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Railway Vehicle Interior Crash Safety Standard – The Missing link?

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Abstract: Crash Energy Management (CEM) in general has been applied to the railway industry to minimise the crash energy that reaches the passenger compartment. This has been achieved by designing vehicles with energy absorbing front end components to minimise the impact of primary collision. Such interventions have resulted in reduction of peak crash pulse from as high as 15g to 5g, as stipulated by new standards such as the European Commission EN 15527. While new crash standards have successfully reduced the crash pulse, injuries created by secondary collision remain high. Fatal and severe injuries are not uncommon as observed in recent train crashes. This indicates that a reduction in the primary collision pulse alone does not guarantee an elimination of severe injuries. Unlike road vehicles where occupant restraint is usually mandatory, there exists no such requirement for railway vehicles, worldwide. Therefore, when a train crashes, occupants become unguided missiles that could collide with the vehicle interior in a phenomenon called secondary collision. The characteristics of such a collision determine the injury mechanism and severity. The most common secondary collision objects (SCO) include seats, partitions, grab handles and tables. This paper presents an analysis of injury mechanisms arising from secondary collision when a constant primary collision pulse of 5g with a velocity change of 5m/s is applied as stipulated by the EN 15527. LS DYNA 3D is applied for crash simulations, while a 50th percentile ATD represents an occupant. Secondary collision objects considered were partition, grab pole and fixed bay table. Based on the results of potential injury mechanisms and severity, recommendations are made on the design of railway vehicle interiors with the aim of reducing occupant injuries. Further, recommendations are made for an interior safety standard.

Key Words: Crash energy management, primary collision, injury severity, ATD, crash pulse, railway vehicle interior

1. INTRODUCTION

Crash Energy Management (CEM) in general has been applied to the railway industry to minimise the crash energy that reaches the passenger compartment. This has been achieved by designing vehicles with energy absorbing front end components to minimise the impact of primary collision. Such interventions have resulted in reduction of peak crash pulse from as high as 15g to 5g, as stipulated by new standards such as the European Commission EN 15527. Such standards have successfully reduced the crash pulse. However, accident data shows that injuries created by secondary collision remain high (Matsika and Peng, 2015).

Fatal and severe injuries are not uncommon as observed in recent train crashes (DSB, 2012, RAIB, 2011). This indicates that a reduction in the primary collision pulse alone does not guarantee an elimination of severe injuries. Unlike road vehicles where occupant restraint is usually mandatory, there exists no such requirement for railway vehicles, worldwide. Therefore, when a train crashes, occupants become unguided missiles that could collide with the vehicle interior in a phenomenon called secondary collision (SC). The characteristics of such a collision determine the injury mechanism and severity. Common secondary collision objects (SCO) are seats, partitions, grab handles, tables, floor, other passengers and luggage.

In the European Union (EU), the most extensive project dealing with interior crash safety was SAFEINTERIORS (EC, 2011) which lasted from 2007 to 2011. It appraised requirements and validation procedures and proposed best practices for future standards, recommendations and regulations to improve the chances of survival in future catastrophic events involving secondary collision. In its final report, the project recommended that the safety of Persons with Reduced Mobility (PRMs) which could not be adequately covered. It was proposed that PRMs, wheelchair users in particular, should be investigated as part of future work. This implies that any designs proposed in the project did not necessarily meet the increasingly important principle of Design for All (DfA).

In addition to the increasing number of passengers travelling by rail, Persons with Reduced Mobility (PRMs) have been increasing as well (Matsika et al, 2013). To this effect any railway vehicle designs are tending to apply principles of DfA, where one design incorporates requirements for abled people, the elderly, children and the disabled. Examples of DfA applied in railway vehicles include design features that are dictated by wheelchair users (PRMs) include the width of the doors, width of aisles and dimensions of toilet doors and interior. In essence designing for wheelchair users automatically satisfies the design requirements of other passengers, therefore meeting the DfA principle.

This paper discusses the kinematics of a railway vehicle occupant in the event of a crash. It also presents the ensuing potential injury mechanisms and severity. The aim is to use this information to propose a general standard or guideline or framework for design of railway vehicle interiors which meet the principle of DfA, and the function-strength-safety (FSS)) balance (Matsika and Peng, 2015). Although the paper makes reference to worldwide research in interior safety, much of the work presented in in the context of the European Union (EU), which is still representative of practices worldwide.

2. OCCUPANT CRASH KINEMATICS AND INJURY SEVERITY

2.1 Occupant Kinematics

Railway vehicle accidents are rare compared to road vehicles but are catastrophic, chaotic events, having durations which in some cases are much higher than those of road vehicles (MIRA, 2001: Bombardier, 2006). Nevertheless, some similarities exist with injury mechanisms for unrestrained motor vehicle occupants.

During a vehicle crash (the primary collision), the occupant continues to travel with their initial motion (Newton's 1st Law of Motion). This motion continues until the occupant makes contact with an object in their trajectory path, which is referred to as secondary collision. The main difference between an unrestrained motor vehicle occupant and a railway vehicle one is the interior furniture or features involved in the secondary collision. Furniture such as partitions, grab poles and tables are common in the latter. The parameter that causes injury is force that may be directly obtained from a force transducer or inferred from the acceleration of the body (AISI, 2004). Figure 1 shows the difference phases of the occupant kinematics.

Phase I: Primary collision - the railway vehicle decelerates. Obeying Newton's First Law of Motion, the occupant continues travelling forward at approximately the primary collision velocity. The relative velocity between the occupant and rail vehicle interior, Vi_R, increases with time.

Phase II: Occupant secondary collision - the occupant collides with a railway vehicle interior at an impact velocity of V_{iR}..

Phase III: Occupant Rebound - the occupant rebounds and travels at some relative velocity in the opposite direction.

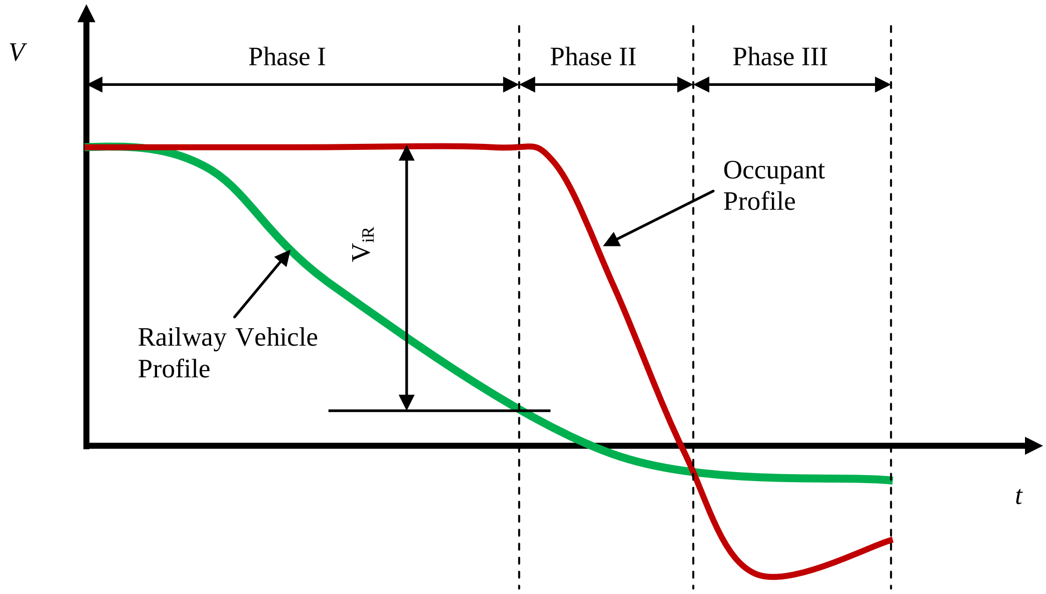


Figure 6: Railway vehicle and occupant velocity history

During secondary collision, all or some of the kinetic energy of the occupant is dissipated proportionally into the deformation of the secondary collision object and the occupant's body. The stiffness of the object determines how much energy it will absorb. Subsequently, the higher the object's stiffness, the less energy it absorbs, and the higher will be the proportion of kinetic energy that the occupant absorbs, thereby increasing the injury severity.

2.2 Past Studies on Interior Crash Safety

Research into the interior crash safety of passengers has been carried out by many researchers, and it has been established that secondary collision is the main cause of injuries depending on the type of SCO. Research has been conducted for two main categories of passenger: Occupants that use ordinary train seats and those that use wheelchairs as a seat.

2.2.1 Ordinary Seating Occupants

Information about such occupants has been obtained from real accident data (RSSB, 2005), full scale tests US DoT (2011, 2009, 2007), sled tests (MIRA, 2010) and computer simulations Carvalho et al (2011). From real accident data, based on the UK database for 1996 to 2004, a study by the Rail Safety and Standards Board (RSSB) showed that for seated occupants, the chest, head and lower leg accounted for 48% of the AIS2+ and 58% of the AIS3+ injuries (RSSB, 2005). The chest and head accounted for 76% of AIS4+ and all of the AIS5+ injuries.

Other than unknown causes and structural intrusion, seats, tables and the floor accounted for the highest cause of injuries. Recent accidents in Suffolk, UK (RAIB, 2011) and Amsterdam, Netherlands (DSB, 2012) support this. The accident report prepared by the Dutch Safety Board (DSB) indicated that although the collision was forceful, the trains did not derail, and no occupants were trapped. Injuries sustained were mainly caused by secondary collision of the train interior (such as seats, tables, glass partition walls and partition doors) and with other passengers. At least 190 out of 425 occupants involved were injured, out of which 24 sustained serious injuries, one of which was fatal.

2.2.2 Wheelchair Occupants

Extensive research in this area has been carried out by Matsika et al (2011, 2013, 2014). Here, the special case of an occupant sitting on a moveable seat (the wheelchair) was considered. Although the kinematics characteristics were more complex and injury severity potential higher than the ordinary seating occupants, the role of secondary collision in causing injuries remained similar to the ordinary seating occupants. With Design for All in mind, as an example, the following section provides an illustration of secondary collision characteristics, injury mechanisms and severity.

2.3 Case Study of a Wheelchair Occupant

As mentioned before, DfA considers requirements for able people, the elderly, children and the disabled. Among all these, the most stringent requirements relate to wheelchair users. The following reasons render design for a wheelchair user as the best representation of DfA:

- Represents the worst case crash scenario for all train passengers because they sit on an unsecured wheelchair, and they are unrestrained.

- Carries the highest kinetic energy (K.E.), with a possible combined wheelchair and user weight of up to 250 - 300kg; noting that KE increases with inceeasing mass (K.E. = ½ mViR2 , where m is the combined mass of the wheelchair and occupant, and ViR is the relative impact velocity).

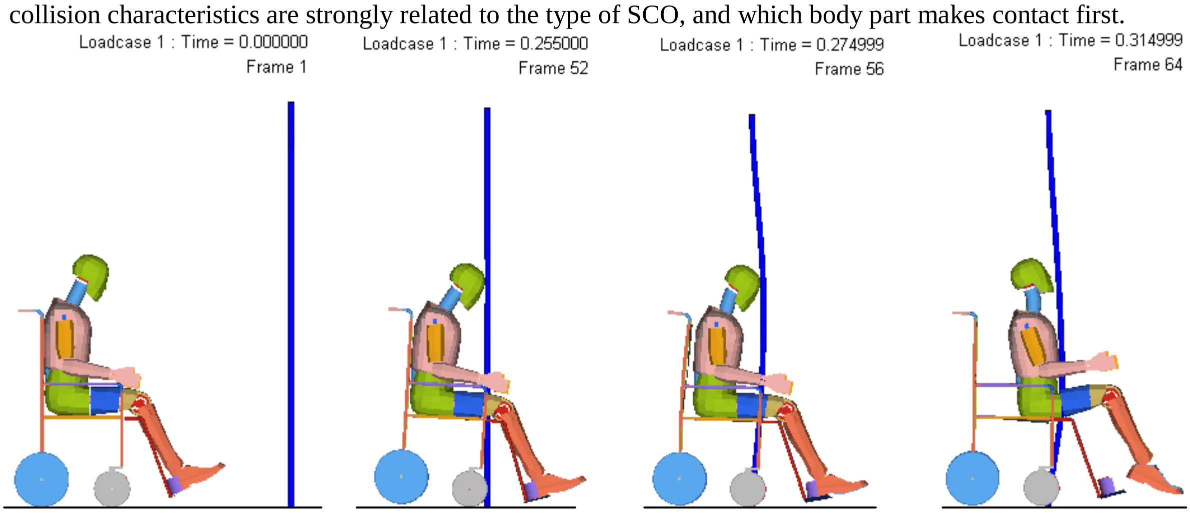
- Presents largest space requirements due to accessbility requirements. Since ViR $\propto$ the initial diatance between the occupant and a SCO, the occupant can attain very high impact velocity, ViR.

In this section are presented results of an analysis of injury mechanisms arising from secondary collision when a constant primary collision pulse of 5g with a velocity change of 5m/s is applied as stipulated by the EN 15527. LS DYNA 3D is applied for crash simulations, while a 50th percentile ATD represents an occupant. Secondary collision objects considered were a partition, grab pole and bay table. Figure 2 shows the crash pulse that was applied.

Figure 7: Crash pulse applied (CIDAUT, 2010)

2.3.1 Occupants kinematics

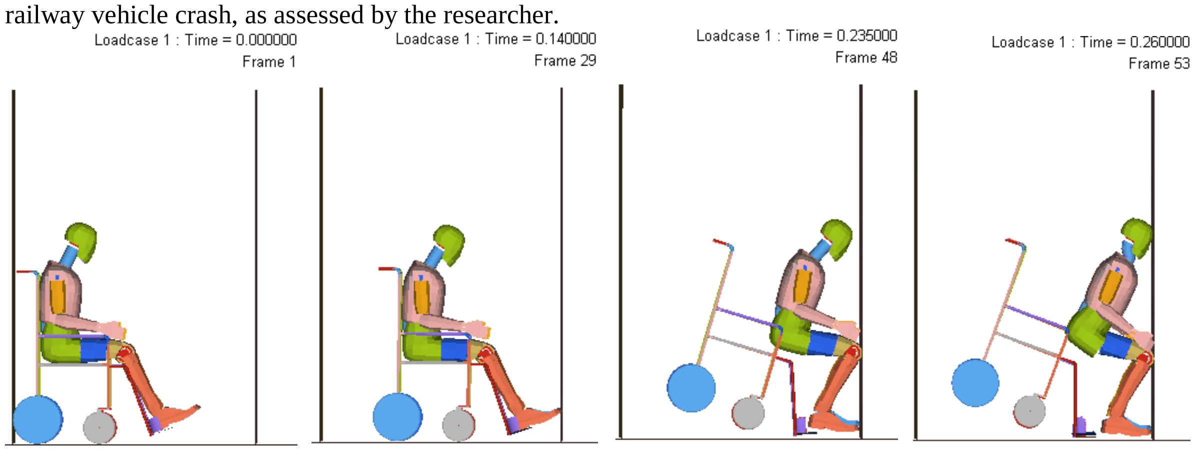
Figure 3, Figure 4 and Figure 5 show the occupant kinematics arising from the 5g crash pulse. Clearly, the secondary collision characteristics are strongly related to the type of SCO, and which body part makes contact first.



(a) *(b)* *(c)* *(d)*

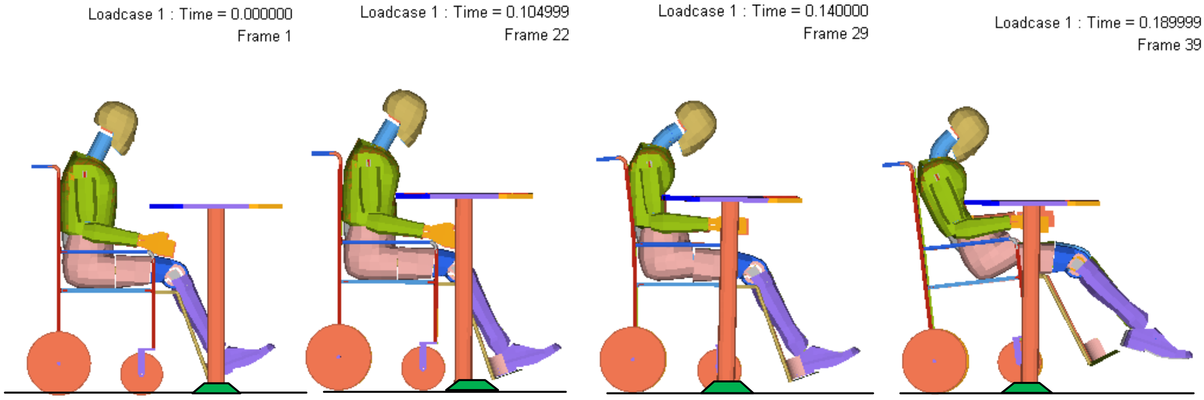
Figure 8: Wheelchair and occupant kinematics for grab pole. (a) start of primary collision; (b) head contacts the grab pole first; (c) head contact loading deforms grab pole; (d) pelvis contacts the grab pole.

From the above kinematics, Table 1, Table 2 and Table 3 show the potential risks to a wheelchair occupant during a railway vehicle crash, as assessed by the researcher.



(a) *(b)* *(c)* *(d)*

Figure 9: Wheelchair and occupant kinematics for partition. (a) start of primary collision; (b) feet contact the partition first; (c) knee contact with partition; (d) head contact with partition loads the neck



(a) *(b)* *(c)* *(d)*

Figure 10: Wheelchair and occupant kinematics for fixed bay table. (a) start of primary collision; (b) chest contacts table edge first; (c) maximum chest deflection; (d) lower body submarines.

Table 3: Open Space Configuration – Grab Pole

		Injury Risk		
		High	**Medium**	**Low**
Secondary Collision	**Highly Likely**	-	Head, Neck	-
	Likely	-	-	Pelvis, Thorax
	Unlikely	-	-	Abdomen, Knee Tibia/foot
	Highly Unlikely	-	-	-

Table 4: Open Space Configuration – Partition

Secondary Collision	Injury Risk: High	Medium	Low
Highly Likely	Head, Neck	Knee	Tibia/ foot
Likely	-	-	Thorax
Unlikely	-	Femur	Abdomen
Highly Unlikely	-	Pelvis	-

Table 5: Fixed Bay Table Configuration

Secondary Collision	Injury Risk: High	Medium	Low
Highly Likely	Abdomen Thorax	-	-
Likely	-	-	-
Unlikely	-	-	-
Highly Unlikely	-	Head Neck	Femur, Pelvis Knee, Tibia/Foot

2.3.2 Occupant Injury Severity

Table 4 shows a summary of the potential injury levels for the occupant. For a given secondary collision object, the injury severity is shown in green colour with a tick (√) if the threshold is met. On the other hand, red with a cross (x) indicates that the threshold has not been met, and represents a serious/fatal injury.

Table 6: Summary of Potential Injury Severity (Matsika et al, 2014)

Secondary Collision Object	Injury Criteria: Head ($HIC_{15} < 500$)	Neck ($N_{ij} < 1.0$)	Chest ($CTI < 1.0$)	Pelvis ($a < 130$g)
Grab pole	√	x	√	√
Partition	x	x	√	√
Bay Table	√	√	x	√

Key

a linear acceleration (m/s^2)

HIC_{15} Head Injury Criterion corresponding to 15ms

CTI Chest Thoracic Index

N_{ij} Neck Injury Criterion accounting for axial loading and moments on the neck

The results show that upon primary collision the occupant and wheelchair travel as a coupled system until secondary collision. The wheelchair occupant injury mechanism is strongly dependant on the kinematics that ensues after the first secondary collision (i.e. which body part and how the collision occurs). In the conditions and constraints for wheelchair safety analysis in this research, the grab pole has overall the lowest injury severity potential, while the partition has highest injury severity potential. Fitting a bay table significantly reduces the risk of head and neck injury. However, it poses a great risk to thoracic injuries depending on the initial gap between the torso and the table edge.

3. CURRENT SOLUTIONS TO IMPROVE CRASH SAFETY

Within the EU, design of railway vehicles is guided by Directives (legal) and standards. It is worth noting that standards are not necessarily mandatory unless a law requires it fulfilled. The main guiding standards in the EU are the Technical Standards on Interoperability (TSI).

Although road vehicles and railway vehicles are subjected to a crash pulse, the pulse characteristics are different. The former experiences a peak of up to 25g over shorter period of time while the latter could be as low as 5g for longer according to EN15227 (EC, 2007). MIRA (2001) points out how railway vehicle accident characteristics differ from automotive road traffic accidents in many ways as follows:

- The number of occupants involved and the potential number of casualties in a rail accident are considerably higher (10 versus 300 per event)

- Railway vehicles can potentially undergo a number of impacts lasting over several seconds from an initial 'Primary' high deceleration longitudinal impact followed by several 'Secondary' impacts.

- Even low levels of injuries can seriously affect the ability of an occupant to evacuate the railway vehicle. This can be life threatening.

Despite the differences that exist between road and railway crash pulses, there are and could be many commonalities in designing for crash safety. Notably, however, by far, road safety has incorporated more technologies, standards/legislation aimed at improving crash safety.

3.1 Road Vehicles

Road vehicles stand out as applying the largest number of safety technologies among land modes of transport. Table 5 shows some key European Commission directives and regulations and standards covering this.

Table 7: Road Vehicle Safety Directives and Standards (Dahl, 2010)

EC Directive/Standard	Description
74/408 – 2006/96 EC	Relating to the interior fittings of motor vehicles (strength of seats and their anchorages)
76/115-2005/41 EC	Relating to anchorages for motor vehicle safety belts
76/115-2005/41 & 74/408-2006/96 EC	Relating to H-Point Determination
77/541-2005/40 EC	Relating to safety belts and restraint systems in vehicles
ECE 44	Relating to child restraint systems (child car seats)
2007/46	Relating to framework Directive for the approval of wheel-chair accessible vehicles
ISO 10542 part 1– 5	Technical Systems and Aids for disabled or handicapped persons -Wheelchair Tiedown and Occupant- Restraint Systems
ISO 10542 part 1	Wheelchair tiedown and occupant restraint systems – Requirements and test methods for all systems
ISO 10542 part 2	Requirements for tiedown and occupant restraint systems – Fourpoint strap-type tiedown systems
ISO 10542 part 3	Establishing requirements for tiedown and occupant restraint systems - Docking-type tiedown systems
ISO 10542 part 4	Relating to requirements for wheelchair tiedown and occupant restraint systems »Clamp-type«
ISO 10542 part 5	Relating to the requirements of restraint systems for specific wheelchairs, for example docking systems
IS O 7176 part 19	Wheelchair standards: Relating to wheeled mobility devices for use as seats in motor vehicles

Among all the safety technologies and products applied in road vehicles, the seatbelt (restraint) has saved more lives than anything (Håland, 2006). With specific reference to wheelchair users, an analysis of real-life accidents in motor vehicles showed that the main reason for higher than expected injuries is because of lack of use of securement and restraint systems even where they are provided (Schneider, 2010; Armstrong, 2004).

3.2 Railway Vehicles

The design of passenger railway vehicles is anchored on two main standards:

EN 12663-1 Railway applications — Structural requirements of railway vehicle bodies Part 1: Locomotives and passenger rolling stock (and alternative method for freight wagons)

EN 15227 Railway applications — Crashworthiness requirements for railway vehicle bodies

Ideally, EN 12663 could address interior crash safety. However, it focusses on functional and structural capabilities only.

While road vehicles have myriad of standards and directives aimed at ensuring that injury due to secondary collision is minimised, there is very little if anything to push for improved secondary collision crashworthiness in railway vehicles. Past studies have shown that both ordinary seating and wheelchair occupants are exposed to serious injuries arising from secondary collision. A seatbelt could provide restraint, and minimise such injuries. It is the most basic protection system in road vehicles. However worldwide it is not legally required to fit restraint systems in railway vehicles.

Ironically, even wheelchair users who are the most vulnerable passengers when there is dynamic instability are not required to apply securement and restraint systems. In USA, as part of guidance to the Americans with Disabilities Act (ADA), securement and restraint systems have been fitted only in some railway vehicles. The Access Board is overseeing an update of the ADA's guidelines for railway vehicles (including rapid, light, commuter, intercity and high speed systems). One of its recommendations was: mobility device securements (straps and tethers) are not required on rail vehicles (Rail Interiors International, 2015). If provided it should be the rider's decision as to whether to use them. Such a strong recommendation comes at a time when the ADA attained 25 years since it was enacted in 1990.

In the United Kingdom, the Mobility and Inclusion Unit of the UK Department for Transport found that various organisations and disability groups firmly did not wish to use restraint systems on board railway vehicles (RSSB, 2007a). Most were unwilling to use wheelchair securement and occupant restraint systems because they were considered to be time consuming, and posed potential difficulties with release of such systems in emergency. Other studies have shown that there was no net safety benefit for seated occupants who chose to wear lap belt restraint (RSSB, 2005) and 3-point restraints (RSSB, 2007b) on railway vehicles. The studies showed that the cost of stiffening the existing seats would be disproportionately high. Generally occupants who chose not to wear restraints in a railway vehicle modified to accept 3-point restraints received marginally more severe injuries.

Currently, there is no push for introduction of restraint systems as a legal requirement, or a design Standard. Subsequently, in the event of heavy braking or crash, the most practical way to minimise potential injuries is through passive safety. The solutions include:

- Compartmentalisation
- Appropriate selection of geometry which minimises injury during a collision
- Mechanical properties of material or combination of materials that are optimised for function, strength and also collision safety.

4. INTERIORS CRASH SAFETY - DESIGN FOR ALL

Dimensions of interior furniture and gaps for the general ordinary seating occupant population may vary, depending on demographics. In the EU, however, there is special consideration for elderly, disabled and persons with reduced mobility. For this reason, the Technical Standard on Interoperability for Persons with Reduced Mobility (TSI PRM) was developed and published in 2008. An updated version came into force on 1 January 2015 (EC, 2014).

As long as there is no regulation that requires railway vehicle occupants to be restrained when travelling by railway, crash injury should be achieved through re-engineering the vehicle interior. Figure 6 shows the flow chart of how a crash pulse is translated into an injury. In order to minimise or indeed eliminate some injuries, there is need to design for interior crashworthiness, which aims at controlling occupant kinematics and the secondary collision characteristics. Both of these ultimately influence the secondary collision injury mechanisms and severity. Matsika (2012) recommends dimensioning such spaces through an optimising process that maximises dimensions for improved accessibility, but also minimises it for improved compartmentalisation (and therefore crashworthiness). Further, he suggests that the surrounding secondary collision objects (e.g. partitions, grab poles and tables) should be designed to be impact friendly. Matsika and Peng (2015) proposed that design of railway interiors need to meet the Function-Strength-(Crash) Safety (FSS) balance (Figure 7).

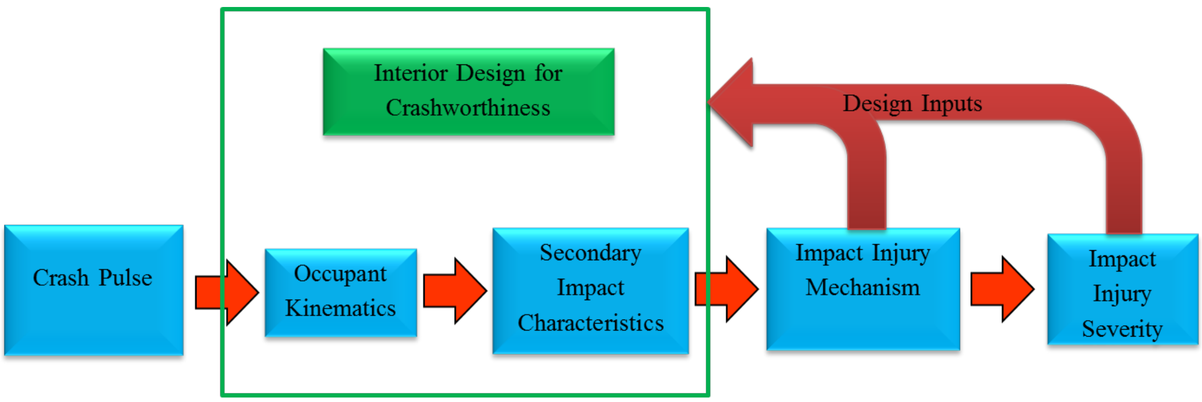


Figure 11: Secondary Collision Flow Chart

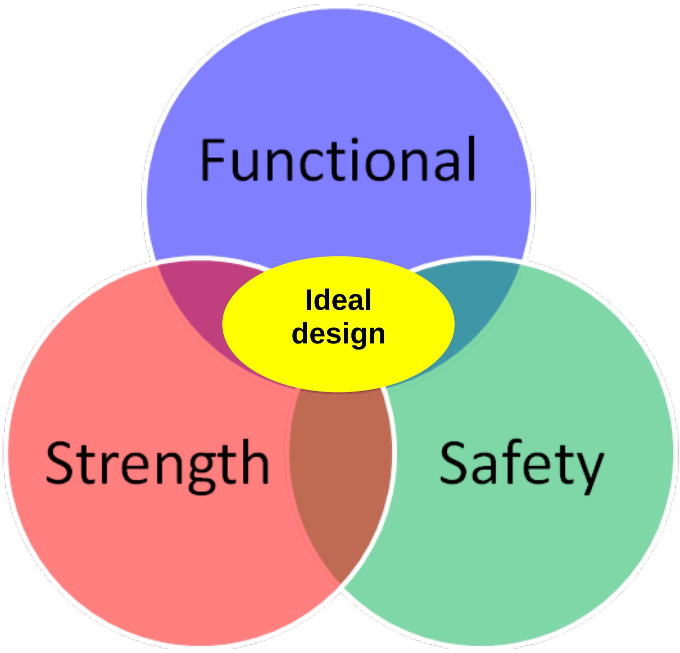


Figure 12: The Function-Strength-(Crash) Safety Design Balance

5. CONCLUSIONS

From the data and information presented in the paper, the following conclusions were made:

- It is unlikely restraints will be applied in the near future
- Secondary collision will remain the main injury mechanism for railway vehicle occupants (with high potential of fatal injuries even at low crash pulse).
- There is adequate information and data from past accidents and studies to develop legislation and/or standards that ensure that both the abled and PRMs are safer should secondary collision occur due to heavy braking or crash.
- Design of railway vehicle interiors should aim to meet not only functional and structural integrity, but also occupant secondary collision safety.
- Design for all based on most vulnerable (wheelchair users)

6. RECOMMENDATIONS

With interior crash safety at the centre of Designing for All, the following is recommended:

- Research into design of impact friendly secondary collision objects (furniture)
  - Optimising dimensions
  - Material selection
  - Design of furniture that will strike a balance between function-strength-safety.

- Development of new standards for improved interior crashworthiness that is inclusive of the abled (ordinary seating occupants) as well as PRMs (specifically wheelchair users).

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