between economic growth and travel, one approach is to apply the projected long-term growth rate of 2.5% as the measure of overall business growth.

## Application

In this section, the results are discussed of applying the methods, model and assumptions discussed earlier to the installation of ATP on the Paddington to Didcot route. The route-specific factors are the costs of installation and the current level of SPADS. The latter has already been discussed, and the former was taken from the COBA study undertaken by Atkins.[23]

Using these figures, both statistically derived and assumed values, the cash flows for the project were simulated 1000 times. Table 2 reproduces these results for a number of scenarios, Case 6 presents findings for what is deemed to be the most likely scenario (in italics), while the remaining columns give the average results for nine other cases using a number of different assumptions identified in the rows, for example, different discount rates or values placed on life. These range from the least to the most favourable for the adoption of ATP. The figures at the bottom under the heading 'Outcomes' give a risk quotient. This is defined as the percentage (expressed as a probability) of times the benefits of implementation outweighed the costs, from the

**Table 2** Monte-Carlo simulation, Cases 1–10, assumptions and results

| *Case* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* |
|---|---|---|---|---|---|---|---|---|---|---|
| Assumptions | | | | | | | | | | |
| Discount rate (%) | 8 | 8 | 6 | 6 | 6 | *3* | 3 | 3 | 3 | 2 |
| Vol inflation (%) | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | *2.5* | 2.5 | 2.5 | 2.5 | 4.0 |
| Value of life (£m) | 1.0 | 2.5 | 2.5 | 2.5 | 2.5 | *2.5* | 3.3 | 3.3 | 3.3 | 3.3 |
| Social cost factor | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | *0.1* | 0.1 | 0.1 | 0.2 | 0.2 |
| Project life (years) | 20 | 20 | 20 | 20 | 25 | *25* | 25 | 30 | 30 | 35 |
| Physical costs (major) (£m) | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | *5.4* | 5.4 | 5.4 | 5.4 | 5.4 |
| Physical costs (minor) (£k) | 55 | 55 | 55 | 55 | 55 | *55* | 55 | 55 | 55 | 55 |
| Casualty reduction (%) | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 | *0.77* | 0.77 | 0.77 | 0.77 | 0.77 |
| Business growth (%) | 1.0 | 1.0 | 1.0 | 2.5 | 2.5 | *2.5* | 2.5 | 4.0 | 4.0 | 4.0 |
| SPADs per annum | 7.9 | 7.9 | 7.9 | 7.9 | 10.68 | *10.68* | 10.68 | 10.68 | 10.68 | 10.68 |
| Accidents/SPADs (%) | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | *3.8* | 3.8 | 3.8 | 3.8 | 3.8 |
| *Outcomes* | | | | | | | | | | |
| Risk quotient | 0.099 | 0.219 | 0.252 | 0.275 | 0.358 | *0.479* | 0.611 | 0.602 | 0.642 | 0.668 |
| Mean value (£m) | −6.36 | −2.25 | −0.95 | −0.31 | 3.16 | *10.83* | 25.22 | 30.50 | 33.37 | 42.26 |
| Median value (£m) | −8.68 | −7.44 | −7.18 | −6.83 | −4.03 | *−0.63* | 6.95 | 8.43 | 8.99 | 11.86 |
| Standard deviation (£m) | 7.20 | 14.53 | 17.54 | 17.20 | 20.99 | *34.42* | 48.38 | 56.72 | 62.95 | 78.14 |

1000 'sample values' of outcome. The mean, median and standard deviation of these sample values are also given.

## Discussion

Decision making in risky situations inevitably has considerable complexity. The structuring and statistical methods of OR utilized in this case are, it is contended here, extremely valuable in generating appropriate information. However, one additional problem that needs resolution is the appropriate objectives of the firms, safety bodies and government regulators. A full OR study of this problem is required, but is unfortunately beyond the scope of this paper.

One suggested new criterion that could be employed is the probability that benefits will exceed costs, or as defined above, the risk quotient. Safety-conscious organizations, that is, those that are risk adverse, would seek a small risk quotient. In the context of rail safety, they would undertake a safety-enhancing investment even if the risk quotient was relatively low. Those with alternative priorities, on the other hand, would use a higher risk quotient as the criterion. Examining the results from a risk neutral position, that is, by applying a simple criterion of 0.5, the decision to invest is strictly marginal, 0.479.

The results also provide interesting contrasts with other approaches. With high standard deviations, the mean and median values provide poor forecasts of likely outcomes. Nevertheless, as the median is less affected by extremes, its values would be more in line with results using an event tree approach. Thus, in our most likely scenario, Case 6, a negative median value would correspond with a negative evaluation using more traditional approaches. This would lead to advocacy of non-investment in ATP.

We would argue, however, that there are considerable dangers when basing judgements on an average value that does not take into account extremities. In Case 6, the risk quotient is marginal and the mean is strongly positive. We believe that the reporting of results in this manner is far more informative and transparent than earlier approaches.

The other results in the table highlight the critical areas to be considered in terms of the assumptions. Ignoring the SPAD rate, which technically should be directly observable, the factors that have the strongest impact are the discounting rate and the value of life. Perhaps surprisingly, the useable life of the investment and the social costs have little significant impact over the feasible range.

## Conclusions

The use of cost–benefit analysis to analyse investment in complex systems involving death and serious injury has not been universally accepted. Quite naturally, putting a value on a life or an arm arouses serious misgivings and the problem of the trade-off between those who pay and those who receive the benefits is always a contentious issue. However, in our view the decision maker always needs to weigh objectives and establish the ability of alternative strategies to meet these objectives. In the safety context, we believe that COBA remains preferable to alternative approaches such as multi attribute utility analysis not least because the government accepts the approach. Correctly conducted COBA provides direct useable, useful information to decision makers.

However, because of the complexity of the problem and the uncertainty surrounding so many of the assumptions and values, sensitivity analysis is absolutely essential. In the case of unlikely but costly events, this should involve a risk analysis (Monte-Carlo simulation) so that under an agreed set of assumptions the decision maker has information on the likelihood of benefits exceeding costs. In our view, OR has an important complementary role to the work of economists and engineers in helping determine objectives, in structuring the problem and in conducting the risk analysis. It is to be hoped that this paper and our work for the Cullen Inquiry will lead to more involvement of OR teams, more adequate analysis and, hopefully, less tragic accidents.

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