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Abstract- In an environment where resources are scarce, decisions to spend more on safety or risk reduction need to be made on a rational basis. The assessment of such a situation must reflect the impact on society as a whole. When death and injury are involved the assessment, hence becomes very complicated. This paper discusses how societal cost models can assist in making these difficult decisions and an example is analysed based on train crashworthiness.

INTRODUCTION

Virtually any engineering project has an effect on the welfare, health and safety of society. Engineers therefore have an obligation to consider the consequences of their actions and designs, direct or indirect, immediate or long term. In general, engineering projects are very safe and have a beneficial effect, but errors and accidents do occur. Consequently, the possibility of a catastrophic event has to be considered. The assessment of such a situation must reflect the impact on society as a whole. When death and injury are involved this assessment becomes very complicated. It is difficult to quantify death and injury with its entire trauma, pain and suffering without inadvertently trivialising such suffering and reducing human life to a commodity value. However, in an environment where resources are scarce, decisions to spend more on safety or risk reduction need to be made on a rational basis.

In recent years societal cost models [12, 16, 23] have been developed to assist engineers and authorities in making these difficult decisions. The purpose of this paper is to demonstrate the use of these cost models to the wider engineering community. The example chosen is concerned with train crashworthiness and forms part of a study analysing Societal costs attributed from railway accidents.

BACKGROUND

A severe train crash has implications and ramifications far beyond the trauma and drama of the immediate event. At one end is the cost of disruption to commuter traffic resulting in lost production and wages. At the other end are the Inquiries and Royal Commissions staged at massive cost to the community. Throughout, are the costs of the pain and suffering of the victims and the bereaved.

Effects are also felt by those in need of emergency and hospital services that as a result of a major train crash will be stretched to capacity. Emergency service delivery to "routine" motor vehicle and industrial accidents must endure triaging to a level not normally experienced. Immediacy of delivery of emergency treatment is a significant factor in fatality rates [7]. Accordingly, a far higher rate of casualties can be expected in areas not directly associated with the train crash.

Rail authorities have a responsibility to consider the possibility of a catastrophic event involving a high-energy device such as a speeding train. Increasing the crashworthiness of the carriages is one way to reduce passenger injuries in the case of a crash. However, this comes at a cost and the decision how much to spend on crashworthiness needs to be made on a rational basis. This assessment should include the impact on society as a whole as an essential part of the return-on-investment decision. Only when all the costs are known can benefit maximisation decisions be made. This is where societal cost models can help.

General Approach

The risk of a rail accident occurring in the life of the train is an important parameter in the overall cost analysis. In order to obtain a Risk Adjusted Savings (RAS) on the crash costs, the potential cost saving is multiplied by the accident frequency of the crash [8]. This relation is shown in the following equation.

$$\text{Risk Adjusted Savings on Crash Cost} = \text{Potential Savings On Crash Cost} \times \text{Frequency (of Crash)} \quad [1]$$

In terms of a crashworthiness device, it can be said that if the rail authority spends more than the RAS on providing the device, the community is "in front". On the other hand, if the authority spends less, it is not carrying its full social responsibility. At the point of indifference, the rail authority spends all of the RAS on providing the crashworthiness device. This relation can be shown in the form of an equation as:

$$\text{Indifference Value of Crashworthiness Device} = \text{Potential Savings On Crash Cost} \times \text{Frequency (of Crash)} \quad [2]$$

This equation will be used in determining how much rail authorities can be expected to spend on the installation of a particular crashworthiness device.

SOCIETAL COST MODEL

General

The costs associated with a major train crash can be divided in the following categories:

1. Cost of death or cost of injury to occupants
2. Cost of carriage repair or cost of replacement
3. Remote costs

Remote costs such as infrastructure damage and injuries beyond a metre radius off occupant are excluded to limit the scope to manageable proportions. The general approach taken is one of conservatism, if the item of cost under consideration is largely inappropriate or appears remote, it is excluded altogether to ensure that the conclusion is understated in terms of the device's value.

Cost of death or cost of injury

Crashworthiness devices generally result in reduced deceleration of passengers during a crash. The lower the deceleration, the lower the severity of injuries that may be sustained by occupants. To determine the potential savings in societal cost, this change in deceleration has to be converted into savings on injury cost. This conversion is quite involving, since deceleration is an engineering parameter whilst injury cost is determined by medical parameters. However, the conversion is herewith described in detail and starts with discussing common medical injury scales, which are subsequently related to cost. It then continues with discussing how biomechanical engineers measure injury and how these injury criteria are related to medical injury levels. Finally a statistical based relationship is presented that can be used to calculate the so-called probability injury costs of a specific crash scenario.

Medical Injury Scales

Medical practitioners use a number of methods for rating injuries. The score allocated has prognostic and triaging use as well as other purposes. An overview of the most common injury severity scores is shown in Table 1. Most researchers in crashworthiness employ the Abbreviated Injury Scale (AIS) [4].

Table 1 – Injury scoring systems

Scoring system	Example	Source
Anatomical Scores	AIS: Abbreviated Injury Scale ISS: Injury Severity Score NISS: New Injury Severity Score	[14]
Physiological Scores	GCS: Glasgow Coma Score RTS: Revised Trauma Score PTS: Paediatric Trauma Score	
Combination Scores	TRISS: Trauma Score-Injury Severity Score ASCOT: A Severity Characterisation of Trauma	
Other	LOS: Length of Hospital Stay	[18]

Abbreviated Injury Scale (AIS)

Injury to the human body during energy exchange occurs at several concentrated points owing to the structure and contour of the human body. To reflect this the American Association for Automotive Medicine published a scale for injury severity known as the Abbreviated Injury Scale (AIS). The Abbreviated Injury Scale was initially devised to standardise the terminology used to describe injuries. Its relative simplicity is its virtue [4]. The scale ranges in severity from AIS 0 (no injury) to AIS 6 (fatal injury or death). The scale is ordinal in the sense that scale 4 (AIS 4) is not twice as severe as scale 2 (AIS 2). The scale is body region specific and reflects a risk of death resulting from the injury.

The Abbreviated Injury Scale can be represented in the form of a table of actual injuries [4] as shown in Table 2.

Relation between Injury Scale and Injury Cost

Quantifying death and injury with its entire trauma, pain and suffering is extremely difficult. Notwithstanding, most people would have no difficulty in choosing between a thumb and a little finger if confronted with the choice of loss of one or the other, emphasising that intrinsic value and relative value do exist. Courts of law are regularly asked to decide on the value of loss of life or limb and do so but seldom to the satisfaction of all parties, highlighting the lack of community consensus rather than criticising the legal systems.

Similarly, the approach discussed here is not without difficulty, some of which is raised below:

- Discrimination as to what is an immediate ramification from the crash and what is remote.

- Determining cost or value of life between say, a lifer in jail, a liability to the community and another Albert Einstein, arguably an asset.
- Determining cost of injury to account for the differences in loss of earnings for different professions.
- Cultural variations reflected in legal, medical and insurance costs. (for example suing propensity).
- Cost of pain and suffering of victims.
- Cost of grief of relatives and friends of victims.

For a discussion of these and other associated matters the reader is referred to "The Economic Cost of Motor Vehicle Crashes 1994" [1]. The societal cost of injuries used in this work is taken from this technical Report, which encompasses only the following:

❑ *Medical Costs*
The cost of all medical treatment associated with the injuries at the particular injury level.

❑ *Emergency Services*
The cost of ambulance or helicopter as well as police and fire department response cost.

❑ *Vocational Rehabilitation*
The cost of job or career retraining.

❑ *Market Productivity*
Lost wages and fringe benefits over the victims remaining life span.

❑ *Household Productivity*
Lost productive household activity valued at the market price to hire someone else to accomplish the tasks.

❑ *Insurance Administration*
The administrative costs associated with processing insurance claims.

❑ *Workplace Cost*
The cost of workplace disruption due the absence of the victim as an employee.

❑ *Legal/Court Cost*
The legal fees and court costs associated with civil litigation. (Pay-outs are deemed capital reimbursements of the relevant costs above)

❑ *Premature Funeral Cost*
Present discounted value of paying for a funeral in the present instead of at the end of the victims life.

A typical victim has injuries of varying severity to several body parts. However, the overall injury cost for a victim is largely determined by the most severe injury level. For example, the injury cost for a victim with an AIS5 injury is not likely to be significantly affected by some additional injuries ranking AIS2. Choosing the most severe injury from the field of AIS severity codes for all injuries sustained by a victim derives the Maximum Abbreviated Injury Scale (MAIS) for that victim. Whilst the Abbreviated Injury Scale is body region specific, injury cost from Maximum Abbreviated Injury Scale becomes anatomically independent once a cost has been assigned.

Table 2. Correlation of AIS and typical body region injury

AIS Code	Body Region: Head	Thorax	Abdomen & pelvic components	Spine	Extremities & bony pelvis
1	Headache or dizziness	Single rib FX	Abdominal wall; superficial lacerations	Acute strain (no FX or dislocation)	Toe FX
2	Unconscious less than 1 hr; Linear FX	2 – 3 rib FX; sternum FX	Spleen, kidney or liver laceration or contusion	Minor FX without cord involvement	Tibia or pelvis or patella: simple FX
3	Unconscious 1 – 6 hours; depressed FX	4 or more rib FX	Spleen or kidney; major laceration	Ruptured disc nerve root damage	Knee dislocation; femur FX
4	Unconscious 6 - 24 hours; open FX	4 or more rib FX + complications	Liver; major laceration	Incomplete cord syndrome	Amputation or crush above knee; pelvis crush (closed)
5	Unconscious more than 24 hours; large haematoma	Aorta laceration	Kidney, liver or colon rupture	Quadriplegia	Pelvis crush (open)
6			Death		

(FX denotes fracture)

Table 3. Total Societal Costs of Injuries By Severity Per Person [1]

Cost item	Maximum abbreviated Injury scale (MAIS) MAIS 0	MAIS 1	MAIS 2	MAIS 3	MAIS 4	MAIS 5	MAIS 6
Medical Costs	\$1	\$956	\$8144	\$28064	\$100820	\$354819	\$12089
Emergency. Services	\$19	\$152	\$337	\$506	\$1150	\$1171	\$1055
Vocational Rehab.	\$0	\$15	\$99	\$217	\$410	\$620	\$0
Market Productivity.	\$0	\$1315	\$11645	\$35776	\$58073	\$184260	\$576266
Household Productivity.	\$28	\$413	\$3598	\$10903	\$18746	\$54119	\$132630
Insurance Admin.	\$69	\$573	\$3481	\$11219	\$21165	\$49576	\$28646
Workplace Cost	\$29	\$217	\$1681	\$3671	\$4043	\$7049	\$7489
Legal/Court Costs	\$0	\$136	\$2179	\$7655	\$17087	\$45919	\$60766
Premature.Funeral	\$0	\$0	\$0	\$0	\$0	\$0	\$3389
TOTALS	**\$146**	**\$3777**	**\$31164**	**\$98011**	**\$221494**	**\$697533**	**\$822328**

Example: The total societal cost of a maximum injury sustained to the level of MAIS 1 is \$3777.

The cost values shown in Table 3 are derived from US motor vehicle crashes. Since the costs are tabulated against injury level and since injury cost stands independent of causal mechanism, the table is therefore useful for train crashes as well. (for example, a broken leg costs the same to fix whether it is sustained in an automobile accident or on a train). No allowance for pain and suffering was included. Injury cost estimates are thus understated but still considered to be a useful measure. The transportability of the table to and from countries that have different suing propensities, large court awards and expensive insurance rates is not claimed absolutely. Even a relative comparison may require some caution in its use. The caution applies also to the difficulties in applying the MAIS value. Since MAIS is estimated soon after the incident, even small injuries may develop complications later. Other items such as whiplash may not be discerned at material time but later account for significant cost.

An Australian conversion of injury costs from US costs is offered by [3] based on earlier work by [9]. Since [1] is a later study than [10], this paper will retain the US dollar as the currency without attempting to convert.

Biomechanical Indices

The system used by biomechanical engineers to measure injury is completely different from that used by the medical profession. Biomechanical engineers measure injury with a different index system for each anatomical part under consideration. Such systems are not only limited to the anatomical part but also to the direction of application of force, owing to the unique response characteristic of each part of the human body. Biomechanical indices in common use are listed in Table 4.

Table 4 some biomechanical indices in common use

Index	Inputs
HIC: Head Injury Criteria	Deceleration + Exposure Time
GAMBIT: Generalised Acceleration Model for Brain Injury Threshold	Linear & Rotational Deceleration [11]
Nij: Neck Injury Criteria	Deceleration
VC: Thoracic Viscous Criterion	Velocity + Deflection [15]
TEC: Translational Energy Criteria	Energy [22]
ΔV: Delta V	Secondary Impact Velocity [17]

The human body consists of many different body parts, having to determine possible injury levels for all these parts, for all possible crash scenarios is extremely time consuming. However, head injury dominates the general injury cost [21]. Therefore, rather than considering injuries to all possible body parts, this paper considers head injury as the barometer of injury cost.

Head Injury Criteria (HIC)

HIC's genesis was the Wayne State University Concussion Tolerance Curve, representative of brain injury rather than head injury. In Society of Automotive Engineers Paper 660793, Gadd proposed a severity index based on raising the head deceleration dose to the power of 2.5 and integrating over the deceleration time period. The exponent of 2.5 was the log-log slope of the Wayne State Curve. The Severity Index (SI) was replaced by the HIC with US Federal Motor Vehicle Legislation (FMVSS 208) specifying a limit of HIC=1000 as the concussion tolerance level. [20]. As can be seen in the equation below for HIC determination, the exponent of 2.5 was retained.

$$HIC = \left(t_2 \;\; t_1\right)\left[\left[\frac{1}{\left(t_2 \;\; t_1\right)}\int_{t_1}^{t_2} a\,dt\right]^{2.5}\right] \quad [3]$$

Where a = acceleration in multiples of g, and
t_1 and t_2 are any two points in time during the impact which are separated by not more than a 36 milliseconds time interval.

Relation between medical and biomedical injury models

The link that connects factual observations of injury by a medical practitioner with prediction of injury by an engineer is a probability function based on statistical data gathered over many events. Irrespective of the injury index used, the format is the same. In its most basic form, the probability function separates death from life in a cumulative distribution curve. Such a curve was put forward as the position of the US delegation to the International Standards Organisation. This much reported curve, shown below, has HIC as the basic index and has superimposed on it the abbreviated injury scale domains [24].

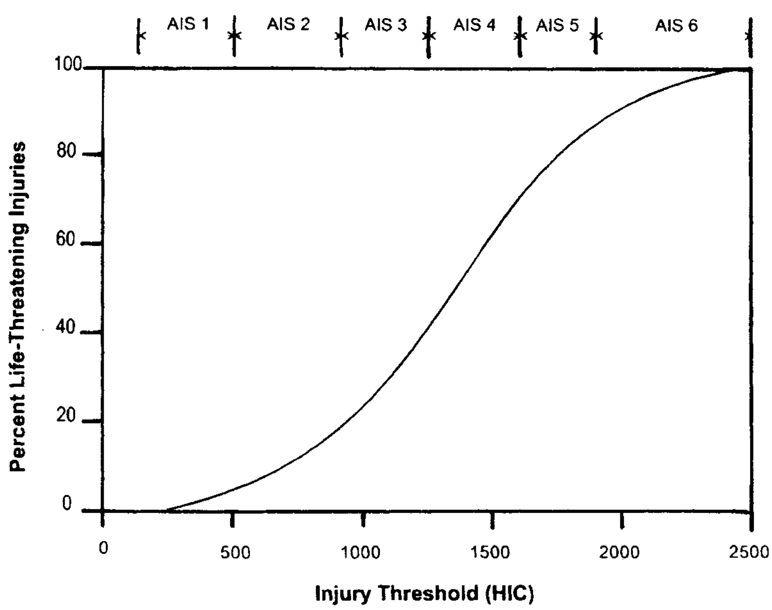

Figure 1 Probability of fatality vs. head injury criteria

Example: A victim with head injury caused by exposure to acceleration to a level of HIC =1000 has approximately an 80% chance of survival and falls in the Abbreviated Injury Scale Domain of AIS 3.

A dichotomous line such as shown in Figure 1 is of limited value since it does not address the risk of injury at each injury level according to the Abbreviated Injury Scale. Also, the same exposure to decelerating forces affects people in different ways. Weight, height, age etc were shown to influence injury severity level significantly [5].

To address these variations, statistics have been accumulated and frequency distributions developed for the head injury criterion. Figure 2 shows the relation between HIC and the Maximum Abbreviated

Injury Scale (MAIS). The bold lines dichotomise injury/no injury and death/life. The dotted lines separate the zones of injury and must be read differentially.

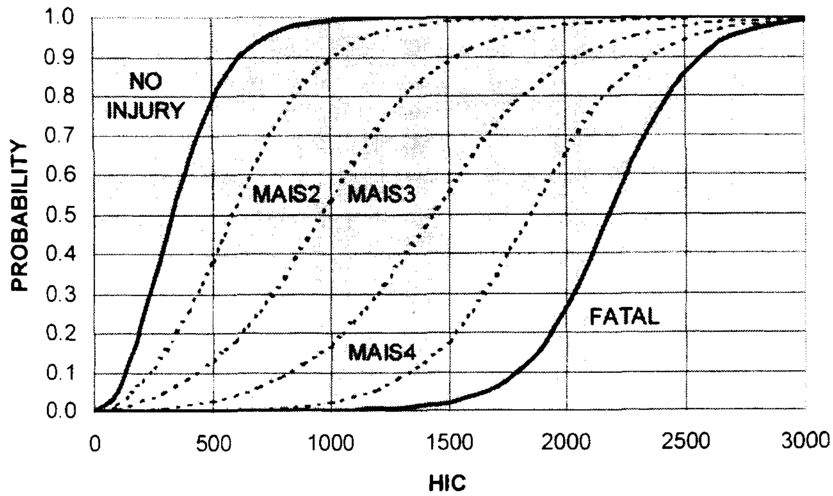

Figure 2 Injury Risk Curves & Protection Reference Values

For example, for a HIC of 1500 the probability of injury severity is as follows:

HIC	**MAIS1**	**MAIS2**	**MAIS3**	**MAIS4**	**MAIS5**	**Fatal**	**No Injury**	**Total**
1500	1.0%	10.5%	32.8%	37.5%	16.2%	2.1%	0.0%	100.0%

A mathematical representation of the curves in Figure 2 is given in Table 5 below.

Table 5 – Expanded Parsed/Merits Formulae [13]

Maximum abbreviated injury Scale	**Probability @ MAIS n =**
MAIS 1 =	$[1 + \exp((1.54 + 200/HIC) - 0.0065 \times HIC)]^{-1}$
MAIS 2 =	$[1 + \exp((2.49 + 200/HIC) - 0.00483 \times HIC)]^{-1}$
MAIS 3 =	$[1 + \exp((3.39 + 200/HIC) - 0.00372 \times HIC)]^{-1}$
MAIS 4 =	$[1 + \exp((4.9 + 200/HIC) - 0.00351 \times HIC)]^{-1}$
MAIS 5 =	$[1 + \exp((7.82 + 200/HIC) - 0.00429 \times HIC)]^{-1}$
MAIS 6 =	$[1 + \exp((12.24 + 200/HIC) - 0.00565 \times HIC)]^{-1}$

The information given in Table 3 and Table 5 can now be used to calculate the so-called probability injury costs of a specific crash scenario. The probability injury costs are defined mathematically below

Probability Injury Costs (Stolinski et al 1997): =

[Probability (MAIS1) x Cost (MAIS1)
+ Probability (MAIS2) x Cost (MAIS2
+ ....
+Probability (MAIS6) x Cost (MAIS6)] [4]

This approach will be further explained in the example at the end of this paper.

Property damage

The typical carriage considered here has a crumple zone at the front and rear, separated by a significantly more robust central section called the survival zone. A minimum repair cost threshold would include recovery from the crash site, cutting affected parts, rewiring, replumbing , repainting and replacement of draft gear. This threshold and a price per metre of crush have been estimated using a fabrication cost manual [2].

A severe impact will use up the entire crush zone and extend to deforming the survival zone. A deformed survival zone is deemed to have rendered the carriage unrepairable. The upper limit of property damage is thus established. The indicative overall cost profile is shown in Figure 3.

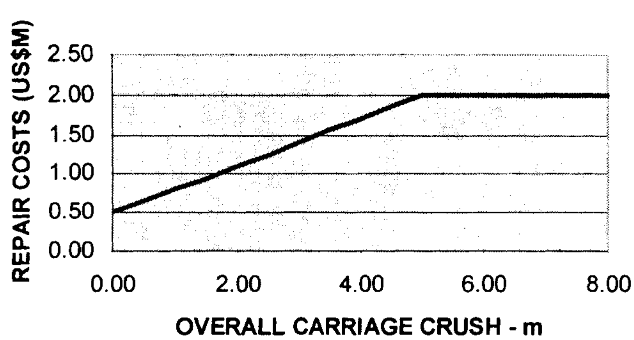

Figure 3 Indicative Carriage Repair Costs

The amount of crush includes both ends, reflecting overall carriage shortening. Repair prices are indicative and will vary depending on the type of carriage and many other factors, consideration of which are beyond the scope of this paper. The US dollar has been retained to be consistent with other costs considered.

Older style carriages with stiff underframes do not have crumple zones. End impact gives rise to a compressive stress in the underframe. This stress is superimposed over bending stresses in the underframe that service the normal functioning of the carriage. The likely failure will occur midway between the bogies where the bending stress is likely to be highest. This has the effect of distorting survival space over the long central section, making repair extremely expensive. Under such conditions, even a low speed collision can render a carriage uneconomical to repair. Accordingly, Figure 3 is inappropriate for carriages with stiff underframes.

INCIDENT LIKELIHOOD

As mentioned earlier, the risk of a rail accident occurring in the life of the train is an important parameter in the overall cost analysis. Figure 4 shows the risk expressed in events per 10^9 passenger kilometres.

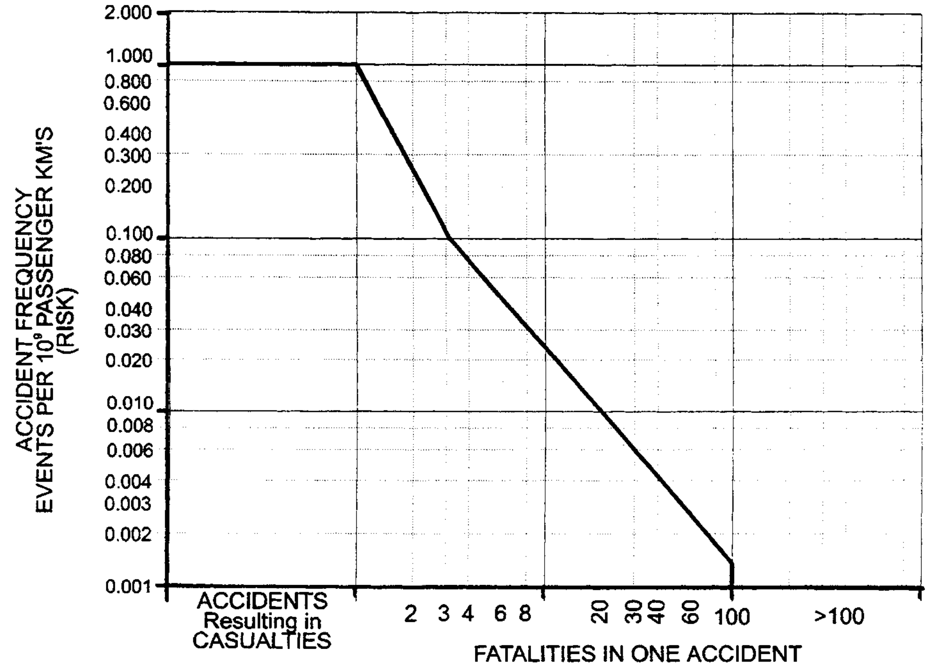

Figure 4. Risk Profiles for US Passenger Railroads

Accident frequency is expressed in events per 10^9 passenger kilometres travelled. The passenger distance (PD) is calculated for a passenger train travelling 500,000 km per year as follows:

PD	=	Annual mileage of train (in km)	
		X Life expectancy of train (in years)	
		X Passenger Density (Average No/train)	[5]
	=	500,000 X 25 X 100	
	=	0.125×10^9 Passenger km's	

Reading Figure 4, the risk of a serious rail accident which results in casualties is once every 10^9 passenger kilometres travelled. For the example train considered above this risk is therefore 0.125.

The risk of a rail accident occurring in the life of a train with a severity of 100 casualties is read from Figure 4 as 0.0014 for every 10^9 passenger kilometres. Hence this risk for the example train is 0.125 x 0.0014 = 0.000175.

WORKED EXAMPLE

Problem description

1. Determine the risk-adjusted societal cost saving of a device that improves Head Injury Criteria from HIC=1450 to HIC=750

2. Assume 100 passengers, 125,000,000 passenger km in the life of the train of 25 years.

3. Ignore property damage and present value calculations.

Solution

The probability injury cost can be determined on a whole person basis, the end result varies only in rounding errors. This approach is preferred since it is deemed inappropriate to consider injury of a portion of a person.

The probabilities are read directly from Figure 2 (or calculated from Table 5 formulae) for all injury severity levels for both HIC=750 and HIC=1450 and recorded in the tables below.

Table 6 Number of persons injured vs. injury level

Maximum abbreviated injury scale	HIC=750		HIC=1450	
	Probability of Injury at MAIS level	Converted to Whole Persons	Probability of Injury at MAIS level	Converted to Whole Persons
MAIS 0	0.044	4	0	0
MAIS 1	0.252	25	0.012	1
MAIS 2	0.408	41	0.122	12
MAIS 3	0.222	22	0.353	35
MAIS 4	0.066	7	0.363	36
MAIS 5	0.007	1	0.135	14
MAIS 6	0	0	0.015	2
TOTAL	1.000	100	1.000	100

The cost of each accident can now be computed as shown in Table 7 below:

Table 7 Probability Injury Cost Comparison

Injury level	HIC=750			HIC=1450		
	No Persons	Table 3 Costs	Injury Cost	No Persons	Table 3 Costs	Injury Cost
AIS 0	4	146	4 x 146= 584	0	146	0 x 146 =0
AIS 1	25	3777	94425	1	3777	3777
AIS 2	41	31164	1277724	12	31164	373968
AIS 3	22	98011	2156242	35	98011	3430385
AIS 4	7	221494	1550458	36	221494	7973784
AIS 5	1	697553	697553	14	697553	9765742
AIS 6	0	822328	0	2	822328	1644656
TOTAL	100		**$5,776,986**	100		**$23,192,312**
SAVING						**$17,415,326**

The saving on societal cost of death and injury for a crash difference of HIC=1450 and HIC=750 is calculated as follows:

=	$23,192,312	-	$5,776,986
=	$17,415,326		

Table 6 above shows 2 fatalities (AIS 6 vs HIC=1450). Figure 4 shows the risk of such an accident to occur as 0.25 times per 10^9 passenger kilometres travelled. Since the typical train as defined travels only 0.125 x 10^9 passenger km's, the risk is computed as follows:Frequency(of Crash)	=	0.25 x 0.125
	=	.03125

Taking into account the number of times that the saving occurs in the life of the train gives the budget for the crashworthiness device:

Indifference Value of Crashworthiness Device	=	Potential Savings On Societal Cost of Crash	X	Frequency (of Crash)
	=	$17,415,326 x 0.03125		
	=	**$544,229**		

Outcome

By improving the crashworthiness of the train where head injury is reduced from HIC=1450 to HIC= 750 a total societal cost saving of $M17.4 would be realised in the event of a crash. However, taking into account the low likelihood that an event of the particular magnitude would occur, spending $544,000 only is justified on the particular crashworthiness device responsible for the improvement.

CONCLUSIONS

A model has been presented that links input engineering parameters such as velocity change with cost to the community of medical, legal and funeral costs as well as loss of productivity of the victim on the basis of injury and death. By the use of the Head Injury Criterion as the critical cost parameter, the need to cost out every type of injury is obviated. Published probability statistics relating to the levels of injury are combined with injury costs to provide a probability injury cost which when adjusted for the crash likelihood becomes the risk-adjusted societal cost.

The model has immediate application in optimising the comparative passive safety values of crashworthiness devices. Indeed, the model presented can assess any incident where blunt injury is caused by the application of force. The model validity is confined to comparative use since the US dollar value is retained as published. However, with a suitable conversion rate that takes account of social differences as well as dollar size, there is scope to extend the model to absolute use.

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