APPLYING FIRST PRINCIPLES FOR THE DESIGN OF CRASHWORTHY SYSTEMS FOR ROAD SAFETY

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Abstract. The road toll in terms of deaths and serious injury arise from impacts that result in transfers of forces that are in excess of human tolerance values. Effective and efficient injury prevention measures therefore must bring the energy and force transfer down to tolerable levels.

The most direct methods for doing so firstly recognise the laws of physics and engineering involved in impacts and secondly draw on fundamental physical principles for effective countermeasure development. In considering countermeasure options for reducing the harm potential in crashes certain design concepts need to be kept in mind to ensure the effectiveness of any proposals.

This paper reviews some of these fundamental principles, and demonstrates their applicability by reference to the range of crashes occurring on the road today. The paper discusses the need for safety researchers, vehicle, and infrastructure designers to recognise and apply these principles to reduce current system failures leading to serious injury.

1. INTRODUCTION

Serious injuries arise from impacts[1] that result in transfers of forces that are in excess of human tolerance values. Injury prevention measures must reduce (filter) the energy and forces down to tolerable levels. Recognition of this principle is at the heart of Sweden's Vison Zero (Tingvall, 1998) road safety philosophy, that '*no foreseeable accident should be more severe than the tolerance of the human in order not to receive an injury that causes long term health loss*".

Tingvall argues that though significant reductions have occurred in the road toll, the world's road toll is still at a level where some 650,000 people are killed per annum, presenting a major public health problem. To achieve a radically safer transport system, a new approach is required - hence Vision Zero.

Adoption of this philosophy, as has occurred in 1997 by the Swedish Parliament, clearly has far reaching ramifications in terms of system design requirements. It moves totally away from the 'blame the victim' viewpoint and explicitly recognises that responsibility for safety is shared by the system designers and the road users. A key principle[2] from Vision zero is that:

> *'The designers of the system are ultimately responsible for the design, operation and use of the road transport system and thereby responsible for the level of safety within the entire system'.*

Vision Zero boldly moves away from the economic- rationalist 'cost-benefit' models, which are used widely in many injury prevention arenas, to a humanistic, indeed, more rational model.

An important consequence of such a human value driven philosophy is that system design integrity becomes important to a far greater extent than has been accepted to date. Whereas a cost-benefit paradigm is essentially a cost-driven model (system failures in terms of lives lost or serious injuries could be rationalised based on cost considerations), a human value driven models regards *each* death or serious injury as unacceptable. Thus a Vision Zero philosophy as well as requiring far greater systems performance effectiveness for injury prevention, will also demand increased scrutiny and accountability of system designers for product performance.

The need for increased system effectiveness for injury prevention leads to the notion of the recognition of the need a *crashworthy systems*, rather than simply crashworthy vehicles.

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[1] A clear distinction needs to be made here between the cause of a crash and the cause of the injury arising from a crash. Refer Rechnitzer (1998) for a more detailed discussion of this area.

[2] The other important aspect of 'Vision Zero' is that it introduces '*ethical rules'* to guide the system designers. Tingvall sites two examples: '*Life and health can never be exchanged for other benefits within the society*' and '*Whenever someone is killed or seriously injured, necessary steps must be taken to avoid similar events'*.

Crashworthy systems

At the heart of any design is the need to consider the compatibility between the vehicle design and the road environment in which it operates in question. In trying to maximise safety of the road system, it is most efficient to develop a holistic *crashworthy system*, which considers a vehicle's crashworthiness in conjunction with (and interaction with) the road infrastructure and other road users. From this viewpoint it is apparent that a vehicle's crashworthiness is not an independent characteristic, but one that is dependent on a given and limited range of collision scenarios and partners.

In this regard Tingvall et al (1999) noted that although one option to improve road system safety would be to simply reduce speeds, *". the more attractive alternative is to see the car and infrastructure (including speed) as a whole system, where the primary role of the infrastructure is to help the vehicle use its inherent safety"*

A *crashworthy system* approach requires a paradigm shift (Rechnitzer & Grzebieta, 1999) in road-safety and crashworthiness thinking. It calls on the different industries (different vehicle designers, infrastructure designers) to collaborate, exchange information and seek a compatible state for the benefit of the users of their particular subsystem. It suggests a systems approach should be used to design vehicles and infrastructure for the environment they have to operate in.

Associated with this view of the need for crashworthy systems and design integrity, is the need to recognize and apply first principles relating to injury prevention in impacts. Whereas adherence to such principles will help ensure design effectiveness, it is also axiomatic that violation of these fundamental principles will inevitably result in systems failures leading to serious injury or death.

Examples where violation of first principles occur are common place, and include the front structures of vehicles for pedestrian impacts, heavy vehicle designs (including trams and buses), and roadside furniture such as guardrail terminals (Rechnitzer, 1998). Examples of crash types that have yet to be dealt with effectively for occupant protection include rollovers, and side impacts particularly with heavy vehicles and 4WDs. Other examples include various Standards[1], which inherently disregard the laws of physics as regards force, acceleration or other performance criteria.

It is the intent of this paper to highlight some of these fundamental principles in the prospect that safety systems will be scrutinized and viewed through such a 'lens'. Application of these basic principles can tell us simply and quickly why certain systems have, in principle, the potential to be effective and also why certain systems cannot be effective and indeed will be injurious. Such basic assessments can be made without having to resort to elaborate computer models or expensive tests, or to wait for yet more detailed biomechanical data before countermeasures can be applied.

2. DESIGN PRINCIPLES FOR INJURY MITIGATION IN IMPACTS

In considering countermeasure options for reducing the harm potential in impacts and the development of crashworthy systems, certain design concepts and principles need to be kept in mind to ensure the effectiveness of any measure. These are primarily:

i) Reduce the exchange of energy between impacting vehicles

ii) Provide energy absorption to reduce forces and accelerations on vehicles, vehicle occupants and unprotected road users

iii) Ensure compatible interfaces (stiffness and geometric) between interacting structures, be they vehicles or humans.

iv) It is the *exchange* of energy that needs to be managed, not necessarily the full kinetic energy of the vehicle(s)/ roadusers involved.

Examining each of these points in more detail:

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[1] Refer Rechnitzer (1998). Discusses, for example, ADR requirements for seatback strength, and rear-underrun barriers for heavy vehicles.

(i) Reduce the exchange of energy

The first point leads to the concept of **deflection of impacting objects**, such that the velocity change (and energy change) of interaction masses is reduced. This is clearly important in considering head on collisions between cars and heavy vehicles where the mass difference can typically result in much higher velocity and energy change for the lighter vehicle than occurs in typical similar mass vehicles. Clearly it also leads to the notion of segregation and control of vehicles by the use of median barriers (or other systems) to prevent head-on collisions, or roundabouts for side impacts.

(ii) Provide energy absorption (maximize stopping distance)

The second point addresses the need to **maximise the stopping distance (**and hence time**)** through which any interaction occurs, and thereby reduce resultant accelerations and forces. This clearly follows the laws of physics and the fundamental relationship[1] between velocity change, acceleration and distance, and is given by the equation:

: $\mathbf{V^2 = 2as}$ (1)

where v = velocity change (to zero)
s = distance over which the speed change occurs
a = the resultant average acceleration (+ve or -ve)

Figure 1 Diagram showing moving mass m (at speed V) impacting a surface resulting in deformation S. D is the thickness of the material impacted.

Equation (1) is derived from equating the kinetic energy of a moving mass and the work done by the resisting average force (F) through a distance ‘s’.

Kinetic energy $E = 1/2mv^2$
Work done $W = Fs$
From Newton’s law $F = ma$

Hence equating the energy loss to the work done: E = W, gives:

$1/2mv^2 = Fs$

and thus $1/2mv^2 = mas$

Giving $\mathbf{v^2 = 2as}$ (1)

This equation (1) is applicable whether one is considering the crush distance and stiffness required on a vehicle to achieve a certain average acceleration level; the thickness of energy absorbing padding needed over a steel bull bar to reduce head acceleration levels to tolerable levels; the thickness of padding on the inside of a helmet for a cyclist or motorcyclist, or why airbags ‘work’.

Importantly, these relationships given in Equation 1, also demonstrates that in terms of energy management there is ‘no free ride’: irrespective of the so called ‘quality[2]’ of the energy absorbing material provided. Acceleration levels are a direct function of deformation distance, which is related to the ‘thickness’ (and force –deformation characteristics) of material provided, or the stiffness of the structure impacted.

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[1] This is given in basic form here, using average values. More complex interactions can be developed similarly.

[2] In some areas of injury prevention ‘quality’ of energy absorbing materials are sometime promoted, yet the material may be quite thin. Application of equation 1 shows the misleading nature of such claims.

Although Equation 1 is fundamental to the understanding of impact mechanics, in the author's experience, it is scarcely referenced in safety research. I regard the application of Equation 1 (**$v^2 = 2as$**) as significant to injury prevention in any type of impact as "$E=mc^2$" is to nuclear physics. It is surely time to make it as well known to safety researchers as Einstein's equation is to physicists!

(iii) Ensure compatible interfaces

This requires ensuring compatibility (stiffness and geometric) between interacting structures, be they vehicles or humans. Broadly, this requires designs to be such that interacting structures 'fit together' to ensure that strong structures interact appropriately and weaker structures are protected. Thus for cars geometric compatibility ensures that the car's energy absorbing structures are engaged so that they are mobilised and hence the occupant protection features of the vehicle are activated. It requires recognition of the needs of the other road users in terms of crashworthiness and biomechanical tolerance.

It also means that the interface between the human and surrounding structure must provide for distributed loading, as well as deceleration distance as previously described, within a protective cocoon.

Thus airbags, for example, provide an ideal interface between the human body and an impacted surface: they provide for both distributed loading as well as extended stopping distance to reduce accelerations and forces.

(iv) Manage the *exchange* of energy.

In any collision, particularly between objects of significantly different masses (such as a car and heavy vehicle; or pedestrian and car), the issue is not one absorbing the kinetic energy of the heavy vehicle but of control of the exchange of energy between the two objects (Rechnitzer, 1998). This is clearly a simpler problem to deal with than that of absorbing the energy of a heavy vehicle.

The later 'problem' is often considered, mistakenly, to be the issue, and has thus prevented the realistic consideration of countermeasures aimed at reducing heavy vehicle aggressiveness in crashes. To illustrate this key point, if a large enough airbag was activated on the front of a speeding train (see Example 1 below), a pedestrian struck by such a train would quite conceivably survive such an impact uninjured! Hence the key issue in these cases is not the very high mass (momentum) and energy of the heavy vehicles but the ***appropriate management of the interface*** between the two impacting objects. This requires both geometric/ stiffness compatibility as well as energy absorption.

3. EXAMPLES OF APPLICATIONS OF FIRST PRINCIPLES TO IMPACTS

Example 1: pedestrian - train impact

The following example is intended to demonstrates that injury outcome is *not* inherently a result of either the mass or speed of impacting partners but rather from the lack of an effective interface between the impacting objects.

The example involves a pedestrian standing on a train track, struck by a train travelling at 100km/h (see Figure 2). In this example a large airbag is fitted to the front of the train. Equation 1 can be used to provide a first estimate of the deformation length required for a 'soft impact' within tolerance. Using a maximum 10g-acceleration level, the crush length needed is given by:

$$v^2 = 2as, \text{ or } s = v^2 / 2a$$

Substituting v =100km/h (28.8m/s), and a= 10g = 10x9.8 =98m/s^2, gives:

$$s = v^2 / 2a = (28.8)^2/(2x98) = 4.2m$$

Hence the deformation distance required is approximately **s = 4.2m**

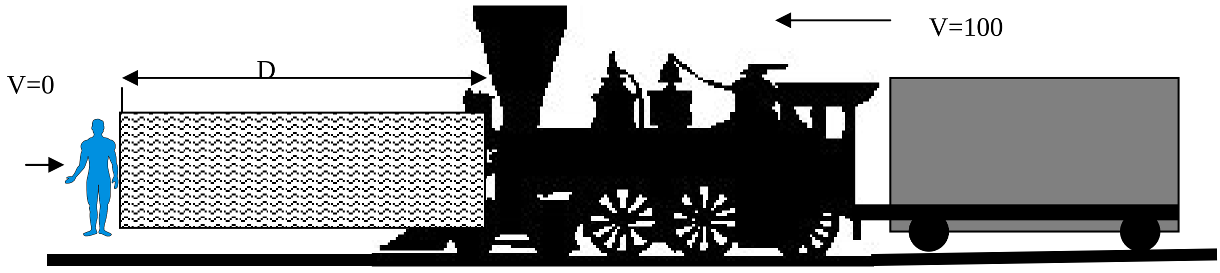

Figure 2a, At impact between pedestrian and train with front airbag.

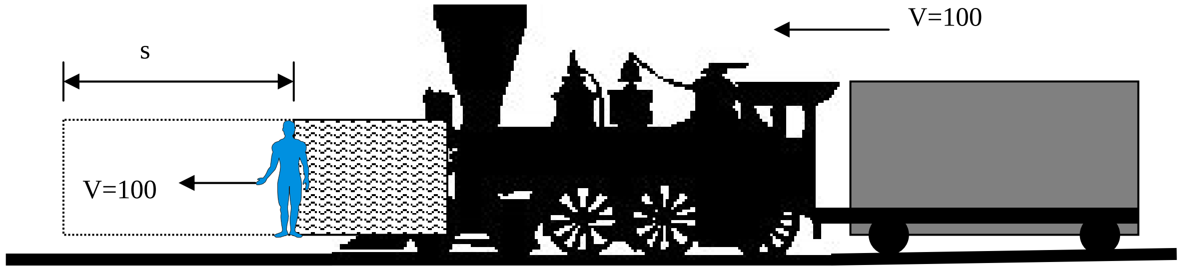

Figure 2b, impact between pedestrian and train with front airbag, after impact and deceleration distance ‘s’.

Hence, if a pedestrian was struck by a train travelling at 100km/h, which had a large airbag fitted to its front[1] (resulting in 4m crush of the airbag), the impact would be quite survivable with the pedestrian likely to be uninjured!

(ii) Example 2: Pedestrian or driver head impact with a steel section.

Examples include: a side-impact with a pole, a pedestrian impact with a vehicle fitted with a bullbar, or a head impact with the interior structure of the vehicle. The resultant head acceleration is directly related to the stiffness (force-deformation characteristics) of the structure impacted, and can be estimated using Equation 1.

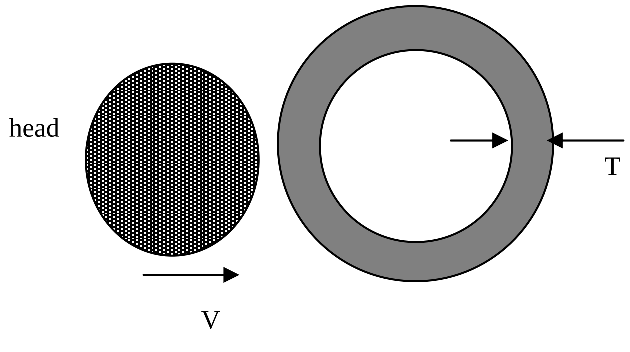

Figure 3. Diagram illustrating a head impact with a deformable surface. V is the relative velocity between the head and impacted surface. T is the thickness of the energy absorbing material or can represent the deformation characteristics of the struck object.

From Equation 1, the resultant acceleration for a given velocity and deformation distance s, is given by:

$$\mathbf{a = v^2/2s}$$

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[1] In anticipation of possible questions such as whether this is practical or not, the issue here is to apply fundamental principles to identify *possible* countermeasures. Practicality and cost should become a consideration only *after* the correct principles have been applied.

These results are summarized in Table 1, below. This clearly demonstrates the benefits of crush distance (padding) in reducing head acceleration in impact with surfaces, and the effective thickness required to achieve tolerable head accelerations. For example, for 5mm of crush the resultant head acceleration is a totally unacceptable 1000g, while with 50mm it drops to 100g. It also shows why head impact with relatively unyielding surfaces such as bullbars, poles in side impacts and other stiff objects, generate such high injury risk – and why such interfaces are *fundamentally* hazardous and unacceptable if injury prevention is a priority.

Impact velocity	*'Crush' distance s (mm)*	*Resultant average head acceleration a (G)*
10m/s (36km/h)	*1*	*5100*
	5	*1020*
	50	*100*

Table 1. Example 2 - Relation between crush distance (s) and average acceleration of the head, for an impact velocity of 10m/s (36km/h)

The above form of calculations can be similarly applied to all head impact scenarios, be it examination of helmet liner requirements, airbag performance requirements, pedestrian friendly vehicle bonnet design, and so on.

CONCLUSIONS

With the advent of the Swedish Vison Zero philosophy and the recognition of the need for crashworthy systems (rather than simply crashworthy vehicles), a consequence of such a human value-driven philosophy is that system design integrity becomes far more important than has been apparent to date under the cost driven cost-benefit approach. Such an approach will also demand increased scrutiny and accountability of system designers for product performance. To achieve these advances in system performance, it will be necessary to more clearly recognize and apply first principles relating to injury prevention in impacts, than has been done to date.

These basic principles include the need to ensure compatible interfaces (stiffness and geometric) between interacting structures, be they vehicles or humans; and that it is the *exchange* of energy that needs to be managed, not necessarily the full kinetic energy of the vehicle(s)/ road users involved.

Also fundamental to injury prevention in impacts is the relationship[1] between velocity change, acceleration and distance, given by the equation $\mathbf{v^2 = 2as}$. This relationship is as significant to injury prevention in any type of impact as "$E=mc^2$" is to nuclear physics.

Example calculations have been presented demonstrating the application of these basic laws of Physics in impacts. These show, for example, that with appropriate interfaces, even impacts between a pedestrian and a train travelling at 100km/h need not result in serious injury.

Whereas adherence to fundamental principles for injury prevention in impacts will help ensure design effectiveness, it is also axiomatic that violation of these fundamental principles will inevitably result in system failures leading to serious injury or death.

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[1] This is given in basic form here, using average values. More complex interactions can be similarly developed.