HEAD INJURY AND EFFECTIVE MOTORCYCLE HELMETS

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ABSTRACT

The wearing of a motorcycle helmet certified to an appropriate standard has been the most significant step in reducing fatal and serious injury among motorcyclists worldwide. Motorcycle helmets have been shown to be at least 50% effective in reducing fatal head injury in motorcycle crashes [1]. Most motorcycle helmet standard requirements have remained substantially the same for 40 years, while over the same period our understanding of causes of injury to the brain has been rapidly improving. Current international motorcycle helmet standards are based around a translational acceleration energy attenuation test.

Reconstruction of crash involved motorcycle helmet damage in the COST 327 study [2] demonstrated that the AIS 2+ head injuries in helmeted head impacts are more likely to be due to indirect (or head motion induced) rather than direct impact. Occupants of crashed vehicles have also been observed by Gennarelli [3] to have a shift in the type of brain injury treated in the emergency room. This shift has been related to improvements in vehicle safety, especially the use of airbag technology. The improved protection for vehicle occupants in crashes due to airbag controlled head impacts has led to a decreasing incidence of focal (direct) brain injury accompanied by a relative increase in diffuse (indirect) brain injury. In sporting head injury, King et al. [4] have shown that football and bicycle helmets built to the current test requirements reduce translation acceleration of the head but do not necessarily reduce the rotational acceleration of the head of the wearer in an impact. These recent advances in our knowledge of the effects and causes of traumatic brain injury have yet to be carried over to motorcycle helmet standards.

The crash characteristics and injuries to the head sustained by helmeted motorcyclists were examined by reference to data from motorcycle crash studies including:

- COST 327 [2], which reconstructed the helmet impact for n=226 motorcyclists with AIS 2+ head injuries;
- MAIDS [5], which investigated n=921 injurious European motorcycle crashes; and,
- Gibson and Thai [6], which examined the helmets and injuries of n=175 riders in fatal motorcycle crashes in Australia.

The crash data regarding the head injury sustained in helmeted head impacts in motorcycle crashes suggests areas available to improve current motorcycle helmet effectiveness and motorcycle helmet standard test methodologies in reducing brain injury. This study defines some of these areas where motorcycle helmet effectiveness in preventing brain injury can be improved, including:

- Changes to helmet test methodology to include biofidelic rotational as well as translational head motion effects to be measured;
- Development of accepted test requirements to mitigate rotational brain injury, with initial emphasis on reducing traumatic brain injury TBI; and,
- Improved facial impact protection, without increasing neck injury risk.

INTRODUCTION

“Vulnerable” road users such as motorcyclists are at greater risk than vehicle occupants and usually bear the greatest burden of injury. In Australia, motorcyclists make up 3% of registered vehicles but represent 16 % of road user fatalities and 22 % of serious injuries. Motorcycle riders are also the fastest growing sector of road user in Australia with motorcycle registrations increasing by 56 % between 2005 and 2010 [7].

According to the World Health Organisation [8], head trauma is the main cause of death and morbidity in motorised two wheeler users. Head trauma contributes to around 75% of motorised two-wheeler deaths in European countries and between and 55-88% of motorised two wheeler rider deaths in Malaysia.

Head Injury Mechanisms

Head injuries can be classified under four major groups: scalp damage, skull fractures, extra-cerebral bleeding or haematoma, and brain damage [9].

Skull fractures are mainly due to direct impact and the force levels required to cause fracture have been studied by many researchers. In contrast, brain injuries can result directly from impact to the head or indirectly by the motion of the head, even without impact.

Ommaya et al. [10] demonstrated that abrupt rotation with impact could affect sensory responses through experiments with primates. In addition to concussion, other brain injuries such as acute subdural haematoma (SDH) due to ruptured bridging veins [11] and diffuse axonal injuries (DAI) [12] have been experimentally produced in primates by acceleration of the head without requiring a direct impact to the head.

Ommaya [13] also identified the important role of the "contact phenomenon" in causing skull deformation. The angular accelerations required to produce concussion in human surrogates by direct impact to the head were shown to be approximately half of those required to produce concussion by pure inertial loading of the head.

Clinical trends also provide insights into the mechanisms for different types of brain injuries. Gennarelli [3] observed a shift in the type of brain injury treated in the emergency room due to the improvements in vehicle occupant safety. The introduction of airbags and softer impacts to the head has been accompanied by a decreasing incidence of focal (direct) brain injury and an increase in diffuse brain injury.

Head Impact Tolerance Criteria

The Wayne State Tolerance Curve (WSTC), first presented by Lissner et al. [14], presents a relationship between average anterior-posterior acceleration of the skull measured at the occipital bone in forehead impacts and the pulse duration, see Figure 1. The "curve" included six points obtained from different experiments with embalmed cadaver heads and has been developed with subsequent cadaver, animal and volunteer tests. Only translational accelerations were used in producing the WSTC. Despite much criticism and the shortcomings of the WSTC [9], which include being based on translational acceleration only, it is the basis for most currently accepted head injury criterion, including the Head Injury Criterion (HIC) commonly used in automotive research.

Hirsch and Ommaya [15] reported that rotational motion appeared to be more critical to the production of brain injury than translation motion stating that "no evidence has to this date been presented which relates brain injury and concussion to translational motion of the head for short-duration force inputs, whether through whiplash or direct impact."

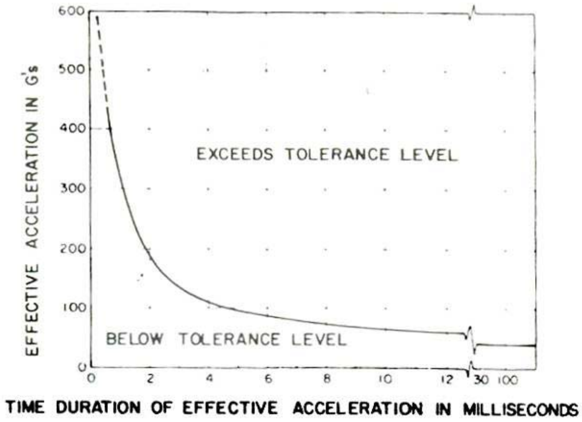


Figure 1. The Wayne State University Concussion Tolerance Curve for linear acceleration, after SAE (1980) [16].

Head injury tolerance to rotational acceleration of the head was investigated by Ommaya [17], who reported that the rotational accelerations necessary to cause concussion and severe diffuse axonal injury (DAI) are 4,500 rad/s^2 and 18,000 rad/s^2 respectively for an adult. Margulies and Thibault [18], using a combination of animal testing and scaling, established tolerance curves for DAI based on peak rotation acceleration and peak change in rotational velocities, see Figure 2.

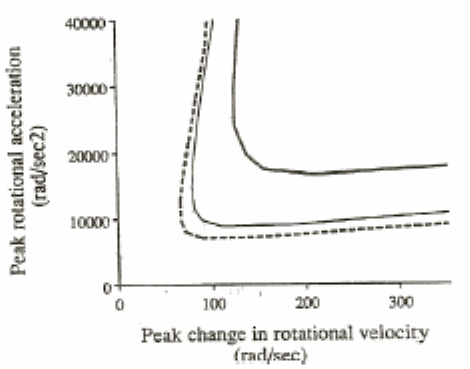


Figure 2. Diffuse axonal injury rotational acceleration and rotational velocity thresholds for infant (500g brain mass, heavy solid line) and adult (1067g brain mass, solid line, 1400g brain mass, dashed line) [18].

Finite element models are increasingly being used as an alternative method for assessing injury risk as they enable investigation of the intracranial response under real world head impact conditions. Deck and Willinger [19] demonstrated that intracranial variables in finite element models demonstrate better correlation with specific injuries than global parameters such as peak linear acceleration and HIC. They reported that intracerebral maximal principal strains, von Mises strains and von Mises stresses are well correlated with both moderate and severe DAI. Similarly, the best correlation with subdural haemorrhage was the minimum pressure within the cerebral spinal fluid.

Motorcycle Helmets

Mandatory motorcycle helmet use is regarded as the single most effective approach for the prevention of traumatic brain injuries among motorcycle users in both developed and developing countries [8]. Motorcycle helmets have been shown to be at least 50% effective in reducing fatal head injury in motorcycle crashes [1].

As explained by van den Bosch [20], *"a motorcycle helmet (to an approved standard) will spread or diffuse any contact impact force and provide for energy absorption beneath that contact point, hence the contact injuries defined by Gennarelli* [skull deformations, coup lesions, epidural haemorrhage] *are those injuries most likely to be prevented - or even excluded - by a motorcycle helmet."* The effect of a helmet on preventing inertial injuries (or indirect injuries due to the motion of the head) is less clear.

The inability of sporting helmets to protect against inertial brain injuries has been demonstrated by other researchers. King et al. [4], for example, demonstrated that American football helmets and bicycle helmets (compliant with current standard test requirements) reduce translational acceleration of the head, but do not necessarily reduce the rotational acceleration of the head in an impact and, in some cases, may increase it.

Performance standards play a large role in the design of helmets. Current international motorcycle helmet standards are based on the WSTC injury criteria and place a limit on the peak linear acceleration and duration of the helmeted headform during an impact (US DOT FMVSS 218, JIS T 8133 and AS 1698 for example) or combined the peak acceleration with a maximum allowable HIC (ECE/UN Regulation 22.05). In the US DOT FMVSS 218, JIS T 8133 and AS 1698 standards the shock absorption test restricts the rotation of the headform by use of a guided drop. On the other hand, the European free flight test allows the headform to rotate, but does not measure or apply limits to the headform rotation.

To assess the protective effectiveness of a helmet in a real (crash based) impact requires the shock absorption test to be a good representation of the actual impact [20]. Figure 3 shows how laboratory (drop) tests attempt to replicate actual crash impacts to correlate the load on the head (form) with the injury. A greater understanding of how the loading to the helmeted head of a motorcyclist in an accident leads to head and brain injury can be used to improve the process for testing the effectiveness of a helmet. However, it must go beyond the deficiencies of the current drop test.

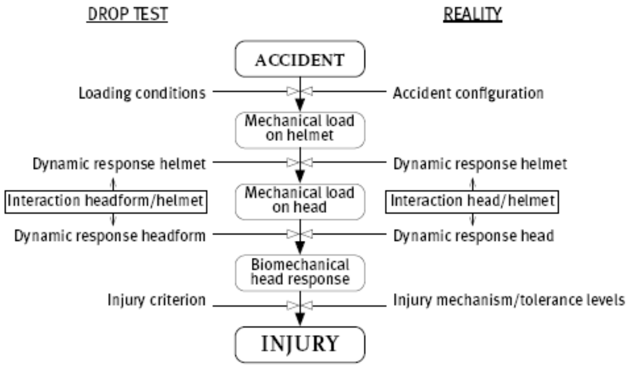


Figure 3 Load-injury scheme for helmeted head impact (van den Bosch [20] modified from Wismans [21])

The first step in this process is to accurately define what happens in real impacts to the helmeted head based on motorcycle crash data.

MOTORCYCLE CRASH DATA

Careful investigation of real world accidents is an integral part of the prevention of injury by the application of biomechanics [22]. In reality, the dynamic helmet and head response (see Figure 3) cannot be directly measured, but crash investigation can indicate the accident configuration and the injury that results.

The MAIDS study [5] of n=921 powered two wheeler accidents in five European countries was carried out by the Association of European Motorcycle Manufacturers. A case control study methodology was used, where data was collected for an additional 923 non-accident involved powered two wheelers. In the crashes, 75% of all powered two wheeler impact speeds were under 50 km/h. When the crash also involved another vehicle, 90% of all other vehicles were to the front of the powered two wheeler rider at impact. The head was the third most injured body region (18.4%) following the lower (31.8%) and upper (24.3%) extremities respectively.

A comprehensive review of the performance of Australian market motorcycle helmets in crashes was performed by Dowdell et al.[23] in NSW, Australia. Cases were included on the basis that the crash was of sufficient severity to have the motorcyclist admitted to hospital and that the motorcyclist was wearing a helmet approved to the current Standard.

200 cases were collected, of which 72 were fatal and 128 non-fatal. More than two thirds of the

impacts to the helmet in these cases were tangential. In the cases where a head or neck injury occurred, 50% of impacts were to the general frontal area of the helmet. Local skull fractures (vault fractures) were associated with impacts adjacent to the fracture site. The authors note that many of the brain injuries were of a type associated with translational or rotational accelerations that are produced by tangential impacts. Brain injuries of this type comprised over 40 percent of the AIS4 injuries. In 42 cases the rider had lost consciousness.

The difficulties which arise when fatal cases are used for motorcycle crash studies are demonstrated by the results of this study [23]. A breakdown of injury severity to the head, neck, face and chest (in Table 1) shows that the fatal cases had a much higher incidence and severity of head and chest injuries.

Table 1.
Comparison of the non-fatal and fatal head, neck, facial and chest injury in motorcycle crashes by severity, based on Dowdell et al. [23].

Body region	Cases with injury	No. of inj.	AIS Injury Severity					
			6	5	4	3	2	1
Non-fatal cases (n=128)								
Head	58	61	0	0	0	5	46	10
Neck	25	25	0	0	1	1	2	21
Face	15	28	0	0	0	0	14	14
Chest	13	18	0	0	1	7	5	5
Fatal cases (n=72)								
Head	58	143	11	11	43	68	10	0
Neck	16	18	8	2	0	3	3	2
Face	17	25	0	0	0	1	8	16
Chest	62	139	12	17	53	37	18	2

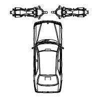
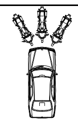
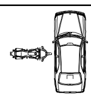
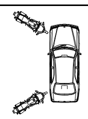
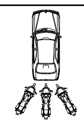
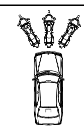
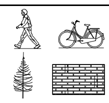
Richter et al. [2] analysed details of 218 European motorcycle accidents which were part of a larger study (COST 327) and examined the head injury mechanisms in these helmeted motorcyclist cases. There were 84 fatalities included, 74 of which suffered fatal head injuries. Of the 205 helmets inspected, there were 196 frontal impacts, including 115 chin bar impacts and 42 impacts to the visor. There were only 2 impacts to the crown. 157 helmets had impacts to the rear and most helmets had lateral impacts. Richter and his co-workers classified the injuries as resulting from either direct force effects or indirect force effects. They found that direct force effects were responsible for a high percentage of skull vault fractures (84.2%), facial fractures (96.3%) and skin injuries (87%), while the majority of brain lesions (96.2%) were the result of acceleration or deceleration forces acting on the head and helmet, i.e. indirect force effects.

A study by Gibson and Thai [6] examined the CASR Head Injury database and abstracted 174, mainly fatal, motorcycle accident cases collected in South Australia between 1983 and 1994. The database included records of the autopsy data (including neuropathology and the incidence of diffuse axonal injury), a helmet inspection and reporting of the crash circumstances. The aim of the study was to investigate basilar skull fracture to helmeted motorcyclists in crashes. The authors reported that 74.7% of cases (n = 174) involved an impact to the helmet or head and almost 50% of the severe impacts to the head were in the facial region. This database was re-analysed in the context of the brain injuries sustained by the fatally injured motorcyclists.

Re-analysis of the CASR Database

The accident types collected in the CASR database are representative of typical motorcyclist crash types. The crash types, from the various studies, are compared in Table 2 based on the classification from the COST 327 study.

Table 2.
Comparison of the COST 327, MAIDS and CASR motorcycle crash type distribution.

Collision Types	Diagram	% (COST 327)	% (MAIDS)	% (CASR)
Type 1		1.8	7.9	7.6
Type 2		8.8	4.1	11.1
Type 3		14.2	20.5	9.0
Type 4		31.0	29.2	25.7
Type 5		5.3	7.2	6.3
Type 6		0	1.7	4.2
Type 7		38.9	29.4	36.1

The CASR fatal motorcycle crash data contains predominantly fatally injured motorcyclists (94%) and so represents only high severity cases. The average estimated impact speed of the motorcycles in the CASR data was approximately 80 km/h. In comparison the average impact speed for COST 327 [2] was 55km/h and for MAIDS [5] 53.6 km/h.

A subset of thirty cases was selected from the CASR database to analyse further, based on the brain injury details being available from the autopsy reports and a helmet inspection being available. For each case, the accident factors and injuries received in the crash were reviewed. The autopsy reports were used to define the injuries. The helmets were visually examined for markings and damage.

The group selected included 27 full face helmets and 3 open face helmets with a total of 40 impacts on the helmets. The distribution of these impacts on the helmets is presented in Figure 4. Further details of the 30 cases are provided in Appendix 1.

The head and brain lesions in the 30 cases were classified as being caused by either direct force effect (DFE) or indirect force effect (IFE), using the same protocol as Richter et al. [2]. These injuries are summarised in Table 3. All coup lesions that were directly caused by a force affecting the damaged structures of the head and brain were defined as DFE, while IFE lesions were all contrecoup lesions and all coup lesions indirectly caused by the effecting force. The lesions were classified by reference to the accident circumstances and the damage to the helmet. In the CASR data, n = 30, the majority of skull vault fracture (77.8%) and facial fracture (100%) were due to direct force effects while most brain lesions (81.3%) were caused by indirect force effects, Table 3. This is similar to general distribution of injury reported by Richter et al. [2].

Table3.

The location and type of the 231 lesions of the head region in the n = 30 CASR fatal motorcycle crashes.

Type of Lesion	Force Effect				Total
	DFE		IFE		
	No.	%	No.	%	
Bone (n = 53)					
Total	**27**	**50.9**	**26**	**49.1**	**53**
Vault	7	77.8	2	22.2	9
Base	0	0	24	100	24
Zygoma	4	100	0	0	4
Orbital	4	100	0	0	4
Nasal	4	100	0	0	4
Maxilla	3	100	0	0	3
Mandible	5	100	0	0	5
Brain (n = 134)					
Total	**25**	**18.7**	**109**	**81.3**	**134**
EDH	0	0	1	100	1
SDH	0	0	9	100	9
SAH	7	25.9	20	74.1	27
Inter ventricular haemorrhage	5	38.4	8	61.6	13
DAI	0	0	6	100	6
Contusion	5	29.4	12	70.6	17
Laceration	8	40	12	60	20
Multi petechial haemorrhage	0	0	19	100	19
Brain Stem	0	0	22	100	22
Skin (n = 44)					
Total	**35**	**79.5**	**9**	**20.5**	**44**
Scalp	13	61.9	8	38.1	21
Face	22	95.7	1	4.3	23
Total	**87**	**37.7**	**144**	**62.3**	**231**

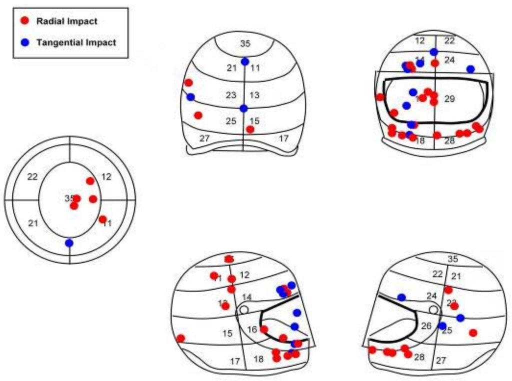


Figure 4. Distribution and type of head impacts in the n=30 fatal motorcyclists cases selected from the CASR Head Injury Study Database.

DISCUSSION

The motorcycle crash investigation studies reviewed here [2, 5, 6, 23] have a similar general distribution of the type of crashes, see Table 2. The crash data defines the accident circumstances and the injuries received by the motorcyclists involved in the crashes. The initial analysis of these available data sources indicates several areas where the effectiveness of motorcycle helmets in powered two wheeler crashes may be improved. The relatively low incidence of skull vault fractures as a result of direct impact on the helmet indicates one area where the current helmet standards are working. The following areas of the current helmets are indicated as worthy of further investigation of possible improvement:

- A high proportion of brain injury results from indirect force effects;
- Both tangential and radial impacts appear to play a part in the causation of indirect brain injuries; and,
- A relatively high incidence of facial fractures and brain injury are the result of direct impacts to the face.

Analytical tools are now available, in the form of human head and neck finite element models which are sufficiently developed to predict brain injuries [20, 28]. Such models allow analysis of the biomechanical response of the head and brain to various types of real crash head impact scenarios and the effect of the helmet on this response (see Figures 3 & 5).

INVESTIGATION METHODOLOGY FOR THE STUDY

The energy absorption "drop" test for helmets is over simplified and a poor representation of a real head impact in a crash. This study will use an advanced dummy, THOR (Test Device for Human Occupant Restraint), combined with a finite element model of the head and neck able to predict the brain injuries which occur in real impacts. The biofidelic THOR head and neck will allow generation of the mechanical loading to the helmet and head from controlled impact tests, while the FE head and neck model will predict the resulting injuries. A flow chart of the methodology is outlined in Figure 5, based upon a modified version of the Wismans biomechanical injury model [21]. A similar methodology has been previously suggested by Deck and Willinger [19].

The test methodology has notable differences to the standard helmet drop test, including human like skull deformation and biofidelic neck responses. The correct neck response is important for reconstructing the correct trajectory of the head after impact and has been found to be necessary for accurately recreating the impacts to COST 327 motorcyclists, American football players and in motorsport (FIA) cases (summarised in [19]).

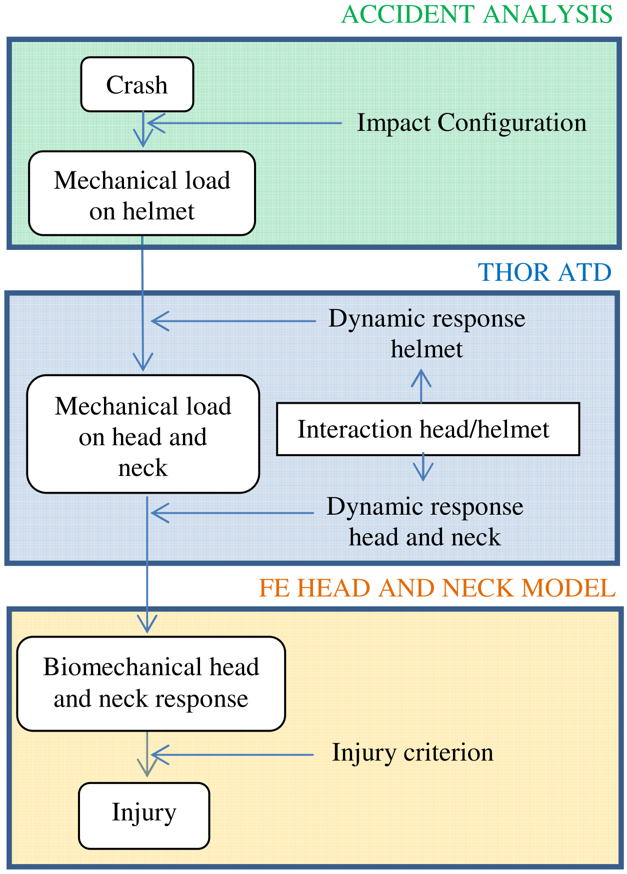


Figure 5 The investigation methodology for the project demonstrating the use of the THOR dummy head and neck and the finite element model.

Impact Testing

An Anthropomorphic Test Device (ATD) or dummy is usually used in vehicle crash testing to predict the injuries sustained by a living person in typical crash circumstances. Such a device must be biofidelic in anthropometry and the response. To assess the protection offered by a vehicle to an occupant in a regulatory frontal crash, biomechanical response data is measured on a Hybrid III crash test dummy. The THOR dummy is an advanced impact dummy, under development by the US National Highway Traffic Safety Administration (NHTSA) since 1993. It is based on more recent and improved biomechanical knowledge than the Hybrid III.

The THOR dummy, to be used in this study, is pictured in a helmeted forehead impact in Figure 6. The THOR head and neck are used in this study for the following reasons:

1. The THOR headform can be instrumented with a 9 accelerometer array (3-2-2-2) for measurement of translational and angular accelerations of the head in 6 axes as a result of impact.
2. A head skin is available with the chin area suitable for wearing a motorcycle helmet.
3. The THOR face has been developed to have human like response to facial impact [24] and is able to be fitted with a complement of force transducers.
4. Finally, the THOR neck has a more biofidelic response than that of the Hybrid III, with improved head lag response and lower stiffness.

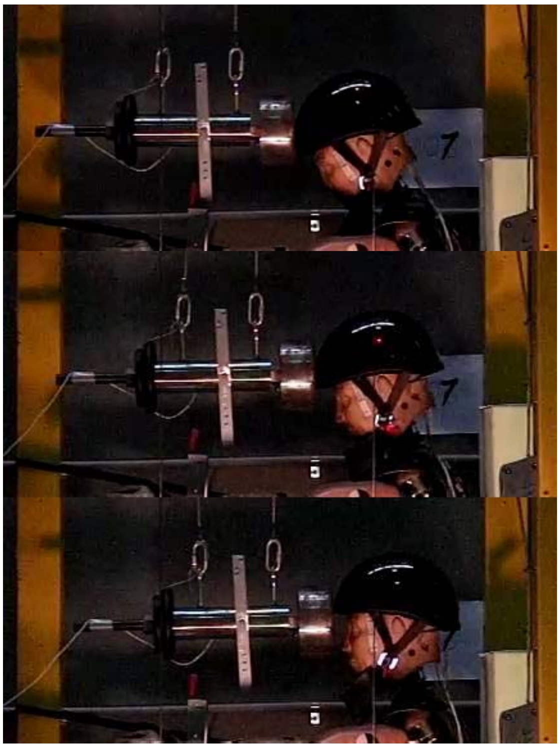


Figure 6 A helmeted THOR head and neck responding to a pendulum impact to the head.

Finite-Element Modelling

Three-dimensional finite element models of the human head have been increasingly used for assessing head injury risk since an early model was developed in 1975 [25]. The development of such finite element models has reached a point which now allows investigation into the intracranial response resulting from an impact to the head.

Injury tolerance limits for intracranial response variables have been proposed and demonstrated for a number of finite element models. As examples, Takhounts and Eppinger [26] suggested a 50% risk of DAI at 55% cumulative strain and a 50% risk of contusion at 7.2% of dilatational damage measure using the SIMon FE model, and the 'Universite Louis Pasteur' (ULP) human head FE model predicts a 50% chance of SDH at cerebral spinal fluid strain energy of 4211 mJ.

This study will use the head and neck components of the finite element H-Model developed by the ESI Group, Figure 7. The model of the human head [27] consists of 48,870 elements, 16 material types and includes the skull (inner and outer table, upper and lower dipole, face bone, mandible), dura, sinus, venous blood, pia, cerebral spinal fluid (CSF), white matter, grey matter, falx cerebri, tentorium, ventricle, cerebellum and brain stem. Contact interfaces are defined between related parts.

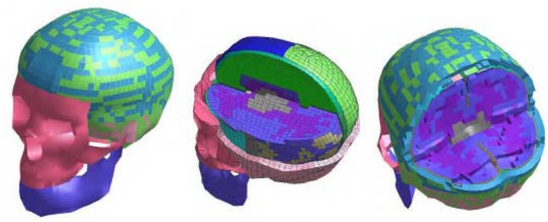


Figure 7 The ESI H-Head finite-element model.

The ESI H-head model has been validated by Xin and Zaouk [28] against the 3D brain motion data of Hardy et al. [29] and the intracranial pressure data of Nahum et al. [30]. The authors subsequently used the ESI H-head model for investigating TBI resulting from blast over-pressure and blast-related impacts. The researchers used the Cumulative Strain Damage Measure (CSDM) and the Dilatation Damage Measure (DDM) to quantify the risk of injury. For this study, the other injury mechanisms defined with the ULP FE model [31] will be investigated on the H-head. These are Von Mises stresses for neurological lesions, global strain in the CSF layer for subdural haemorrhage and local strain energy in the skull for skull fracture.

Discussion

The investigation methodology outlined here provides a realistic approach to testing the effectiveness of a motorcycle helmet in preventing injury to the head, face and brain. Motorcyclist crash data provides a means of real crash validation of the experimental and numerical models, which are themselves independently validated against cadaver, animal and volunteer studies.

The THOR represents one of the most biofidelic mechanical head/neck complexes available. It will allow investigation of a wide range of impact types including the effect of the helmet. The finite element modelling permits prediction of the risk of specific injury determined by the response of the head to the impact, such as skull fracture, subdural haemorrhage and diffuse axonal injury.

SUMMARY

The wearing of a motorcycle helmet certified to an appropriate standard has been the most significant step in reducing fatal and serious injury among motorcyclists worldwide. The following areas of current helmet performance in crashes are worthy of further investigation for possible improvements:

- A high proportion of brain injury results from indirect force effects;
- Both tangential and radial impacts appear to play a part in the causation of indirect brain injuries; and,
- A relatively high incidence of facial fractures and brain injury are the result of direct impacts to the face.

Most helmet standard requirements have remained substantially the same for 40 years, while over the same period our understanding of the mechanisms of brain injury has been rapidly improving. The following suggestions reflect areas available to improve current motorcycle helmet effectiveness and motorcycle helmet standard test methodologies:

- Include measurement of biofidelic rotational as well as translational head motion effects in standard test methodologies;
- Development of accepted test requirements to mitigate rotational brain injury, with initial emphasis on reducing traumatic brain injury TBI; and,
- Improved facial impact protection, without increasing neck injury risk including development of test methods to the facial area.

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REFERENCES

1. Liu, B., et al., *Helmets for preventing injury in motorcycle riders (Review)*, in *The Cochrane Collaboration*. 2009, John Wiley & Sons, Ltd.
2. Richter, M., et al., *Head injury mechanisms in helmet-protected motorcyclists: prospective multicenter study.* The Journal of Trauma: Injury, Infection and Critical Care, 2001. **51**(5): p. 949-958.
3. Gennarelli, T. *Head injuries: How to protect what*. in *Snell Conference on HIC*. 2005.
4. King, A., et al. *Is head injury caused by linear or angular acceleration?* in *IRCOBI Conference*. 2003. Lisbon (Portugal).
5. MAIDS, *In-depth investigations of accidents involving powered two wheelers. Final report 2.0.* The Association fo European Motorcycle Manufacturers (ACEM), 2009.
6. Gibson, T. and K. Thai, *Helmet protection against basilar skull fracture*, in *ATSB Research and Analysis Report*. 2007.
7. ATC, *National road safety strategy*. 2011, Australian Transport Council Canberra.
8. Seay, A., et al., *The global impact*, in *World report on road traffic injury prevention. World Health Organization*, M. Peden, et al., Editors. 2004.
9. Prasad, P., et al., *Head*, in *Review of biomechanical impact response and injury in the automotive environment. Task B final report.*, J. Melvin and K. Weber, Editors. 1985, National Highway Traffic Safety Administration. Department of Transport: Ann Arbor, Michigan.
10. Ommaya, A., A. Hirsch, and J. Martinez. *The role of whiplash in cerebral concussion*. in *Proc. 10th Stapp Car Crash Conference*. 1966. New York: Society of Automotive Engineers.
11. Gennarelli, T. and L. Thibault, *Biomechanics of acute subdural hematoma.* Journal of Trauma, 1982. **22**: p. 680-686.
12. Gennarelli, T., *Cerebral concussion and diffuse brain injuries*, in *Head Injury*. 1982, Williams and Wilkins: Baltimore/London. p. 83-8.
13. Ommaya, A., *Biomechanics of head injuries: Experimental aspects*, in *Biomechanics of Trauma*, A. Nahum and J. Melvin, Editors. 1984, Appleton-Century-Crofts: East Norwalk, Conn.
14. Lissner, H., M. Lebow, and F. Evans, *Experimental studies on the relation between acceleration and intracranial pressure changes in*

man. Surgery, Gynecology, and Obstetrics, 1960. **111**: p. 329-338.

15. Hirsch, A. and A. Ommaya. *Protection from brain injury: The relative significance of translational and rotational motions of the head after impact*. in *Proc. 14th Stapp Car Crash Conference*. 1970. New York: Society of Automotive Engineers.

16. SAE. *Human tolerance to impact conditions as related to motor vehicle design*. in *SAE Information Report no. SAE J885 APR80.* 1980. Warrendale, PA.

17. Ommaya, A., W. Goldsmith, and L. Thibault, *Biomechanics and neuropathology of adult and paediatric head injury.* British Journal of Neurosurgery, 2002. **16**(3): p. 220-242.

18. Margulies, S. and L. Thibault, *A proposed injury tolerance criterion for diffuse axonal injury in man.* Journal of Biomechanics, 1992. **25**(8): p. 917-923.

19. Deck, C. and R. Willinger, *Improved head injury criteria based on head FE model.* International Journal of Crashworthiness, 2008. **13**(6): p. 667-678.

20. van den Bosch, H., *Crash helmet testing and design specifications*. 2006, Technische Universiteit Eindhoven.

21. Wismans, J., et al., *Injury Biomechanics. nr. 4552*. 2nd ed. 1994, Eindhoven University of Technology, The Netherlands.

22. Mackay, M. *The contribution of accident investigation research to biomechanics*. in *IUTAM Proceedings on Impact Biomechanics: From Fundamental Insights to Applications*. 2005.

23. Dowdell, B., et al., *A study of helmet damage and rider head/neck injuries for crash involved motorcyclists*. 1988, Road Safety Bureau. Crashlab.

24. Beach, D., et al., *THOR advanced test dummy - biofidelity and injury assessment*. 1998, Nathonal Highway Traffic Safety Administration (NHTSA), D.O.T.: Washington, DC.

25. Ward, C. and R. Thompson, *The development of a detailed finite element brain model.* Proceedings 19th Stapp Car Crash Conference, 1975: p. SAE Paper 751163, 641-674.

26. Takhounts, E. and R. Eppinger, *On the development of the SIMon finite element head model.* Proceedings 47th Stapp Car Crash Conference, 2003: p. SAE Paper 03S-04, 107-133.

27. Trameçon, A., et al., *Design of soldier's protection equipment: Recent trends in biomechanical models and comfort.* Proceedings of 74th Shock and Vibration Symposium, 2003.

28. Xin, X. and A. Zaouk, *Interaction of blast and head impact in the generation of brain injuries*. 2009, Foster-Miller, Inc.: Waltham, MA.

29. Hardy, W., et al., *Investigation of head injury mechanisms using neutral density technology and high-speed biplanar x-ray.* Stapp Car Crash Journal, 2001. **45**: p. 337-368.

30. Nahum, A., R. Smith, and C. Ward, *Intracranial pressure dynamics during head impact.* Proceedings 21st Stapp Car Crash Conference, 1977: p. Paper No. 770922, 339-366.

31. Willinger, R. and D. Baumgartner, *Human head tolerance limits to specific injury mechanisms.* International Journal of Crashworthiness, 2003. **8**(6): p. 605-617.

APPENDIX 1 – Summary of 30 cases studied in detail from the CASR Database.

Case	Head impact	Region of head impacted	Impacted Object	Direct Brain Injury	Indirect Brain Injury	Skull Vault Fracture	Basilar Skull Fracture
1	Radial	Forehead/ facial	Car roof edge	Y	Y	Y	Y
2	Radial	Right chin bar	Truck	N	Y	Y	Y
3	Radial	Crown	Edge truck tray	Y	Y	Y	Y
4	Tangential	Facial	Road surface/car	N	Y	N	Y
5	Radial	Left chin bar/right frontoparietal	X member behind bumper	N	Y	N	Y
6	Crushing and/or radial	Right chin bar/ right temporo-parietal	Car wheels	Y	Y	N	Y
7	Radial	Right mid facial	Pylon cross-brace	Y	Y	N	Y
8	Radial	Right chin bar/face	Road surface/car	N	N	N	Y
9	Radial	Right chin bar/face	Kerb or road	N	Y	N	Y
10	Radial	Crown	Utility pole	N	Y	N	Y
11	Radial/ Tangential	Forehead/ occipital	Tree/Road surface	N	Y	N	Y
12	Radial	Facial	Car/road surface	N	N	N	Y
13	Radial	Facial	Car	N	Y	N	Y
14	Tangential	Sun Visor, Left Temporal	Truck wheels/ underside	N	Y	N	Y
15	Radial	Left occipital/ chin bar	Utility pole	N	Y	N	Y
16	Radial and Tangential	Right frontal	Car	N	Y	N	Y
17	Tangential	Rear parieto-occipital	Tree	N	Y	N	Y
18	Radial	Right occipital	Truck/road	N	Y	Y	Y
19	Radial	Right facial	Helmet	Y	Y	Y	Y
20	Radial	Crown	Utility pole	Y	Y	Y	Y
21	Radial	Facial/chin bar	Edge truck tray	N	Y		Y
22	Radial	Crown/chin bar	Armco rail/ road	Y	Y	Y	Y
23	Radial	Crown/chin bar	Utility pole	Y	Y	Y	Y
24	No Evidence of Impact			N	Y	N	Y
25	Tangential	Frontal/Facial	Road	N	Y	Y	Y
26	Radial and Tangential	Right frontal/ facial	Utility pole	N	Y	N	N
27	Tangential	Left temporal/ Right chin bar	Road	N	Y	N	N
28	Tangential	Left temporal	Road surface	N	Y	N	N
29	Tangential	Frontal/facial	Road surface	N	Y	N	N
30	Radial	Left/Right temporo-parietal	Van/Road Surface	N	N	N	N

CRASH DETECTION METHOD FOR MOTORCYCLE AIRBAG SYSTEM WITH SENSORS ON THE FRONT FORK

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Paper Number 13-0113

ABSTRACT

Honda's previous motorcycle airbag system employs a crash detection method to deploy the airbag according to signals the system receives from four accelerometers where two of them installed on each of the front suspension fork legs. However, the system can be used only on models with larger vehicle sizes due to larger area required for the installation of the four sensors.

This paper describes the development of a method to overcome the space limitations of the prior method. In developed method, the crash detection can be carried out by only two sensors where one of them installed on each front suspension fork leg. This makes it possible to apply an airbag system to other motorcycle models as well.

In this developed method, the threshold value, which is used for crash discrimination, is processed as a function of longitudinal displacement of the front suspension. At each time step in the discrimination execution processes, the deceleration value is compared with the threshold processed as described above.

Through the analysis using spectrogram, it was revealed that the accelerometer outputs, when traveling on rough roads, show sinusoidal oscillation waves derived from the natural oscillation of the system composed of the front wheel and the suspensions. Consequently, waveforms of the longitudinal deceleration and the displacement, where the displacement is calculated by the second order integration of the deceleration, show the opposite phase to each other. On the other hand, in a frontal impact, the output of the accelerometer is generally expressed by the approximation of a half sine wave. Accordingly, the displacement from a frontal impact shows a monotonic increase. Utilizing these characteristics, a two-sensor crash detection method has been developed. The developed method was evaluated using data measured in various tests, including full-scale impact tests and rough roads tests, using large touring motorcycles and large scooters.

INTRODUCTION

Motorcycle airbag exploratory studies began in the 1970's. Early works addressed the crash detection necessary to trigger airbag deployment as well as the airbag concepts themselves. Sporner et al examined the usefulness of a crash detection system that utilized the sound emitted when front suspension is deformed during an impact [1]. Chinn et al analyzed acceleration data obtained from sensors mounted at different locations on a motorcycle to identify the characteristics of sensor outputs for a trigger system [2]. In these previous studies, preliminary crash detection methods were proposed based on the impact measurements on the system composed of the front wheel and the suspensions (front wheel-suspension system). However, those researches did not include the practical issues associated with the actual system application for a motorcycle.

In the 1960s, Honda began its research, aiming to enhance rider protection, and its research on motorcycle airbag systems has been seen by some as a significant breakthrough.

In an early exploratory study on a large touring motorcycle, a prototype triggering device was used [3]. The device consisted of an electric control unit and an accelerometer located near the front axle on each of the two front suspension fork legs. The signals from the accelerometers were calculated separately to generate the triggering signals and the airbag was triggered by the earlier signal.

As another example, a preliminary study of an impact sensing system for a large scooter was conducted [4]. On each front suspension fork leg, an accelerometer was installed and the other accelerometer was located on the front cowl framework. Two crash detection processes were applied. One of them used the averaged value of signals from the two accelerometers on the front suspension fork legs, while the other used the signal from the accelerometer on the front cowl frame. The airbag was triggered when either one of the two processes indicate a moderate to severe frontal impact.

Based on these studies of various kinds of detection methods, Honda decided to apply a crash detection method that used the signals from a total of four accelerometers, a pair on each front suspension fork leg. The first production airbag system incorporating this method was introduced on the 2006 Honda Gold Wing. Figure 1 shows the airbag system configuration applied to the Gold Wing.

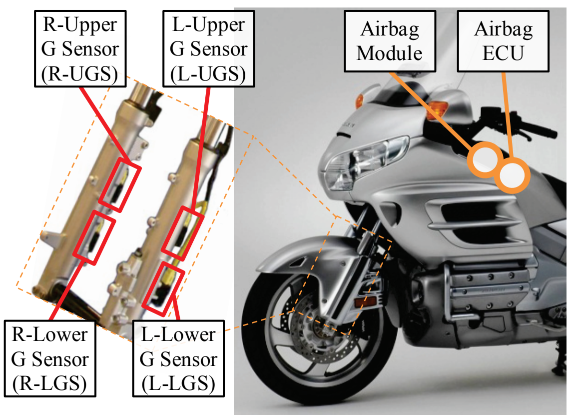


Figure 1. Previous Motorcycle Airbag System Configuration.

The front wheel-suspension system is the part of the motorcycle that experiences the initial impact forces in a typical motorcycle frontal collision. Because of this, the crash deceleration pulse from the right and the left front suspension fork legs are utilized in the crash detection system.

Within existing motorcycle structures, the space for installation of accelerometers depends on the structure of the base model. For example, suspension arrangements (normal telescopic, inverted, trailing link etc.), suspension length, and pre-installed peripheral devices, such as brake calipers, limit the available space to install accelerometers. Therefore, this method only is applicable to a limited number of models which have a space large enough to install two sensors on each front suspension fork leg.

The current study was intended to help overcome these limitations with the result being that it was possible to develop a crash detection method using a total of just two accelerometers, one each on the right and the left front suspension fork legs. This was made possible by extracting the characteristics of deceleration waveforms measured at the front suspensions in a crash and during normal operation.

MOTORCYCLE CRASH DETECTION METHOD

Table 1 shows the major specifications of the large touring motorcycle used for our study.

Table 1.
Specifications of the test motorcycle

Length	(mm)	2,630
Width	(mm)	945
Height	(mm)	1,525
Wheelbase	(mm)	1,690
Curb Mass	(kg)	425
Engine Displacement	(cm^3)	1,832

Crash Detection Method for Previous Motorcycle Airbag System

Figure 2 shows the block diagram of crash detection for the previous motorcycle airbag system.

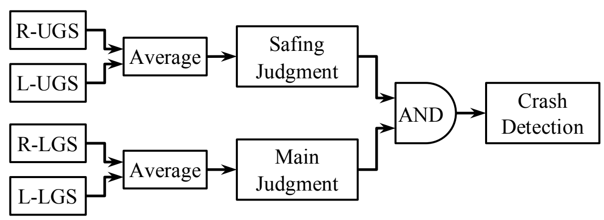


Figure 2. Block Diagram of Previous Crash Detection.

The Main Judgment portion discriminates whether a sufficiently severe crash requiring deployment of the airbag has occurred. The Safing Judgment portion is a failsafe function to prevent undesired deployment of the airbag that might be caused by the failure of, or an erroneous signal from, the accelerometer configuring the Main Judgment.

Right and Left Averaging and the Safing Judgment

The previous crash detection method adopts the Main and Safing Judgments based on the average of the signals from the right and the left accelerometers. The averaging processes can reduce the effect caused by the front wheel-suspension system being forcefully steered by the impact at the early stage of a crash. As an example, Figure 4 shows the deceleration signals measured at the front suspension fork legs in the two ISO13232 [5] impact configurations shown in Figure 3.

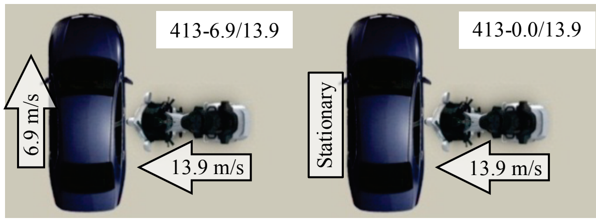


Figure 3. Impact Test Configurations Defined in ISO13232.

The impact configuration code comprises a series of three digits describing the opposing vehicle contact point, the motorcycle contact point, and relative heading angle, respectively, followed by the opposing vehicle impact speed, and the motorcycle impact speed.

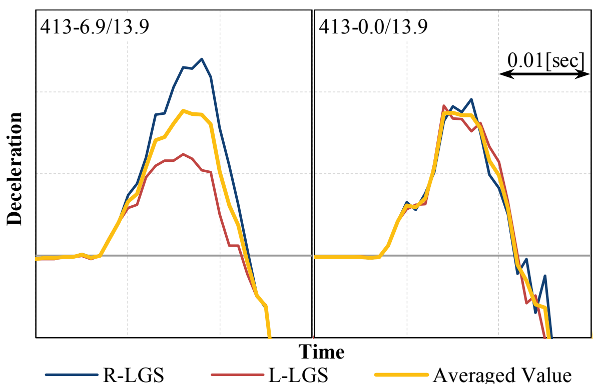


Figure 4. Comparison of R/L-LGS Deceleration.

While R-LGS deceleration value is equivalent to L-LGS deceleration value in the stationary car impact configuration 413-0.0/13.9, the deceleration value of L-LGS is lower than that of R-LGS in the both moving impact configuration 413-6.9/13.9. This is because the front wheel-suspension system was forcefully steered by impact with the opposing vehicle that was moving in a lateral direction relative to the motorcycle. However, the averaged value of the deceleration values from R-LGS and L-LGS is equivalent in both impact configurations. Consequently, by the use of the averaging process, the effect of the steered front wheel is significantly reduced.

The Main Judgment, which is based on the averaged signals from R-LGS and L-LGS, detects a crash erroneously when one of LGSs outputs a high deceleration value due to malfunction of, or an erroneous signal from the accelerometer. The Safing Judgment is provided in order to reduce the probability of an undesired deployment of the airbag due to failure of the accelerometer, or the like, during normal operation. With the previous airbag system, an additional pair of accelerometers (R/L-UGS) is installed on the right and the left front suspension fork legs for the Safing Judgment, which is, again, based on the averaged value of the two figures. As crash detection is made by the logical conjunction of the Main Judgment and the Safing Judgment, even if any one of the Judgments detects a crash by the failure, or the like, of one accelerometer, the other Judgment prevents an improper deployment signal to the airbag.

Two-Sensor Crash Detection

Based on the previous crash detection method, with R/L-UGS removal, we developed a two-sensor crash detection, the block diagram of which is shown in Figure 5.

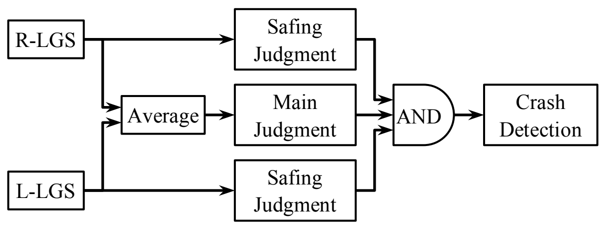


Figure 5. Block Diagram of Two-Sensor Crash Detection.

With this configuration, if an output abnormality occurs in R-LGS, because the Main Judgment is calculated with the averaged value of LGSs outputs, it may incorrectly detect that a crash has occurred. And besides, one of the Safing Judgments, which is calculated with R-LGS output, may also output an improper ON signal. However, because the other Safing Judgment, which is calculated with L-LGS output, is OFF, an undesired deployment can be avoided.

In the two-sensor crash detection system, the Main Judgment has the comparable performance of discrimination because the same judgment process is applicable as in the previous system. On the other hand, the Safing Judgment is based on the individual signals from R-LGS and L-LGS and they are affected by the steered motion of the front wheel as described above. Therefore, the same judgment process cannot be applied as in the previous system. That is why we needed to develop a different method for our system.

The target performance for the Safing Judgments is to output OFF signals at all times in normal operations including rough road running and to output ON signals at the time when a crash requires the airbag to be deployed. The waveforms measured when running along rough roads are shown in Figure 6 as an example of the situations where OFF judgment is required. As shown in the graph, the spikes of high deceleration can be observed and these are considered as sudden decelerations when the front tire experiences the impacts when the vehicle runs over the edges of potholes.

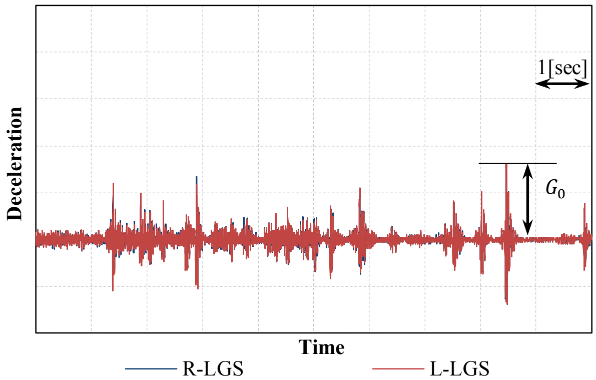


Figure 6. Deceleration Time History in Rough Road Running.

In the next step, a collision where a passenger vehicle impacts a motorcycle while the rider is waiting to turn left is simulated as an example of a situation where ON judgment is required. The waveforms measured in such a collision are shown in Figure 7.

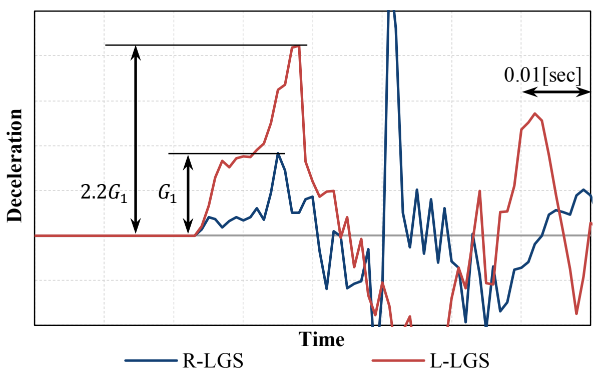


Figure 7. Deceleration Time History in Steered Collision.

The scales of the vertical axes (Deceleration) of Figure 6 and Figure 7 are the same. There is a difference between the measured decelerations of R-LGS and L-LGS, which reaches the maximum of 2.2 times, caused by the collision accompanying the left-steered state.

The deceleration peak of R-LGS (G_1) shown in Figure 7 is at the same level as the deceleration peak (G_0) during rough road running, which is shown in Figure 6. Therefore it was found that the Safing Judgment is difficult by only comparing the peak deceleration values.

Characteristics of Displacement-Deceleration Curve

In the waveform measured during rough road running shown in Figure 6, the waveform in the vicinity of peak value is shown in Figure 8.

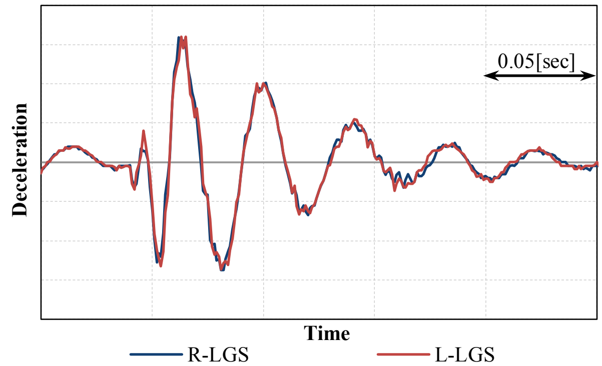
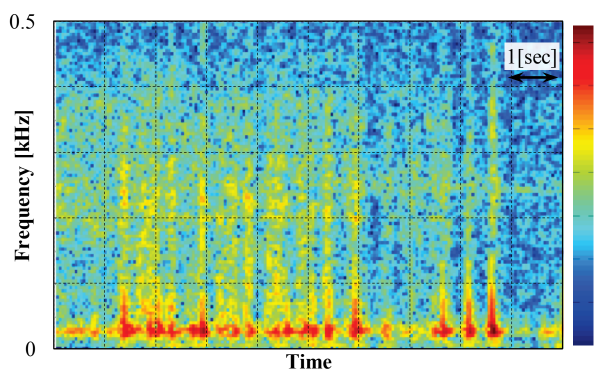


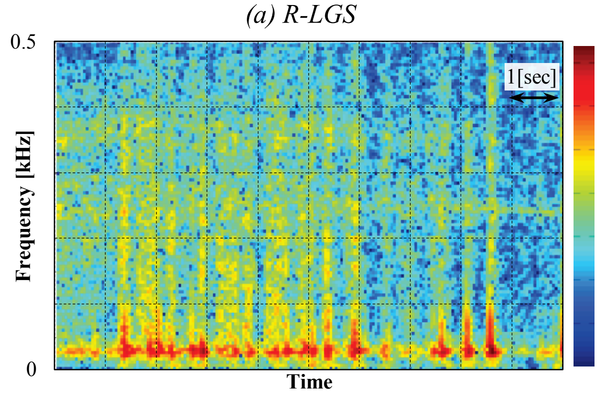
Figure 8. Oscillation Waveform of Front Suspensions.

The spectrogram of measured deceleration value is shown in Figure 9 (a) and (b).

The vertical axis of the figure indicates the frequency, the horizontal axis indicates the time of the measurement, and the colors of the pixels indicate the intensity of the signals.



(a) R-LGS

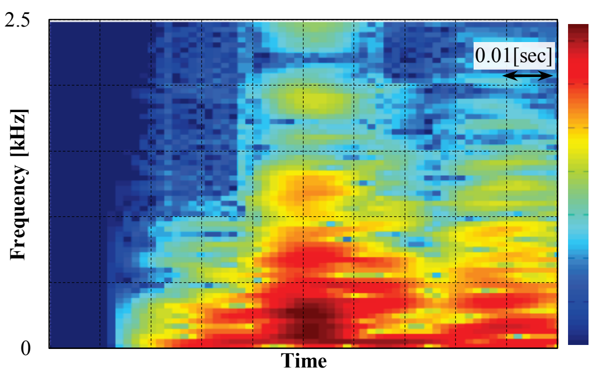


(b) L-LGS

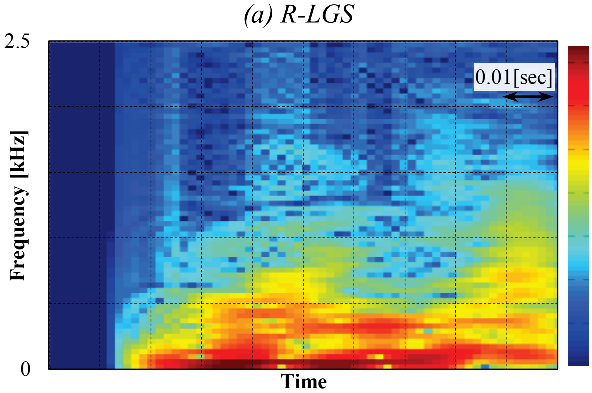
Figure 9. Spectrogram of Rough Road Running Deceleration.

The spectrogram shows high density in a fixed low frequency area around 0.02 kHz even though the random-like exciting forces applied to the front wheel-suspension system with the uneven road surfaces in the rough road running. This low frequency area is almost close to of the natural frequency of the front wheel-suspension system. As the direction of the sensing axis of the accelerometer is orthogonal to the stroke direction of the front suspension, the acceleration along the axis of the suspension, which is caused by the suspension stroke absorbing the road unevenness, is not detected by the accelerometers. On the other hand, the front wheel-suspension system with cantilever structure is excited back and forth by the road unevenness in an orthogonal direction to the stroke of the front suspension. The oscillation period during rough road running is determined by the front wheel-suspension system characteristics regardless of the road unevenness.

We have made the same frequency analysis on the deceleration measured at the occurrence of steered collision (Figure 10).



(a) R-LGS



(b) L-LGS

Figure 10. Spectrogram of Steered Collision Deceleration.

As the front fork is deformed over the elastic region during a steered collision, the detected waveform is not dependent on the natural oscillation. As a result, the spectrum dispersed over the wide area below 1.0 kHz.

Based on the result of measured waveform examination, we have verified the Safing Judgment with waveforms that approximate the deceleration measured in the actual tests. The deceleration waveform measured when running rough roads is approximated by the equation (1) as a damped oscillation.

$$m\ddot{x} = -kx - c\dot{x} \qquad (1).$$

Where

m	:	Mass
k	:	Spring constant
c	:	Damping coefficient

Assuming initial position as $x(0) = 0$ and initial velocity as $\dot{x}(0) = v_0$, the real root is as follows:

$$x(t) = \frac{v_0}{\sqrt{1-\zeta^2}\,\omega_0} e^{-\zeta\omega_0 t} \sin\left(\sqrt{1-\zeta^2}\,\omega_0 t\right) \qquad (2).$$

$$\ddot{x}(t) = -\frac{v_0\omega_0}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_0 t} \sin\left(\sqrt{1-\zeta^2}\,\omega_0 t + 2\varphi\right) (3).$$

Where

$$\zeta = \frac{c}{2\sqrt{mk}}$$

$$\omega_0 = \sqrt{\frac{k}{m}}$$

$$\varphi = \tan^{-1}\left(\frac{\zeta}{\sqrt{1-\zeta^2}}\right)$$

We determined each parameter experimentally from the results of measurements in actual running tests, and obtained the approximate waveform shown in Figure 11.

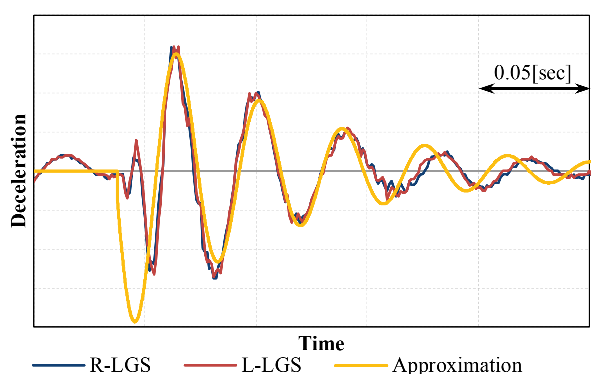


Figure 11. Approximation of Oscillation of Front Suspension.

The damping coefficient was $\zeta = 0.08$. Assuming $\varphi \simeq 0$ from $\zeta \ll 1$, equation (4) can be obtained from equation (2) and equation (3).

$$\ddot{x}(t) \simeq -\omega_0^2 x(t) \tag{4}$$

The acceleration represents an oscillation almost reverse in phase to the displacement.

On the other hand, the initial deceleration pulse in a steered collision is approximated by the equation (5) as a half-sine wave.

$$\ddot{x}(t) = \begin{cases} 0 & (t < 0) \\ a_0 \sin \omega t & (0 \le t \le \pi/\omega) \end{cases} \tag{5}$$

The displacement is expressed by equation (6).

$$x(t) = \begin{cases} 0 & (t < 0) \\ a_0(\omega t - \sin \omega t)/\omega^2 & (0 \le t \le \pi/\omega) \end{cases} \tag{6}$$

The approximate waveform of R-LGS, which is shown in Figure 7, is shown in Figure 12 when the constants of a_0 and ω are assumed the same as in those of the damped oscillation in equation (3).

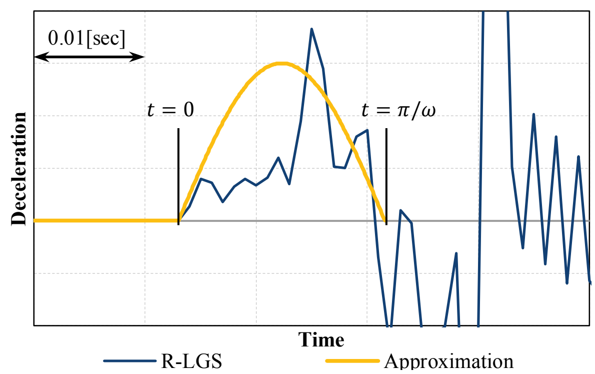


Figure 12. Approximation of Deceleration of Steered Collision.

Regarding these approximate waveforms, the displacement-deceleration curves are shown in Figure 13 with the vertical axis defined as deceleration and horizontal axis defined as displacement.

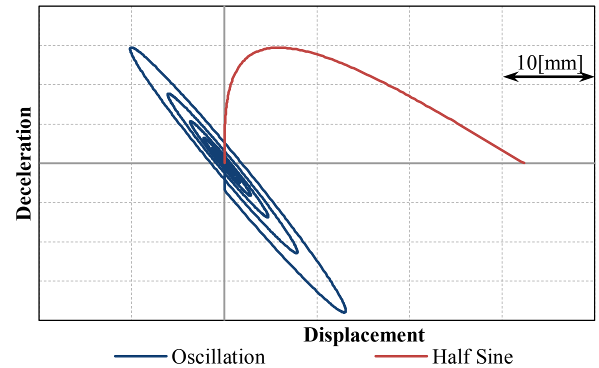


Figure 13. Displacement-Deceleration Curves of Approximations.

Distribution of the damped oscillations is situated over the second and fourth quadrants as the displacement and the deceleration have the opposite phases to each other. On the other hand, distribution of the half-sine wave is situated in the first quadrant as the displacement increases monotonically. By utilizing these characteristic, it becomes possible to distinguish between the rough road running and a steered collision with an appropriate judgment threshold line in the first quadrant of the displacement-deceleration plane.

Application to Crash Detection

Distinction between rough road running and a steered collision by means of displacement-deceleration curves was applied to the Safing Judgment in Figure 5. The displacement-deceleration curves of data, which are measured in rough road running and steered collision, are shown in Figure 14 together with and judgment threshold line.

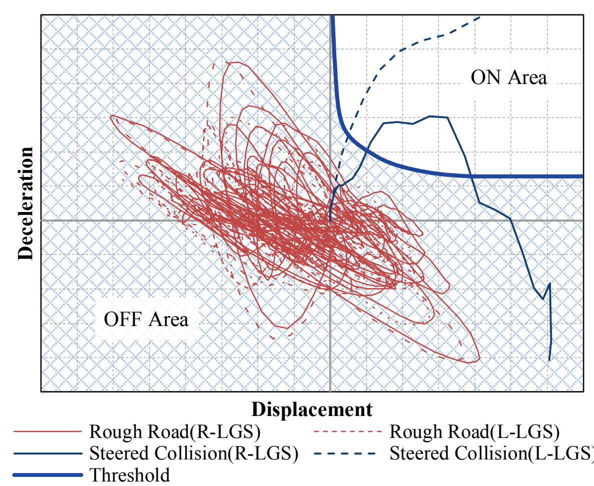


Figure 14. Displacement-Deceleration Curves and Threshold of Two-Sensor Safing Judgment

The first quadrant on the displacement-deceleration plane shows that the status of the front wheel-suspension system is shifted to an area behind the normally located position and is decelerating as well. In this area the ON area was set, because it is translated that the impacts were applied to the extent at which the deformation of the front wheel-suspension system lead to the plastic range and the threshold line shown in Figure 14 was specified. The waveforms when running rough roads and when experiencing the steered collision are distinguishable on the displacement-deceleration plane even though those deceleration peaks reach to the same levels.

VERIFICATION

We compared the ON/OFF judgment results between the previous technology and the two-sensor crash detection method by using the result of the acceleration measured with a large touring motorcycle (Table 2). We have obtained the ON/OFF judgment results equivalent to those obtained using the previous technology in all configurations.

Table 2.
Evaluation result of the two-sensor Safing Judgment

Configurations	Result				
	Main Judgment		Safing Judgment		
	Previous Method	Two Sensor	Previous Method	Two Sensor	
				R	L
Rough Road	OFF	OFF	OFF	OFF	OFF
Low Speed Crash	OFF	OFF	ON	ON	ON
413-0.0/13.9	ON	ON	ON	ON	ON
413-6.9/13.9	ON	ON	ON	ON	ON
Steered Collision	ON	ON	ON	ON	ON

The verification of the method is conducted with a large scooter as well. The vehicle specifications are shown in Table 3.

Table 3.
Specifications of the large scooter

Length	(mm)	2,185
Width	(mm)	750
Height	(mm)	1,180
Wheelbase	(mm)	1,545
Curb Mass	(kg)	204
Engine Displacement	(cm^3)	248

Unlike the large touring motorcycle, the large scooter does not have an upper triple clamp on its front fork and has a smaller front wheel. However, the waveforms measured in the rough road running tests show damped oscillations (Figure 15).

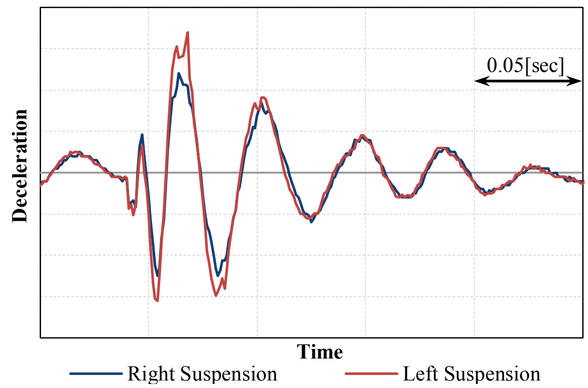


Figure 15. Oscillation Waveform of Front Suspension of Large Scooter in Rough Road Running.

The displacement-deceleration curves of the large scooter, shown in Figure 16, show similar features to those of the large touring motorcycle, even though the parameters of natural oscillation in the large scooter are different from those of the large touring motorcycle because of the difference in the constructions of the front wheel-suspension system.

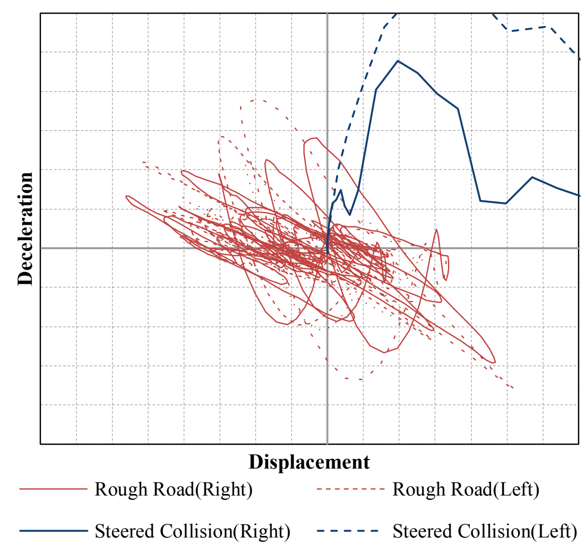


Figure 16. Displacement-Deceleration Curves of the Large Scooter.

CONCLUSIONS

The two-sensor crash detection method was developed to apply to mass-production large motorcycles.

The developed method utilized the characteristics which were investigated through analyses of oscillation behaviors in motions of front wheel-suspension systems while driving in rough roads and while experiencing impacts in the vehicle collisions.

Following the method development, the validity of the method was confirmed with the equivalent judgment performance obtained in the comparison tests of the previous method with the data measured in the large touring motorcycle.

In addition, it was confirmed that this method was also applicable to the motorcycles with different constructions of the front wheel-suspension system based on the data measured in the large scooters.

REFERENCES

[1] Sporner, A., Langwieder, K., Polauke, J., 1987, "Development of a Safety Concept for Motorcycles - Results From Accident Analysis and Crash Tests." in Proceedings of 11th International Technical Conference on Experimental Safety Vehicles, Washington D.C., 835 - 842.

[2] Chinn, B.P., Okello, J.A., McDonough, P.J., Grose, G., 1996, "Development and Testing of a Purpose Built Motorcycle Airbag Restraint System." in Proceedings of 15th International Technical Conference on the Enhanced Safety of Vehicles, Melbourne, Paper Number 96-S7-O-13.

[3] Iijima, S., Hosono, S., Ota, A., Yamamoto, T., 1998, "Exploratory Study of an Airbag Concept for a Large Touring Motorcycle." in Proceedings of 16th International Technical Conference on the Enhanced Safety of Vehicles, Paper Number 98-S10-O-14.

[4] Kuroe, T., Iijima, S., Namiki, H., 2004, "Exploratory Study of an Airbag for a Large Scooter-Type Motorcycle." in Proceedings of 5th International Motorcycle Conference 2004, Munchen.

[5] International Organization for Standardization, 2005, "Motorcycles - Test and analysis procedures for research evaluation of rider crash protective devices fitted to motorcycles -." International Standard ISO 13232 2005(E)

MOTORCYCLE HELMET STANDARDS – HARMONISATION AND SPECIALISATION?

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ABSTRACT

There are a number of major motorcycle helmet standards, e.g. AS/NZS 1698, DOT, JIS T 8133, Snell M2010 and UN/ECE 22. With international trade agreements, on-line purchasing, and motorcycling growth there is a need to assess whether there is scope for harmonising motorcycle helmet standards as well as specialising standards for specific environments. This paper will compare and contrast standards requirements and consider opportunities for improvements and international harmonisation.

A desktop review of standards, motorcycle helmet and relevant biomechanical literature was undertaken. The results of impact performance tests on 31 helmets that met at least AS/NZS 1698 and combinations of other standards were assessed by standard certification. Tests included 2.5m flat and hazard anvil impacts with an ISO "M" headform. Peak headform acceleration was measured. Results from oblique impact tests on motorcycle helmets were evaluated in terms of identifying the benefits of such a test. The test rig consisted of a Hybrid III head and neck falling on guided rails onto the top of a powered striker plate. Tests were conducted up to a drop height of 1.5 m and a horizontal speed of 35 km/h. Linear and angular headform acceleration were evaluated.

There are many commonalities between each standard, but there are subtle to substantial differences also. All standards have tests of acceleration management, retention system strength and stability. No standard has a true oblique impact test and chin bar assessment is varied. There are no studies that compare the performance of helmets in real world crashes by standard certification. There were few significant differences in helmet performance in lab tests by standard certification, particularly when only full-face helmets were included in the analysis. There was an overall correlation (Pearson Correlation = □0.60 ($p<0.01$)) between helmet mass and impact performance. Average maximum linear and angular headform accelerations for four helmets in oblique impact tests were 150g (SD=30) and $9.5 rad/s^2$ (SD=3.3), respectively.

Motorcycle helmets have been shown to reduce the risk of death by 42% and head injury by 69%. Mild traumatic brain injury appears to be the prevalent form of injury suffered by helmeted motorcyclists. Although there are differences between each standard, some potentially would make at best only a marginal difference in a crash. Some, such as Snell M2010 appear to be associated with heavier helmets. Oblique helmet testing can identify performance differences between helmets that are related to injury mechanisms not assessed directly by current standards. The climate and road environment are issues that need to be considered and might lead to helmet specialisation as found in JIS T 8133. In other words, operators of low powered motorcycles in hot and humid climates might have a helmet certified to a different part of a common standard compared to operators of high powered motorcycles ridden at speed on major roads. Also critical to the motorcyclists is the incorporation of a quality control system including batch testing.

These issues indicate opportunities exist for harmonisation, specialisation and improvement in motorcycle helmet standards that will benefit motorcyclists, government, trade and road safety groups.

INTRODUCTION

Ideally, the objective of a motorcycle helmet safety standard is to provide performance criteria that ensure a minimum level of head trauma reduction during a range of head impacts. Obviously this reduction in head trauma is comparative, i.e. compared to a situation had the person not worn a helmet and was subjected to the same magnitude head strike. A 'safe' helmet might thus be defined as one that provides 'significant' reduction in risk of head injury given the same impact conditions for a helmeted compared to a non-helmeted rider. However, what may be a significant reduction for one motorcycle stakeholder may not necessarily be sufficient for another, and may indeed be a hindrance to another (manufacturer/supplier), and thus may vary depending on the stakeholder; e.g. a motorcyclist, a government road safety official, a helmet manufacturer/supplier, an engineer, a trade official, etc. Those stakeholders concerned with safety would like to know how 'safe' a helmet is that meets the standard, and whether a helmet meeting one standard is 'safer' than one meeting another. Other stakeholders may see any onerous safety requirements as financially detrimental to their business, e.g. manufacturers/suppliers. Obviously there are absolute and relative comparisons that can be made.

Public confidence in any standard that specifies a particular level of safety requirement is very important. Considering that those members of the public that care about safety may not be able to assess the technical specifications of a standard, the reputation of the organisation may be the single most important factor in imparting public confidence that in the event of a crash, a helmet that meets the standard's safety performance criteria will protect a motorcyclist's head. How the standard is applied and the certification regimes are important in developing and maintaining confidence in the standard, and may be fundamental to protecting the motorcyclist's head.

One or more of the following standards govern the performance of motorcycle helmets internationally. Those standards are:

- AS/NZS 1698 Protective helmets for vehicle users (Australia and New Zealand)
- UN/ECE 22.05 Uniform provisions concerning the approval of protective helmets and of their visors for drivers and passengers of motorcycles and mopeds (Europe).
- Snell M2010: Standard for protective headgear for use with motorcycles and other motorized vehicles (USA)
- Snell 2005 Standard for protective headgear for use with motorcycles and other motorized vehicles (USA)
- USA DOT 571.218 Standard No. 218; Motorcycle helmets (USA)
- JIS T 8133 Protective helmets for motor vehicle users (Japan)
- BS 6658:1985 Specification for protective helmets for vehicle users

There is national and international interest in helmet standard comparisons, how the standards influence helmet performance and ultimately mitigate the risk of head injury for Powered Two Wheelers (PTW), i.e. motorcycle/moped riders and pillion passengers. In Australia, it has been reported that in 2008 motorcycles accounted for only 1% of vehicle-kilometres, but 15% of motor vehicle user deaths being approximately 30 times the rate for car occupants. In regards to serious injury the rate is approximately 41 times higher than for car occupants [1]. This trend for motorcyclists is counter to the falling rates of fatalities and serious injuries for other road users and similarly exists in the other countries [2]. As the international and national markets for helmets grow with increasing PTW use, and as 'on-line' retail increases, there are many reasons to review the variety of helmet standards from different countries.

METHODS

A desktop review of six motorcycle helmet standards listed above, excluding BS, was undertaken. The review covered technical aspects, epidemiological data, crash analyses and laboratory tests.

RESULTS

Impact performance

Impact performance is assessed in all the six standards using guided free fall impacts of a helmeted headform onto an anvil. Centre of Gravity (CoG) headform acceleration parameters are used to assess performance in all standards. However, there is a great deal of variation in test specifications.

<u>Test Rig and Headforms</u>

Impacts can be conducted with two-wire guided drops with a unixial accelerometer, three-wire guided drops with a triaxial accelerometer (UN/ECE 22), or with a rail mounted device and uniaxial accelerometer. There are potential differences in impact acceleration outcomes between the guided (uniaxially restrained) impacts and the unrestrained UN/ECE 22 tests.

The specific headform dimensions and sizing have not been compared, but appear similar except for the DOT standard that still mandates DOT headforms. All others mandate ISO headforms. ISO and DOT headforms are not equivalent in either mass or circumference. All impact tests utilise a rigid headform. UN/ECE 22 uses a full headform compared to the half headform used in 1698 and Snell.

<u>Test Areas</u>

In brief, the test area covers the cranium, but not the face, and is similar between standards. The "Basic Plane" is common to all as is the "Frankfurt Plane". There are some differences, e.g. the test line for AS/NZS 1698 is lower than in the Snell standards.

There is suggestion in some of the research literature that there may be an interaction between impact site and headform restraint in the specific test rig that effects headform acceleration. This is the case, for example, in the unrestrained impact when the centre of impact and centre of gravity may not be aligned.

There is an option to test over a "protective lower face cover", i.e. chin bar, in UN/ECE 22.

Flat Anvil Impacts

All standards include impacts against a flat rigid anvil of the same dimension; around 130 mm diameter. UN/ECE 22 does not require two successive impacts per impact site, unlike all other standards.

The impact velocities are different for each standard, ranging from 6m/s in 1698 to 7.75m/s in M2010. Impact energies derived for either a "J" headform of mass 4.7kg, or for DOT 5kg for the first or only impact are presented in table 1.

Table 1.
Comparative impact energies

Standard	Energy (J)
AS/NZS 1698	84.4
UN/ECE 22	132.3
M2010	141.2
M2005	150
DOT	89.8
JIS	115.3

AS/NZS 1698 has the lowest severity impact of the standards. According to Thom et al [3], the DOT flat anvil impacts, and thus AS/NZS 1698, corresponded to the 90th%ile of all motorcycle traffic crashes analysed in a 1981 report.

Other Anvil Impacts

In addition to flat anvil impacts, hemispherical, kerb or edge anvils are used in one or many of the standards. Impact against a hemispherical anvil is required in all standards, except ECE 22. ECE 22 requires impacts against a kerb anvil and M2010 and M2005 against an edge anvil. Although these impacts might introduce localised loading, only the headform acceleration is measured. Impact energies and their spread are similar to those for flat anvil impacts, although lower in both 1698 and DOT tests.

Acceleration Requirements

CoG linear headform acceleration is measured in all standards, either with a unixial accelerometer in uniaxially restrained impacts or a triaxial accelerometer in unrestrained impacts. There are potential differences in the measurements due to the different methods. Although there are minor differences, the linear acceleration requirements in five of the standards (1698, ECE, M2005, M2010 and JIS) are similar and in the range 275g to 300g. The DOT standard has a 400g requirement, which appears to be the least stringent, until the "dwell time" limit of 2.0ms at 200g is considered. ECE also has a HIC 2400 requirement. Presumably, the DOT requirements mimic the Wayne State University head impact tolerance curve [4].

There is concern that the inclusion of "dwell time limits", e.g. 2.0ms at 200g, in some standards and not others may require helmet design and construction requirements to pass more than one standard, e.g. Snell and DOT. [3,5,6] These limits are highlighted in *Figure 1*. These requirements, e.g. a stiffer shell and liner to satisfy the high energy impact requirements in Snell, may result in longer dwell times in lower severity impacts in the DOT standard and thus failures. There is also a view that in order to meet the 2.0ms 200g acceleration requirement in the DOT standard, the maximum headform acceleration will be as a rule less than 250g, in spite of the 400g limit [7,8]. It can be seen in *Figure 1* that the shapes of the permissible acceleration time histories are tightly constrained above 150g by the time constraints in 1698 and DOT standards. In contrast, the Snell and UN/ECE could expose the head to higher accelerations for longer durations.

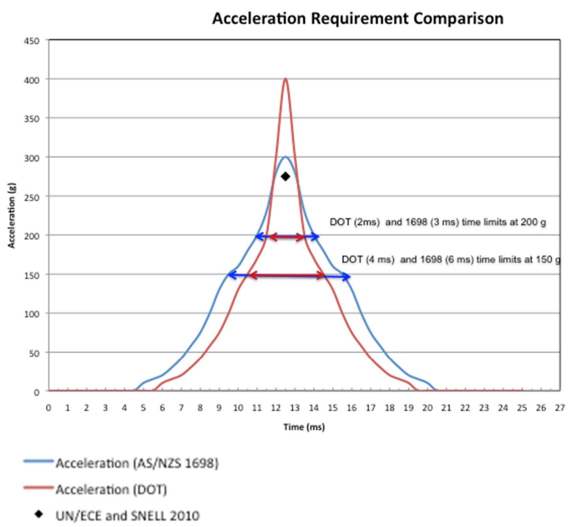

Figure 1. Schematic comparison of theoretical acceleration time histories for four standards highlighting the time limits (dwell times).

Penetration Test

All standards, except ECE 22, include a resistance to penetration test. The striker is essentially the same; 3kg with a 60° conical head, but impacts in 1698, M2005, M2010 and DOT are from 3 metres, whereas the requirement for the equivalent type 2 helmet in JIS is from 2 metres. The required outcome is the same; no contact with the headform. A rationale expressed for the penetration test is that it is a test of the integrity and build quality of the helmet. The test may fail so-called 'novelty' helmets that exist in the USA.

Chin Bar

M2005 and M2010 assess chin bar rigidity in a dynamic test. The chin bar may be assessed in ECE 22, if designated as a "protective lower face cover". It is not assessed in the other standards.

Load Distribution

There are no load distribution tests in any of the six standards. There has been no recent discussion about replacing the penetration test with a test of localised load distribution as occurred in AS/NZS 2063, bicycle helmets.

Oblique Test

Only ECE 22 (and BS 6658) has a test for projections and surface characteristics that may induce rotational forces. The other standards have an inspection regime to assess the dimensions of internal and external projections. AS/NZS 1698 has the provision to impact test internal projections greater than 2mm and oblique test for external projections greater than 5mm.

ECE 22 describes two equivalent oblique test methods. In short, a tangential load is applied to a helmeted headform by dropping it onto an inclined anvil or dragging a horizontal plate underneath the helmet. In both cases either an abrasive or a shear edge engages the helmet. The peak 'friction' force and destruction of any projections are assessed.

There is no measurement of angular acceleration or change in angular velocity in ECE 22. Therefore, the ECE 22 test is not considered by researchers to be a test of the helmet's ability to manage angular acceleration or velocity induced brain injuries [9]. The test has been criticised also because it does not replicate an impact with both tangential and radial forces; the latter causing a flattening and widening of the contact area between the helmet and the collision partner, and thus changing the tangential forces and moment.

Rigidity

Only ECE 22 has a test for transverse and longitudinal rigidity. This test may assess some properties in common with the penetration test.

Impact performance summary

On paper Snell M2010 has arguably the most stringent impact performance requirements evidenced by: the high energy input and the lowest peak acceleration output requirements; repeat impacts; penetration test; chin bar test; and, impacts against three anvils. DOT has arguably the least stringent requirements, although the effect of the acceleration dwell times may make the real peak acceleration closer to 250g. ECE 22 has a large suite of tests, some comparable to Snell M2010, and includes the only specific oblique impact test. However, the oblique test does not appear to be configured to correlate with specific angular acceleration induced injuries. ECE 22 is the only standard with transverse and longitudinal rigidity tests. These tests might evaluate some characteristics common to the penetration test. On paper AS/NZS 1698 appears to be less rigorous than ECE 22, but the repeat impact requirement in 1698 might lead to a similar level of protection in a single high energy impact for the 1698 certified helmet. Another issue to consider is the relationship between helmet mass, impact energy and the impact performance requirements in each of the standards. Whether these test requirements translate into differences in helmet performance will be examined later in the report.

Retention

The strength of the retention system is assessed in all standards. It is assessed statically in 1698, DOT and JIS through the application of a defined force and dynamically in ECE 22, M2010, M2005, and as an alternative in JIS, through a guided drop mass. ECE 22 and JIS subject the retention system to a 73.6J load and limit the dynamic displacement to 35mm, which is more than M2010 and M2005 (44.7J and 30mm maximal dynamic displacement).

Stability

Dynamic stability is assessed in all standards, except DOT. JIS and ECE 22 are the same for equivalent helmets (type 2 JIS) and require 10kg to be dropped 500mm, in comparison to only 300mm in 1698. Helmet rotation is limited to 30° in those standards. M2010 and M2005 load the helmet with a 4kg inertial hammer dropped 600mm and only require that the helmet remains on the headform.

Peripheral Vision

Peripheral vision requirements for the lateral aperture are the same on all standards, 105° on either side of the sagittal plane. 1698 and DOT do not have a requirement vertically, up and down, whereas all others are similar.

Visor

ECE 22 defines a series of optical and mechanical visor tests. M2005 and M2010 have a resistance to penetration test in which a lead pellet is fired at 500km/h at the visor. AS/NZS 1698 requires the visor to comply with AS/NZS 1609.

Batch and Continuous Control

Written into UN/ECE 22 are batch and continuous control requirements for helmets. M2005 and M2010 have random sample testing requirements conducted by Snell of helmets obtained at the point of sale. JIS and DOT do not appear to have any batch or continuous control test requirements. Batch testing requirements are being considered as part of AS/NZS 1698.

Labelling and Certification Mark

All helmet standards have some requirements for helmet labelling. These requirements include information on the helmet (make, model, month and year of manufacturer and size) as well as care and use instructions (correctly fastened, no alteration, replacement guidelines and exposure to solvents).

Helmets that are certified to Snell standards are identified by a serialised certification label. The label includes the registered trademark of the Snell Memorial Foundation (examples are found at http://www.smf.org/cert). The label can be used under licence from Snell. The JIS standard requires that the number of the standard is included in the labelling. UN/ECE requires the certified helmet be labelled with the "international approval mark". This mark comprises the letter "E" surrounded by a circle and then additional coded information on the country in which approval was granted, whether the face cover is protective and a serial number. AS/NZS 1698 requires a certification mark, where required by statutory authorities. However, AS/NZS 1698 does not describe the certification mark. The DOT standard requires that the helmet be labelled with the symbol "DOT" in one centimetre high letters on the rear external surface of the helmet.

Real world comparisons of helmet effectiveness

There is no peer reviewed published research or grey research literature that examines, using a suitable study design, whether helmets meeting one standard perform better in a crash than another. The most likely comparison would be between Snell and DOT certified helmets in the USA. However, it would be challenging to undertake such a study because the results could easily be confounded by [10,11]:

- Crash severity
- Specific characteristics of the impact
- Age of motorcyclist
- Lack of controls
- Variation in performance within helmets meeting one standard
- Helmets meeting more than one standard
- Post crash injury management
- Road rules and laws governing the sale and use of helmets in a region
- Between factor confounding, e.g. a young inexperienced rider, travelling too fast and wearing an unsuitable helmet or an older rider with a lower impact tolerance wearing a 'safer' helmet.

At a very macro-level, i.e. comparing motorcycle head injury rates in the USA between Australia and Europe, some of the same confounding factors would be present. In their 2004 meta-analysis of motorcycle helmet effectiveness studies, Liu et al [12] noted that there was "insufficient evidence to demonstrate whether differences in helmet type confer more or less advantage in injury reduction." The following summarises some recent work on this topic.

The National Highway Traffic Safety Administration (NHTSA) reported that in 2007 58% of motorcyclists wore a DOT compliant helmet, 16% wore a non-compliant helmet and 26% wore no helmet [13]. In 2009 this had changed to 67% DOT compliant, 9% non compliant and 24% no helmet [14]. NHTSA estimated that in 2008, helmets saved the lives of 1829 motorcyclists [15]. Further, that the helmets are 37% effective in preventing fatal injuries. This statement could be generalised that DOT compliant helmets are 37% effective in preventing fatal injuries. However, the lead author has noted many helmets available in Australia that signify compliance with both Snell and DOT standards, as well as AS/NZS 1698. Therefore, a proportion of the DOT compliant helmets in the USA will be compliant with Snell as well.

A retrospective case series analysis of 422 motorcycle crash victims treated at a level one trauma centre over three years in the USA showed that helmets reduced the likelihood of a traumatic brain injury by almost 50% [16]. Helmet use was not found to be associated with cervical spine fracture, although there was a small (13%) non-significant reduction in the chance of a cervical fracture for helmet wearers.

The European 'In-depth Investigation of Motorcycle Accidents' (MAIDS) concluded that a helmet was "capable of preventing or reducing the severity of head injury" in 68.7% of the 921 cases studied [17]. The analysis of the 921 cases also concluded that the PTW crash speeds were less than 50km/h in 75% of cases. Ninety-seven percent (97%) of cases sampled required at least hospitalisation, including the 11% fatalities. Therefore, the sample was biased towards the more severe spectrum of injury outcomes. There were 3417 injuries of severity greater than AIS 1 to the PTW riders and 18.4% were to the head. Around 75% of the head injuries were AIS 1 and 2 (minor and moderate). Only 90.4% of the motorcycle riders wore a helmet, despite their use being mandatory. It was observed that the helmet was ejected from the rider's head in 9.1% of cases and in the majority of cases this occurred because the helmet was not appropriately fastened.

Unfortunately, the data available from MAIDS does not facilitate a comparison with NHTSA's estimation of helmet effectiveness. An earlier 1998 study from Greece estimated that during the period 1985 and 1994, helmets reduced the risk of death for a motorcyclist by 36% [18]. They concluded that 38% of the 1994 deaths could have been avoided if the rider wore a helmet. This is the same as in the USA, however the type of helmets and the severity of crashes is not accounted for in these general figures. It could be reasonably assumed that helmet effectiveness has improved since 1994.

Research by Richter et al [19], indicated that misuse of the helmet retention system and failure of the retention system were factors resulting in the loss of a helmet. The authors also compared the head impact speed and impact location to ECE 22-4 in some cases. They observed that 90% of the impacts were below the ECE 22 test line.

The COST project examined the performance of helmets in detail, but did not compare the performance of helmets meeting different standards [20]. A summary and interpretation of results from the COST project will be presented in the next section.

In Australia, where all helmets must be certified to AS/NZS 1698, it is challenging to compare the performance of helmets meeting different standards. Although some helmets are certified to multiple standards, it is unclear which is the most suitable for the crash that the rider experienced. Between 1999 and 2003, 53% of fatal motorcyclists were known to have worn a helmet, in an additional 13% of cases the helmet came off, and in 7% of cases a helmet was known not to have been worn [21]. In 27% of cases helmet use was unknown. Within these cases the ratio of fatal head injuries to fatal thorax injuries for helmeted motorcyclists was 32:15 compared to unhelmeted 45:7. An interesting factor regarding helmet performance requirements is the observation that "riders aged over 44 years accounted for most of the annual increase in deaths". From a helmet performance perspective, consideration for the relationship between rider age and injury tolerance may be required in helmet standards or consumer information.

Data on 220 motorcycle riders admitted to a level one trauma centre in Sydney were extracted for an 18 month period (July 2008-December 2009). 190 motorcycle riders wore a helmet. Compared to not wearing a helmet, the results showed that there was a statistically significantly lower likelihood of a helmeted motorcycle rider experiencing a head injury (Exp(B) = 0.35), intracranial injury (Exp(B) = 0.34), intracranial injury including concussion ((Exp(B) = 0.34), but not concussion (Exp(B) = 0.42) [22]. In absolute terms this shows that AS/NZS 1698 certified helmets are providing a high level of protection compared to no helmet.

In yet another study, the US Fatality Analysis Reporting System (FARS) database was queried for the years from 2000 to 2009 (inclusive), and 11,681 fatal motorcycle rural roadway departure collisions with fixed objects were identified. It was found that enforcing helmet use would provide reductions in fatality risk by around 11% [23].

To conclude, there are no suitable real world crash data that facilitate a comparison of the effectiveness of motorcycle helmets certified to specific standards in reducing head injury. Based on very limited evidence, it appears that the effectiveness of helmets in Europe and the USA in reducing fatal head injuries is similar. Finally, the data indicate the importance of the retention system, crash performance, consideration for radial and tangential impacts, the function of the chin bar, and potential biomechanical issues around the demographics of motorcyclists.

Laboratory and crash analyses of helmet efficacy

Some attempts have been made to quantify using laboratory methods performance differences between helmets certified to specific standards, and how a helmet certified to one standard might perform when tested against the requirements of another standard [7,24].

The SNELL 2005 workshop showed that the ECE 22 certified helmet deformed during the impact more than the M2000 certified helmet and the M2000 helmet had a higher maximum acceleration and HIC [24]. Tests using the M2000 impact test (J headform) against a hemispherical anvil demonstrated that the ECE helmets deformed more, but they performed especially poorly on the second impact and often worse than the M2000 certified helmet on the first impact. At that time performance differences were influenced by the headform size differences between SNELL and UN/ECE standards. SNELL and other motorcycle helmet standards in contrast to UN/ECE 22 have a double impact to the same location. The purpose of this was identified; whether this may be a more appropriate substitute for a single higher energy test, rather than an expectation that two impacts might occur in a real crash.

Thom undertook comparative testing of motorcycle helmets to four standards: DOT, DOT + Snell 2000/2005, DOT + UN/ECE 22 and DOT + BS 6658 [7]. Medium sized full face helmets conforming to a 57cm circumference headform were tested using an ISO "J" headform on a monorail test rig. The results showed some differences between helmet performance across the four impact tests (table 2). Contrary to expectation, the DOT only certified helmets performed best across all four tests and DOT + Snell compliant helmets the worst. However, the test results reveal a pronounced difference between the performance criteria in the standard and the actual performance across a range of impacts. The helmets outperformed the minimum standard.

Table 2.
Summary of comparative helmet testing [7]

	Average Maximum headform acceleration (g)			
Standard Certified	Front Left 2 m Asphalt	Front right 3 m Asphalt	Rear left 2 m Asphalt	Rear right 2 m edge
DOT	157	177	164	138
DOT + ECE	162	192	183	144
DOT + Snell	187	223	198	167

Table 3 presents a similar analysis to table 2, except with AS/NZS 1698 as the common standard. 2-wire guided free fall drop rig with a "M" headform (mass of drop assembly 5.6kg) were undertaken on 19 helmets. The impact test results are very similar, except for depth of penetration where the UN/ECE 22 helmets had the greatest penetration. This is consistent with the absence of a penetration test requirement in UN/ECE 22.

Table 3.
Comparison of Impact Test Performance by Standards Certification. Full Face helmets only (n=19)

	Pooled Standards Certification			
	AS/NZS 1698 only Mean	Snell 2005, not 2010 or UN/ECE Mean	At least Snell 2010 Mean	UN/ECE, Not Snell 2010 Mean
High Energy Impact - average peak acceleration (g)	187.8	179.8	189.5	193.9
Kerb Anvil Impact - average peak acceleration (g)	172.5	171.7	157.2	163.7
Depth of penetration (mm)	23.4	24.8	21.1	30.6

The European COST 327 project reported on a range of motorcycle helmet issues [20]. The crash analyses reinforced the importance of oblique, or tangential loads, in generating head angular acceleration and velocity. Associations between angular head kinematics and injury were observed. Using 60km/h (16.67m/s), the corresponding head impact speed for the 50% cumulative frequency for skull fracture and brain injury, as the benchmark for the impact velocity in an impact energy attenuation test, the drop height would be over 14 m, i.e. much greater than any current test. However, this head impact speed reflects both vertical and horizontal components. All helmet standards test requirements are inconsistent with the observations in the COST 327 report that oblique impacts and resultant angular acceleration contribute to brain injury. On one hand these findings suggest some deficiencies in current standard, on the other, the real world performance of helmets suggests that even in these severe impacts, helmets are offering a great deal of protection to the wearer. The reasons for this include that the helmets may exceed the performance requirements of the standard and the ability of the helmet to attenuate energy in a controlled drop does impart some benefits in oblique impacts.

DISCUSSION

Despite the differences in the performance requirements between the standards, there is no evidence from crash or epidemiological studies that helmets meeting one standard are 'better' than those meeting another. Comparative terms such as "stricter", "tougher", "better" are often used to compare standards, however such terms are inappropriate; the requirements are in most cases just different. Where a standard could be "stricter", for example, is if under the same impact conditions the pass criterion for peak headform acceleration in one standard was lower than another or if there are a larger range of characteristics assessed. The question of 'which is the "strictest" standard', is very difficult to address because of multiple confounding factors. All helmet standards address the characteristics that are considered fundamental to preventing trauma: impact energy attenuation (or acceleration management); stability; retention system strength; vision; and, internal and external projections.

In a 2012 survey of 245 motorcyclists in the Sydney metropolitan region, respondents were asked to rate the level of protection offered by helmets meeting one of five standards and no standard [25]. The analysis showed that AS 1698 compliant helmets were rated significantly higher than other equally rated standards complaint helmets, e.g. Snell and DOT. Helmets not certified to a standard were perceived to offer less protection. This survey is indicative of the importance of brand (standard) recognition and reputation, as well as familiarity. A move to harmonisation of standards would need to address this issue.

Analysis of the results of laboratory testing of motorcycle helmets by the standard to which they are certified, does not reveal any major differences in performance in those tests that would highlight a 'better' helmet in terms of reducing the risk of brain injury. In fact, the laboratory results highlighted the extent that motorcycle helmets, regardless of the standard to which they are certified, exceed the performance requirements and offer a much higher level of protection to the head than might be anticipated. It should be noted that this comment might not apply to all helmets and specifically novelty helmets.

One confounding factor in the available analyses is that most helmets are certified to at least two standards. In some cases, specific requirements in each of two standards, e.g. "dwell time" and high energy impact testing, might lead to a de-facto most stringent standard.

Although on paper the linear acceleration limits set in standards are relatively high in comparison to human tolerance levels (even after consideration for issues of test headform biofidelity), the actual acceleration levels achieved in a range of impact tests are more 'tolerable'. This might indicate the reason that helmets are more effective in real crashes than is suggested by a review of test requirements in standards.

There is still a general need for more information on real crashes and reconstructions of the impact dynamics.

A great deal of research has identified the importance of angular acceleration and/or angular velocity in the mechanism of brain injury, e.g. concussion, bridging vein rupture and diffuse axonal injury. No standard appears to assess the ability of a helmet to reduce optimally angular acceleration in a valid test. Although UN/ECE 22 has a test that appears to assess this characteristic, it is possible that it adds little to the inspection regimes that are in place in other standards. It may be that further improvements in motorcycle helmet performance will arise when this issue is addressed.

A number of oblique test rigs have been developed and reported [26,27,28]. Some included a neck, others not. A device developed at UNSW included a Hybrid III head and neck that was dropped onto a moving striker plate [26]. In lateral impacts from a drop height of 1.5m and landing on the striker plate moving at 35 km/h the mean Head Injury Criterion (HIC_{15}) and mean maximum headform acceleration were respectively 648, 150 g for four helmet models; the mean $+\alpha y$ (neck extension) was +9.5 krad/s^2 and $+\alpha x$ (neck right lateral flexion) was +5.1 krad/s^2. Within many qualifications, the results with and without a neck were comparable. The availability of data from a diverse range of test rigs will assist in discussion about an appropriate oblique impact test method. Further research is required.

It thus appears there are some common deficiencies in all the helmet standards:

- Lack of oblique impact test that can be used to assess the helmet's ability to manage linear and angular head kinematics and minimise brain injury risks;
- Impacts in the real world are frequently below the test line. Therefore, there is an opportunity to assess, and possibly improve, helmet performance across the range of impacts that occur to motorcyclists;
- No standard has a load distribution test (e.g. AS/NZS 2512). This test would be a more suitable method for assessing the effects of

internal projections on head loads specific to the relevant injury mechanisms. It would also be more relevant than the penetration test, in terms of both construction quality and assessing a specific head loading mechanism.
- Head acceleration criteria are too high. The probably cause for the success of helmets is that many manufacturers do not make minimum performance only helmets, but within limits, produce helmets that exceed by a large margin the standard requirements.
- There is confusion concerning the need for repeat impact tests and what they represent. One explanation is that a second impact might occur and the helmet should provide protection in those circumstances. The other explanation is that the first and second impact combined are equivalent to a higher severity impact.
- Consideration for how new technologies may be included inside helmets, e.g. communication devices and emergency management alerts, and how these should be tested to ensure that they do not cause harm.
- Absence, except in UN/ECE 22, of a comprehensive continuous control or batch control processes for motorcycle helmets. Such a system should also require independent approval of the certification bodies and test laboratories, e.g. International Laboratory Accreditation Cooperation, and the prevention of batches of helmets entering the market unless batch testing is successful. There is a real risk that helmets appearing to meet a standard could be dumped in a market when that batch or model no longer complies with the standard.

The potential to harmonise motorcycle helmet standards does exist as do a number of mechanisms, e.g. ISO and UN/ECE. There are also treaties that encourage international harmonisation of standards, e.g. free trade. One barrier is representation. The actual technical aspects of the standard should not necessarily be a barrier to harmonisation, except where the end result would be a standard with fewer requirements and a worsening of performance requirements. The emerging issue may not be harmonisation, rather specialisation might be the key issue.

There exists currently a level of specialisation in helmets, e.g. full-face, open-face, flip-up and motocross. At present these must meet the same performance requirements. JIS T 8133 has a specialisation option based on the intended use. There is a demand for motorcycle helmets that are fit for purpose in different climates and traffic networks. There may also be a need or opportunity for helmets tailored in performance to motorcyclist age. In Africa and Asia, for example, there is a need and demand for safe helmets but that are suitable for hot and humid climates. Current helmets may not be satisfactory in terms of ventilation and heat dissipation for those climates and may be tuned towards highway speed collisions. A harmonised standard might consider how to address these needs, in the manner of JIS T 8133.

Evident in accident statistics and motorcyclist demographics is the emergence of an older cohort of motorcyclists. It is well understood biomechanically that with age comes a decline in our ability to tolerate impacts. There may also be a need and opportunity to develop versions of standards that are tuned for older motorcyclists.

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REFERENCES

[1] DITRDLG, 2008. Fatal and serious road crashes involving motorcyclists. Research and Analysis Report, Road Safety Monograph 20. Department of Infrastructure, Transport, Regional Development and Local Government, Australia.
[2] International Transport Forum (IRTAD), 2010. Annual Report, International Traffic and Safety Data & Analysis Group, OECD.
[3] Thom DR, Hurt HH, Smith TA and Ouellet JV, 2007. Feasibility study of upgrading FMVSS No. 218, Motorcycle helmets, Final Report to NHTSA Contract Order No. DTNH22-97-P-02001.
[4] Gurdjian ES, Roberts VL and Thomas LM, 1966. Tolerance curves of acceleration and intracranial pressure and protective index in experimental head injury. Journal of Trauma, 6(5), 600–604.
[5] Snell M2005 Standard for Motorcycling Helmet, 2005. Snell Memorial Foundation, Inc., North Highlands, CA, USA.
[6] Standard No. 218; Motorcycle helmets, 2007. Code of Federal Regulations, Title 49, section 571.218. National Highway Traffic Safety Administration.
[7] Thom DR, 2006. Comparison tests of motorcycle helmets qualified to international standards, report commissioned by Motorcyclist Magazine
[8] Thom DR and Hurt HH, 1992. Conflicts of contemporary motorcycle helmet standards, 36th

Annual proceedings of the Association for the Advancement of Automotive Medicine, October 5-7, Portland, Oregon, pp. 163-174.
[9] Mills NJ, 2010, Critical evaluation of the SHARP motorcycle helmet rating, International Journal of Crashworthiness, 15: pp. 331- 342.
[10] Lin M-R & Krauss JF, 2008. Methodological issues in motorcycle injury epidemiology, AAP 40: pp. 1653-1660.
[11] Lin M-R & Krauss JF, 2009. A review of risk factors and patterns of motorcycle injuries, AAP 41: pp.710-722.
[12] Liu BC, Ivers R, Norton R et al, 2008, Helmets for preventing injury in motorcycle riders, Cochrane Database Syst Rev. 23;(1):CD004333.
[13] Glassbrenner D & Jianqiang Ye T, 2007, Motorcycle helmet use in 2007 – overall results, NHTSA, 2007, DOT HS 810 840
[14] Pickrell T & Jianqiang Ye T, 2009. Motorcycle helmet use in 2007 – overall results, NHTSA, DOT HS 811 254.
[15] Traffic Safety Facts, 2008. Data – Motorcycles, DOT HS 811 159.
[16] Goslar PW, Crawford NR, Petersen SR, Wilson JR, and Harrington T., 2008. Helmet use and associated spinal fractures in motorcycle crash victims, J Trauma, 64: 190-196
[17] MAIDS, In-depth Investigation of Motorcycle Accidents, Final Report 2.0.
[18] Petridou E, Skalkidou A, Ioannou N, and Trichopoulos D, 1998. Fatalities from non-use of seat belts and helmets in Greece: A nationwide appraisal, Accid. Anal. Prev., 30(1), pp.87-91.
[19] Richter.M, Otte D, Lehmann U, Chinn B, Schuller E, Doyle D, Sturrock K, Krettek C, 2001. Head injury mechanisms in helmet-protected motorcyclists: prospective multicenter study, J Trauma, 52, pp. 949-958.
[20] Chinn B, (editor in chief), 2001. COST 327 Motorcycle Safety Helmets, final report of the action.
[21] Johnston P, Brooks C and Savage H, 2008. Fatal and serious road crashes involving motorcyclists, Department of Infrastructure, Transport, Regional Development and Local Government, Research and Analysis Report, Road Safety Monograph 20.
[22] McIntosh AS, Curtis K, Rankin T, Cox M, Pang TY, McCrory P and Finch CF, Helmets prevent brain injuries in injured pedal- and motor-cyclists: A case series analysis of trauma centre presentations, Australian College of Road Safety Journal, in press
[23] Bambach M and Grzebieta RH, 2012. Fatality Risk Mitigation for Rural Motorcycle Collisions with Trees and Utility Poles, Proc. 91st Annual Meeting of the Transportation Research Board, Washington DC, USA.
[24] Fenner H, Thomas DJ, Gennarelli T et al (eds), 2005, Final Report of Workshop on Criteria for Head Injury and Helmet Standards, Medical College of Wisconsin and Snell Memorial Foundation, Inc
[25] Gibbins C, 2012, Online trading and motorcycle helmets, the risks of a global age. Honours thesis, School of Civil and Environmental Engineering, UNSW, October 2012.
[26] McIntosh AS & Lai A, Motorcycle Helmets: Head and neck dynamics in helmeted and unhelmeted oblique impact tests, Traffic Injury Prevention, accepted 4 February 2013
[27] Aare M, Halldin P. 2003, A new laboratory rig for evaluating helmets subject to oblique impacts. Traffic Inj Prev;4: pp. 240-248
[28] Mills NJ, Gilchrist A. 2008, Oblique impact testing of bicycle helmets. I J Impact Engineering;35:pp.1075-1086

EFFECTIVENESS OF ANTILOCK-BRAKES (ABS) ON MOTORCYCLES IN REDUCING CRASHES, A MULTI-NATIONAL STUDY

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ABSTRACT

This study set out to evaluate the effectiveness of Antilock-Brakes (ABS) on motorcycles in reducing real-life crashes.
Since the European Parliament has voted a legislation to make ABS mandatory for all new motorcycles over 125cc from 2016, the fitment rate in the entire Europe is likely to increase in the years to come. Previous research, however, analyzed mostly large displacement motorcycles. Therefore the present study used police-reported crash data from Spain (2006-2009), Italy (2009) and Sweden (2003-2012) in an attempt to analyze a wide range of motorcycles, including scooters, and compare countries with different motorcycling habits.

The statistical analysis used an induced exposure method. As shown in previous research, head-on crashes were the least ABS-affected crash type and were therefore used as non-sensitive to ABS in the calculations. The same motorcycle models, with and without ABS, were compared; the calculations were carried out for each country separately. Crashes involving only scooters were further analyzed.

The effectiveness of motorcycle ABS in reducing injury crashes ranged from 24% in Italy to 29% in Spain and 34% in Sweden. The minimum effectiveness with 95% confidence limits was 12%, 20% and 16%, respectively. The reduction of severe and fatal crashes was even greater, at 34% and 42% in Spain and Sweden, respectively. The minimum effectiveness was 23%-24%.
The overall reduction of crash involvement with ABS-equipped scooters (at least 250cc) in Italy and Spain was 27% and 22%, respectively.
The minimum effectiveness was 12% in Italy and 2% in Spain. ABS on scooters with at least a 250cc engine was found to reduce the involvement in severe and fatal crashes by 31%, based on Spanish data only.

At this stage, there are more than sufficient scientific-based proofs to support the implementation of ABS on all motorcycles, even light ones. However, further research should be aimed at understanding the injury mitigating effects of motorcycle ABS.

INTRODUCTION

In 2011, 30,500 persons were killed in road traffic crashes in the European Union (CARE, 2012). That corresponds to a fatality reduction by 43% since 2001 when 54,000 persons were killed. The positive trend in road safety could be observed in all modes of transport, except for motorcycles. Instead the number of killed motorcyclists has been rather constant with a slight decrease only in 2011, from about 5,000 killed in 2000 to 5,200 in 2005 and just over 4,400 in 2011 (CARE, 2012). As the number of fatalities in other transport modes is decreasing, motorcycle fatalities account for an increasing share of all road fatalities in Europe, from 10% in 2001 to 15% in 2011. Furthermore, the Swedish Transport Administration (STA, 2012a) has predicted that this trend is likely to continue and that by 2020 motorcycle fatalities might account for 23% of all road deaths in Sweden, which stresses the importance of taking appropriate countermeasures in this area.

Previous studies have calculated that the risk of being killed on a motorcycle per passenger mileage is approximately twenty times higher than for a passenger car occupant (Strandroth and Knudsen, 2008). Also, the risk of being killed or severely injured when a casualty crash occurs has been approximately the same since the 1980s for motorcycle riders, while the risk for passenger car occupants has systematically reduced by more than 50% (Rizzi et al, 2009). Consequently, there is a need for interventions aimed at reducing both crash

risk and crash severity in order to reduce injury risk for motorcyclists.
Analysis of in-depth studies (MAIDS, 2004; Hurt et al, 1981) has shown that braking prior to collision had occurred in 49%-56% of all investigated crashes. In crashes between passenger cars and motorcycles, braking has been reported to occur in 65%-75% of cases (Sporner and Kramlich, 2003; Rizzi et al, 2009). Hence, enhanced stability during braking could have a great potential in reducing motorcycle crashes and injuries. Anti-lock brakes (ABS) on motorcycles were introduced in the late 1980s in order to improve stability by maintaining wheel rotation under hard braking. While ABS has been shown to generally provide shorter stopping distances (Green, 2006), ABS could also increase braking stability and thereby prevent the motorcyclist from falling to the ground, as pointed out by Teoh (2011).

In terms of effectiveness on crash reduction, several studies based on real-life data have reported the benefits of motorcycle ABS (Teoh, 2011; HLDI, 2009; Rizzi et al, 2009). Rizzi et al (2009) found head-on crashes to be a non-sensitive scenario to ABS and therefore used those crashes with an induced exposure approach to evaluate the effectiveness of ABS in Sweden. The study estimated the overall effectiveness of ABS to be 38% on all injury crashes and 48% on all severe and fatal crashes, with 95% lower confidence limits of 11 and 17%, respectively. In 2009 the Highway Loss Data Institute (HLDI) used regression analysis to quantify the effectiveness of ABS on motorcycle losses in the US. The analysis showed a 22% significant reduction in claim frequencies for motorcycles equipped with ABS. However, no significant differences were found regarding claim severity. A later study by Teoh (2011) compared motorcycle driver involvement in fatal crashes per 10,000 registered vehicles in the US. The comparison was made between motorcycles models with optional ABS and those same models without ABS. The fatality rate was found in this study to be 37% lower for the model versions with ABS compared to the non-ABS versions.
As ABS has been proved by several studies to significantly improve motorcycle safety, actions have been taken by many stakeholders in Sweden in order to increase the fitment rate of motorcycle ABS (STA, 2012b). According to the Swedish Moped and Motorcycle Industry Federation (McRF), the fitment rate among new motorcycles in Sweden has increased from approximately 15% in 2008 to 70 % in 2012. Furthermore, according to Bosch Corporation the ABS installation rate in Europe among motorcycles with at least 250cc engine size has increased from 27% in 2007 to 36% in 2010. Since the European Parliament has voted for a legislation to make ABS mandatory for all new motorcycles over 125cc from 2016, the fitment rate in the entire Europe is likely to increase even more in the years to come.

Until the early 2000s, ABS was mostly fitted on up-market motorcycle models, similarly to ABS and ESC (Electronic Stability Control) on passenger cars (Lie et al, 2006). Therefore previous research on real-life crashes could analyze mostly large displacement motorcycles. Teoh (2011) and HLDI (2009) did include some light motorcycles in their studies, showing impressive overall results; however, further research may be needed in order to confirm the effectiveness of ABS on scooters. Another issue is that previous studies only included real-life crash data from countries where motorcycles are primarily used for leisure riding, i.e. Sweden and the US. It could therefore be useful to expand the evaluation of ABS with crash data from countries with different motorcycling habits, i.e. countries in southern Europe where motorcycles are also used for everyday transportation.

STUDY OBJECTIVES

The purpose of this study was to:

- estimate the effectiveness of ABS in reducing real-life crashes involving a wide range of motorcycle models, including scooters;
- compare the effectiveness of ABS between Sweden and two other countries, Italy and Spain, that may have dissimilarities in vehicle fleets characteristics, different motorcycling habits and road environments.

MATERIAL

The present study used police records from three different countries: Italy, Spain and Sweden. Each database from which the data was collected is briefly described below.

Italy

In Italy, the national road crashes database is managed by the Italian Institute of Statistics (ISTAT). Crashes included in the national database must have occurred on the public road network and involved at least one injured person. However, it is not possible to distinguish between slightly and severely injured. The crash type classification includes the following main categories:

- Frontal collisions
- Side-frontal collisions
- Side collisions
- Rear-end collisions
- Single-vehicle
- Collisions with a pedestrian
- Collisions with a train

Spain

The Spanish road crash database is managed by the General Directorate of Transport (DGT). Crashes occurring on public roads causing at least one injured are recorded by the police. The crash type classification is similar to the Italian one. The injury outcome is normally judged for each casualty by a police officer at the crash scene. Four levels are used: fatal, serious, slight and uninjured.

Sweden

The Swedish Transport Accident Data Acquisition (STRADA) is managed by the Swedish Transport Agency and includes police as well hospital reports. Crashes occurring on public roads and having caused at least one injured person are recorded by the police. Four injury levels are assigned by the officer attending the crash scene: fatal, serious, slight and uninjured. The crash type definition normally describes the pre-crash movement of the vehicles involved rather than the direction of force during the impact (i.e. a head-on crash can involve a frontal-side impact).

A brief overview of the material available for analysis is given in Table 1. The material from a previous Swedish study (Rizzi et al, 2009) based on STRADA 2003-2008 was expanded with the latest crash data (2009-2012). The Italian material included crashes occurred in 2009, while the Spanish one was the larger dataset in the study, including crash data from 2006 to 2009. The share of motorcycle crashes occurred in urban areas was higher in Italy and Spain (72% and 66%, respectively) than in Sweden (47%). Also, the share of scooters varied greatly across these three countries, from 4% in Sweden to 63% in Italy. The age group 18-34 had lower crash involvement in Sweden (38%) than in Italy and Spain (46% and 49%, respectively).

Table 1.
Overview of available crash data

	ITA	SPA	SWE
Period	09	06-09	03-12
n crashes available for analysis	13,695	57,160	8,720
% urban roads	72%	66%	47%
% scooters	63%	42%	4%
% 18-24 years old riders	19%	10%	14%
% 25-34 years old riders	27%	39%	24%

METHOD

An analysis using induced exposure can be used when true exposure is not available (Evans, 1998; Lie et al, 2006; Strandroth et al, 2012).

With this approach, the key point is to identify at least one crash type or situation in which the system under analysis can be reasonably assumed (or known) not to be effective. In this case, motorcycles with and without ABS were compared. If the only noteworthy difference in terms of crash risk is ABS, the relation between motorcycles with and without ABS in that non-sensitive situation would be considered as the true exposure relation. This means that any deviation from the relation in non-sensitive situations is considered to be a result of ABS. Therefore the effect of ABS is considered to be zero if R in Equation 1 is equal to 1.

$$R = \frac{A_{ABS}}{N_{ABS}} \div \frac{A_{non-ABS}}{N_{non-ABS}} \qquad (1).$$

A_{ABS} = number of crashes sensitive to ABS, involving motorcycles with ABS
$A_{non-ABS}$ = number of crashes sensitive to ABS, involving motorcycles without ABS
N_{ABS} = number of crashes non-sensitive to ABS, involving motorcycles with ABS
$N_{non-ABS}$ = number of crashes non-sensitive to ABS, involving motorcycles without ABS

Thus, the effectiveness in crash reduction in relation to non-sensitive crashes can be expressed as:

$$E = 100 \times (1 - R)\% \qquad (2).$$

The standard deviation of the effectiveness was calculated on the basis of a simplified odds ratio variance, according to Equation 3. This method gives symmetric confidence limits but the effectiveness is not overestimated.

$$Sd = R \times \sqrt{\sum_{i=1}^{4} \frac{1}{n_i}} \qquad (3).$$

Where n is the number of crashes of each type. The 95% confidence limits are given in Equation 4.

$$\Delta E = 100 \times R \times Sd \times 1{,}96 \qquad (4).$$

The overall effectiveness in crash reduction and the 95% confidence limits can therefore be calculated as follows:

$$E_T = E \times \frac{A_{ABS} + A_{non-ABS}}{N_{ABS} + N_{non-ABS}} \qquad (5).$$

$$\Delta E_T = \Delta E \times \frac{A_{ABS} + A_{non-ABS}}{N_{ABS} + N_{non-ABS}} \quad (6).$$

The analysis was performed in three main steps. The first one was to identify ABS fitment across the datasets, also based on the generally different standard fitment rates in the three countries. The possible fitment of Traction Control Systems (TCS) was also checked. The second step was to determine which crash type was to be used as non-sensitive in the calculations (see Equation 1) and to check whether the share of such non-sensitive crashes in the analyzed material was comparable with official statistics or previous studies. Finally, in the third step controls were made on factors that could affect crash involvement (i.e. rider age and gender, engine displacement etc) in order to make sure that any crash risk difference between the ABS and non-ABS groups was most reasonably due to the ABS fitment itself. The effectiveness of ABS was calculated with an induced exposure approach as presented above. Each step is further described below.

Step 1

The Vehicle Identification Numbers (VIN) of the motorcycles involved in the crashes were included in the Italian data. Each VIN was checked and in some cases the manufactures were contacted in order to retrieve information about ABS and TCS fitments. During the process, the crash data were handled according to confidentiality restrictions.

With regard to Spanish and Swedish crash data, it was possible to identify ABS fitment through model name and MY. This was based on the standard fitment rate for each models or the presence of the word ”*ABS*” in the model name when ABS was optional at the time of the crash. Most of BMW and Harley Davidson models with optional ABS had therefore to be excluded from the Spanish material, as they normally do not include this information in their model names. The same process was carried out separately as Sweden and Spain had different ABS fitment rates during the analyzed periods. The possible optional fitment of TCS was also checked through the material.

While previous research (Rizzi et al, 2009) has grouped ABS and non-ABS motorcycles of the same category (i.e. standard, on/off or dual purpose, touring, sport-touring), the material in the present study was considered to be large enough to attempt a more direct comparison between the same motorcycle models, with and without ABS, as in Teoh (2011). However, crash data involving only the ABS-version of some models (i.e. most of BMW models in Sweden) were included in the study.

The ABS and non-ABS motorcycles that belonged to the standard, on/off, touring and sport-touring categories had an engine displacement of at least 600cc. The MY ranged from 1997 to 2012 in Swedish material, while in Italian and Spanish ones it was 2004 and onwards. While the number of scooters in the Swedish material was too limited for analysis, two super-sport models were included (Honda CBR1000RA and BMW S1000RR). Scooters included in the Italian and Spanish materials had an engine displacement ranging from 250cc to 600cc. Table 2 shows the number of ABS and non-ABS motorcycles included in the analysis, per motorcycle category; the make/models used for calculations in each database are shown in Appendix I. In total, some 90 motorcycle models were included in the analysis.

Table 2.
Number of ABS and non-ABS motorcycles, per motorcycle category

	ITA		**SPA**		**SWE**	
	ABS	**non-ABS**	**ABS**	**non-ABS**	**ABS**	**non-ABS**
Standard	45 12%	1032 37%	188 24%	2897 50%	65 15%	147 31%
On/off	88 23%	305 11%	58 7%	259 4%	113 27%	52 11%
Scooter	183 49%	1332 47%	235 29%	1345 23%	- -	- -
Supersport	- -	- -	- -	- -	23 5%	33 7%
Sport-touring	45 12%	128 5%	109 14%	1133 19%	103 25%	146 31%
Touring	16 4%	23 1%	209 26%	180 3%	116 28%	92 20%
Total	**377 100%**	**2820 100%**	**799 100%**	**5814 100%**	**420 100%**	**470 100%**

Step 2

Previous research based on Swedish in-depth studies of motorcycle fatal crashes (Rizzi et al, 2009) has shown that head-on crashes, as defined in Sweden, were the least ABS-sensitive crashes. However, the crash type classification used in Italy and Spain differs from the Swedish one, as mentioned above. In Sweden, a crash is classified as head-on when two oncoming vehicles (i.e. approaching each other with opposite travelling directions) crash with any direction of force. For instance, a crash in which a rider falls off the motorcycle in a bend and slides into the side of an oncoming car would be classified as head-on in Sweden. It was therefore necessary to make assumptions on which crash types could be used as non-sensitive in the Italian and Spanish datasets. It was hypothesized that frontal and side-frontal crashes in non-intersections could be a reasonable proxy of the Swedish head-on crash definition. Analysis of the share of ABS-equipped motorcycles per crash type was also made to verify this hypothesis, as ABS motorcycles would logically be over-represented in a non-sensitive crash type to ABS, compared to the whole population of ABS-crashes.

Checks were also made to ensure that the analyzed material included a representative share of non-sensitive crashes for the three countries. The Spanish and Italian materials were compared with a previous analysis of crashes involving Powered-two-wheelers (PTW) in Europe (2 Be Safe, 2010), while official crash statistics were used for the Swedish material.

Caution is needed when comparing police-reported crash data from different countries, as these are generally known to suffer from a number of data quality problems. However, it was assumed that this limitation would equally affect both the ABS and non-ABS group, therefore it was not expected to affect this analysis to any large degree.

Step 3

Calculations were made within the ABS and non-ABS group to verify that the only relevant difference was ABS. This was done by analyzing the variation of the ratios $\frac{A_{ABS}}{N_{ABS}}$ and $\frac{A_{non-ABS}}{N_{non-ABS}}$ (see Equation 1), depending on a number of factors that may affect crash risk involvement. These factors were speed area, road conditions, driver age and gender, vehicle age, weight-to-power ratio, engine displacement, motorcycle category, reported speeding (when available) and possible TCS fitment. The effectiveness calculations were performed according to Equations 1-6 for each country. Crashes involving only scooters were further analyzed.

RESULTS

The analysis described in step 2 showed that the largest share of ABS-equipped motorcycles in Swedish crashes was involved in head-on crashes (58%), which confirmed the finding of the previous study (Rizzi et al, 2009). The results for Italy and Spain (see Table 4) suggested that frontal and side-frontal crashes in non-intersections could be used as non-sensitive crashes, as the involvement of ABS-motorcycles in those crashes was the highest (15% and 16%, respectively).

Side crashes also had a higher share of ABS-motorcycles (14%) than the average (12%), suggesting that these crashes were not particularly sensitive to ABS. Side crashes, however, were included in the sensitive group as this would give a conservative approach to the analysis, see Equation 1. It should be noted that considering a partly non-sensitive crash type as sensitive to ABS would lead to an underestimation of the overall effectiveness.

Table 3.
Share of ABS-equipped motorcycles per crash type in Sweden

	SWE
Crashes in intersections	43%
Head-on crashes	58%
Rear end crashes	48%
Single-vehicle crashes	47%
Average for all crash types	**47%**

Table 4.
Share of ABS-equipped motorcycles per crash type in Italy and Spain

	ITA	SPA
Front + front-side crashes in intersection	12%	12%
Front + front-side crashes in non-intersection	15%	16%
Multiple collision	-	13%
Rear end crashes	11%	14%
Side crashes	14%	14%
Single-vehicle crashes	10%	11%
Average for all crash types	**12%**	**12%**

Checks were also performed to compare the share of non-sensitive crashes in each country with official statistics or previous studies (2 Be Safe, 2010). The findings showed that these were very similar, if not identical, which suggested that the analyzed material was representative and that the effectiveness would not be overstated (see Appendix II for further results). Analysis of the variation of the ratios $\frac{A_{ABS}}{N_{ABS}}$ and $\frac{A_{non-ABS}}{N_{non-ABS}}$ showed no substantial variations from the overall trends, except for Swedish riders aged 18 to 24 in the non-ABS group which were found to have a greater sensitive/non-sensitive ratio (see Appendix II). A similar result was found in the previous study (Rizzi et al, 2009). While this aspect could give an overestimation of the actual effectiveness of ABS in Sweden, it should be noted that riders between 18 and 24 accounted for only 15% of the non-ABS group. It was therefore decided to include them in the study as this would have only a minor effect on the overall results. The possible fitment of TCS was not found to influence the sensitive/non-sensitive ratio, although the number of case motorcycles that could have been fitted with TCS was limited (n=37 for Italy; n=71 for Spain; n=50 for Sweden).

The results of the analysis with induced exposure are presented in the tables below with 95% C.I. As mentioned above, the calculations were performed for each country separately; it was not possible to distinguish between slightly and severely injured in the Italian database and therefore it was excluded from the effectiveness calculations for severe and fatal crashes. With regard to injury crashes, the overall reduction of crash involvement with ABS was statistically significant in all countries. The reductions were 24% +/- 12% in Italy, 29% +/-9% in Spain and 34% +/-18% in Sweden. All results for rural and urban areas were statistically significant at the 95% level, except from Swedish rural roads. However, no statistically significant difference between the effect of motorcycle ABS on rural and urban roads was found for any country. The results for injury crashes in intersections as well as rear-end injury crashes were also statistically significant, with exception of rear-end in Italy. The effectiveness of ABS in these crash types was similar to the one for all injury crashes, although the Swedish results for crashes in intersections was higher at 46%, with a 95% lower confidence limit of 30%.

The reductions of fatal and severe crashes with motorcycle ABS were generally greater, compared to all injuries, as they ranged from 34% to 42% for the Spanish and Swedish data, respectively. The 95% lower confidence limits were almost identical, at 23% and 24% for Spain and Sweden. The effectiveness of ABS in rural and urban areas was similar to the overall results for severe and fatal crashes for both countries, although the result for Swedish urban roads was not statistically significant. The results for severe and fatal rear-end crashes were even more impressive, ranging from 57% to 60% in Spain and Sweden, respectively. The 95% lower confidence limits were similar, at 45% and 42% respectively. With regard to fatal and severe crashes in intersections, motorcycle ABS was found to reduce crash involvement by at least 62% in Sweden. The result for Spain was impressive too, with a 48% reduction and a 95% lower confidence limit of 33%.

Table 5.
The overall effectiveness of motorcycle ABS on injury crashes, with 95% confidence limits

Injury crashes	ITA	SPA	SWE
All crash types	24% +/- 12%	29% +/- 9%	34% +/- 18%
All crash types in urban areas	22% +/- 15%	28% +/- 12%	46% +/- 21%
All crash types in rural areas	27% +/- 19%	30% +/- 14%	*21% +/- 31%*
Crashes in intersections	25% +/- 20%	29% +/- 13%	46% +/- 16%
Rear-end crashes	27% +/- 21%	*15% +/- 20%*	33% +/- 27%

Table 6.
The overall effectiveness of motorcycle ABS on fatal and severe crashes, with 95% confidence limits

Severe and fatal crashes	SPA	SWE
All crash types	34% +/- 10%	42% +/- 19%
All crash types in urban areas	41% +/- 10%	*40% +/- 42%*
All crash types in rural areas	29% +/- 17%	38% +/- 25%
Crashes in intersections	48% +/- 15%	70% +/- 8%
Rear-end crashes	57% +/- 12%	60% +/- 18%

Table 7.
The overall effectiveness of motorcycle ABS on injury crashes, only scooters (at least 250cc), with 95% confidence limits

Injury crashes	ITA	SPA
All crash types	27% +/- 15%	22% +/- 20%
All crash types in urban areas	29% +/- 16%	*20% +/- 25%*
All crash types in rural areas	*19% +/- 42%*	34% +/- 26%
Crashes in intersections	31% +/- 23%	35% +/- 20%
Rear-end crashes	*24% +/- 32%*	28% +/- 27%

Table 8.
The overall effectiveness of motorcycle ABS on fatal and severe crashes, only scooters (at least 250cc), with 95% confidence limits

Severe and fatal crashes	**SPA**		
All crash types	31%	+/-	19%
All crash types in urban areas	41%	+/-	15%
All crash types in rural areas	*21%*	*+/-*	*44%*
Crashes in intersections	84%	+/-	3%
Rear-end crashes	67%	+/-	14%

Crashes involving only scooters were further analyzed, although Swedish material was excluded because of the limited number of scooters in the crash data (see Table 2). The findings for injury crashes in Italy and Spain are presented in Table 7: both results are statistically significant and similar to the effectiveness found for all ABS-equipped motorcycles, see Table 5. The reduction of crash involvement with ABS-equipped scooters was found to be 27% in Italy and 22% in Spain. Interestingly, in Italy the 95% lower confidence limit for scooters was the same as for all case motorcycles, 12%. However, this was not the case for Spanish data as the 95% lower confidence limit for scooters was only 2%. The reduction of crash involvement in rural and urban areas did not seem to deviate from the overall results for all case motorcycles, although two results were not statistically significant. The results for crashes in intersections were statistically significant and were in line with the findings for all motorcycles, ranging from 31% to 35% with a 95% lower confidence limit of 11% and 15% for Italy and Sweden, respectively. With regard to rear-end injury crashes with scooters, the Italian and Spanish results were also similar to each other and to the overall results. The effectiveness in those crashes ranged from 24% to 28%, although the Spanish result was not statistically significant.

The calculations for fatal and severe crashes involving only scooters could be carried out on the Spanish material only. ABS on scooters was found to reduce the involvement in severe and fatal crashes by 31%. This result was statistically significant and similar to the effectiveness for all case motorcycles in Spain (34%). However, the 95% lower confidence limit was lower, 12%. Again, the results for urban and rural areas did not deviate from the overall results, although the effectiveness for rural roads was not statistically significant. The effectiveness of ABS on scooters in reducing severe and fatal crashes in intersection was found to be at least 81%. The results for severe and fatal rear-end crashes with scooters were also impressive, with at least a 53% reduction. Both results were higher than the ones for all case motorcycles in Spain which had a 95% lower confidence limit of 33% and 45%, respectively (see Table 6).

DISCUSSION

Previous research has shown the positive effect of ABS on motorcycles (Teoh, 2011; HLDI, 2009; Rizzi et al, 2009). However, these studies were based on real-life crashes involving mostly large displacement motorcycles in countries where leisure riding is probably more common. Also, with the upcoming EU legislation making ABS mandatory for all new motorcycles over 125cc from 2016, the fitment rate in Europe will increase among light motorcycles too. Therefore the present study set out to evaluate the effectiveness of ABS on a wide range of motorcycle models, including scooters. A further objective was to compare the effectiveness of ABS between three countries that may have different vehicle fleets, motorcycling habits and road environments.

An induced exposure approach was used, as explained and used in several previous studies (Evans, 1998; Lie et al, 2006; Strandroth et al, 2012). While true exposure, such as number of registered vehicles or vehicle mileage, can also be used for this kind of evaluations, it can be difficult to compare between different countries and may also include confounding factors. For instance, as long as ABS is not standard equipment on all motorcycles on the roads, it could be argued that the choice of purchasing an ABS-equipped motorcycle is not randomly spread throughout the rider population. In other words, motorcyclists who choose ABS are probably more concerned about their safety in the first place, which could naturally lead to a lower crash involvement. While it is possible to control for these factors (Teoh, 2011), an induced exposure approach would normally compensate for this, as the result is given by relative differences within the ABS and non-ABS groups. It should also be noted that any behavioral adaptation, if at all present, would intrinsically be present in real-life crash data and included in the overall results.

The present method, however, is based on some assumptions that are important to discuss. The most critical step in the analysis is to determine which crash types are non-sensitive to the analyzed system. In this case, previous research addressing this issue was used (Rizzi et al, 2009), although this referred to Swedish crashes only. Assumptions were then made in order to identify the non-sensitive crash types in the Italian and Spanish databases. Checks were also made to ensure that this assumption was reasonable, which was found to be the case (see Table 4). Side crashes were found not to be particularly sensitive to ABS either, although it was argued that this would give conservative results: including such crashes among the sensitive ones would most likely decrease the calculated effectiveness of ABS.
Furthermore, it is important to stress that the non-sensitive crash type used in the calculations does not need to be identical across the three databases. With this method, the overall effectiveness of ABS in the three countries is believed to still be comparable, as E is multiplied with the total share of sensitive crashes in each country (see Equation 5). In fact, this aspect would imply a more robust analysis: positive results were found by using slightly different induced exposures (non-sensitive crash types), which would suggest that motorcycle ABS does have the calculated benefits.

Another critical step in this study was to properly match the ABS and non-ABS motorcycles. While crashworthiness is limited for motorcycles irrespective of model, the only reasonable difference in terms of crash and injury risk between the analyzed motorcycles should result from ABS itself. Previous research has shown that it is also possible to compare different motorcycle models with similar properties (Rizzi et al, 2009); however, it is clear that the present method is more robust. Also, the rider population with and without ABS should be better targeted in terms of age, driving experience etc. A limitation of this study is that VINs were not available for the Spanish and Swedish materials. While several checks were made to ensure a sound categorization, the possibility of merging VINs with crash data is always preferable when performing an evaluation of a vehicle safety system. On the other hand, this is less of an issue if the fitment of a safety system is standard on at least one model with sufficient selling volumes. It should be noted, however, that any misclassification would give an underestimation of the results.

The analysis showed statistically significant crash reductions for all ABS-equipped motorcycles, ranging between 24% in Italy and 34% in Sweden. The reduction of severe and fatal crashes was even more impressive, at 34% and 42% for Spain and Sweden, respectively. In general, the results for Italy and Spain seemed in line with the Swedish ones. It can be argued that this did not necessarily need to be case, because of different distributions of rural and urban crashes, crash types as well as scooters across these three countries (see Table 1). However, no evidence of a different effectiveness of motorcycle ABS in rural and urban areas was found. Besides, the results for scooters were comparable across the analyzed countries. The combination of these specific results can fully explain the similarity of the overall results for the three countries. While data quality issues could also be a possible explanation, the overall results would be most likely conservative. It should also be noted that the results for crashes at intersections were also similar and generally higher than for all crash types. This is consistent with previous research (Rizzi et al, 2009) as these crashes often involve braking (MAIDS, 2004), which also suggests that the material is reliable.
In conclusion, the findings of this study do not seem unreasonable as they are in line with previous research (Teoh, 2011; HLDI, 2009; Rizzi et al, 2009). ABS is effective in reducing crashes with scooters as well, which may have great safety implications in those regions of the world where this kind of motorcycles is used on a daily basis as a mean of transportation, often the only available one.

There might be several interpretations of these results. It should also be noted that the present study used police records and therefore could not perform any analysis of the actual functionalities of motorcycle ABS. However, previous research has shown that ABS generally provides shorter stopping distances and increased stability (Green, 2006; Vavryn and Winkelbauer, 2004). Tests of avoidance maneuvers performed on gravel surfaces by a Swedish motorcycle magazine (MC Folket, 2011) also reported similar results. Roll et al (2009) suggested that ABS may increase riders' confidence when applying full brakes, although stability improvements per se could also explain the large benefits of ABS.
While all these aspects can explain the effectiveness of motorcycle ABS in avoiding crashes, it should be noted that they could also be relevant for mitigating the crash severity and injury severity in crashes with ABS-equipped motorcycles. Little research is available on this issue at the moment, although some insights were given in the previous study (Rizzi et al, 2009). An increased deceleration during hard braking, as reported by the studies mentioned above, would logically decrease the impact speed if a crash occurs, thus mitigating injuries. Other studies also suggest that injury severity is reduced in crashes in which the rider is an upright position, compared to similar crashes

with prone riders (Sporner and Kramlich, 2003; Rizzi et al, 2012). The latter study reported statistically significant reductions of serious injuries among upright riders, as well as a 51% risk reduction of sustaining long-term injuries, although non-significant. Interestingly, none of the 6 riders with ABS had fallen off the motorcycle prior to the crash. It is important to stress that this study (Rizzi et al, 2012) was based on limited material and only analyzed crashes into road barriers. However, these findings could raise the question of whether the reduction of injury crashes with ABS is due to crash avoidance only. The possibility that a system that was originally designed to avoid crashes, such as ABS, might also have injury mitigating effects is intriguing and could have great safety implications. These effects, if confirmed, could be boosted even further by Autonomous Emergency Braking (AEB), which is being developed and evaluated for motorcycles too (Savino et al, 2012). These issues seem promising and should therefore be further investigated by future research.

During the latest years other vehicle safety systems have been introduced on motorcycles, although with generally lower fitment rate than for ABS. Such systems are Combined Brake Systems (CBS), Traction Control Systems (TCS) and integrated airbags, among others. In general, these systems are optionally fitted on ABS-equipped motorcycles and, in the case of TCS, even share some of the ABS sensors. While real-life crash data are still too limited for evaluation of these systems, this raises the possibility of combined effects that could enhance the total effectiveness of these systems. This aspect should also be investigated as soon as possible.

While these, among others, are important research questions that should be addressed in a near future, at the present stage there are more than sufficient scientific-based proofs to support the implementation of ABS on all motorcycles, even light ones. Manufactures should work toward a broad fitment of ABS, on light scooters as well, before 2016 in Europe and other regions of the world, while consumers should be encouraged to purchase only ABS-equipped motorcycles.

CONCLUSIONS AND RECOMMENDATIONS

- The effectiveness of ABS on injury crashes ranged from 24% in Italy to 29% in Spain and 34% in Sweden. The minimum effectiveness was 12%, 20% and 16%, respectively.

- The reduction of severe and fatal crashes with ABS ranged from 34% to 42% in Spain and Sweden, respectively. The minimum effectivenesses were 23% and 24%.

- The overall reduction of crash involvement with ABS-equipped scooters (at least 250cc) was found to be 27% in Italy and 22% in Spain. The minimum effectiveness was 12% and 2%, respectively.

- ABS on scooters with at least a 250cc engine was found to reduce the involvement in severe and fatal crashes by 31%, based on Spanish data only.

- Manufactures should therefore work toward a broad fitment of ABS, on light scooters as well, before 2016 in Europe and other regions of the world. Consumers should be encouraged to purchase only ABS-equipped motorcycles, for instance by insurance discounts, scrapping programs and other countermeasures.

- Further research should be aimed at understanding the injury severity mitigating effects of ABS, possibly in combination with AEB.

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REFERENCES

2 Be Safe, Two-wheeler Behavior and Safety. 2010. "Interaction between Powered Two-Wheeler Accidents and Infrastructure". Deliverable 1.2.

CARE (Community Road Accident Database). 2012: http://ec.europa.eu/transport/road_safety/pdf/observatory/trends_figures_2001.pdf Accessed February 16th, 2013

Evans L. 1998. "Antilock Brake Systems and Risk of Different Types of Crashes in Traffic". In proceedings of the 1998 ESV Conference. Paper Number. 98-S2-O-12.

Green D. 2006. "A Comparison of Stopping Distance Performance for Motorcycles Equipped with ABS, CBS and Conventional Hydraulic Brake Systems". In proceeding of the 2006 International

Motorcycle Safety Conference. Long Beach, CA, USA.

Highway Loss Data Institute. 2009. “Motorcycle Antilock Braking System (ABS)”. Insurance Special Report, December 2009 A-81.

Hurt H.H.J., Ouellet J.V., Thom D.R. 1981. “Motorcycle Accident Cause Factors and Identification of Countermeasures, Volume 1.” NHTSA Report. Washington DC: U.S. Department of Transportation.

Lie A., Tingvall C., Krafft M., Kullgren A. 2006. “The Effectiveness of Electronic Stability Control (ESC) in Reducing Real Life Crashes and Injuries.” Traffic Injury Prevention 7, pages 38-43.

MAIDS. 2004. “MAIDS: In-depth Investigation of Accidents Involving PTW, Final Report 1.3”. ACEM, Brussels, Belgium.

MC Folket [Magazine of the Swedish Motorcyclist Association]. 2011. Avoidance maneuvers on gravel roads, with and without ABS. Number 6, pages 42-46.

Rizzi M., Strandroth J. and Tingvall C. 2009. “The Effectiveness of Antilock Brake Systems on Motorcycles in Reducing Real-Life Crashes and Injuries”. Traffic Injury Prevention, 10:5, pages 479-487.

Rizzi M., Strandroth J., Sternlund S., Tingvall C., Fildes B. 2012. “Motorcycle Crashes into Road Barriers: the Role of Stability and Different Types of Barriers for Injury Outcome”. In proceedings of the 2012 IRCOBI Conference, Dublin, Ireland.

Roll G., Hoffmann O., König J. 2009. “Effectiveness Evaluation of Antilock-brake Systems (ABS) for Motorcycles in Real-world Accident Scenarios”. In proceedings of 2009 ESV Conference.

Savino G., Pierini M., Rizzi M., Frampton R. 2012. “Evaluation of an Autonomous Braking System in Real World PTW Crashes”. Traffic Injury Prevention 2012, article in press.

Strandroth J., Knudsen E. 2008. ”Trafikskador ur ett genusperspektiv”. Swedish Road Administration Consulting Services. SRA Pub. No. 2008:63. SRA, Sweden.

Sporner A. and Kramlich T. 2003.“Motorcycle Braking and its Influence on Severity of Injury”. In proceedings of the 2003 ESV Conference.

Strandroth J., Rizzi M., Olai M., Lie A., Tingvall C. 2012. “The Effects of Studded Tires on Fatal Crashes with Passenger Cars and the Benefits of Electronic Stability Control (ESC) in Swedish Winter Driving”. Accident Analysis & Prevention, Volume 45, pages 50-60

Swedish Transport Administration 2012 a. “Översyn av Etappmål och Indikatorer för Säkerhet på Väg mellan år 2010–2020 [Review of Interim Road Safety Targets and Safety Performance Indicators for the Period 2010-2020]”. Available at: http://www.trafikverket.se/PageFiles/19656/oversyn_av_etappmal_och_indikatorer_for_sakerhet_pa_vag_mellan_ar_2010_2020_version_0_9.pdf. Accessed February 16th, 2013.

Swedish Transport Administration. 2012 b. “Analys av Trafiksäkerhetsutvecklingen 2011 [Analysis of the Traffic Safety Development 2011]”. Available at: http://www.trafikverket.se/PageFiles/19656/analys_av_trafiksakerhetsutvecklingen_2011.pdf. Accessed February 16th, 2013

Teoh E.R. 2011. “Effectiveness of Antilock Braking Systems in Reducing Motorcycle Fatal Crash Rates”. Traffic Injury Prevention, 12:2, pages 169-173.

Vavryn K. and Winkelbauer M. 2004. “Braking Performance of Experienced and Novice Motorcycle Riders - Results of a Field Study”. International Conference on Transport and Traffic Psychology, Nottingham, United Kingdom.

APPENDIX I

The table below shows the motorcycle models included in the induced exposure analysis.

n ABS / non-ABS	ITA	SPA	SWE	n ABS / non-ABS	ITA	SPA	SWE
APRILIA MANA 850		3 / 8		HONDA CBR 1000 R			2 / 30
APRILIA SCARABEO 500	6 / 38			HONDA FJS 400	1 / 141	1 / 74	
APRILIA SHIVER 750	3 / 11			HONDA FJS 600	3 / 22	1 / 2	
BMW F 650 CS			8 / 0	HONDA GL 1800	2 / 0	1 / 13	8 / 5
BMW F 650 GD			2 / 1	HONDA NSS 250	35 / 20	2 / 0	
BMW F 650 GS	3 / 13		17 / 14	HONDA NT 700		1 / 115	2 / 2
BMW F 800 GS	8 / 14		17 / 0	HONDA SH 300	8 / 486	9 / 0	
BMW F 800 R	1 / 0		1 / 0	HONDA ST 1100			10 / 0
BMW F 800 S			12 / 0	HONDA ST 1300	1 / 1	7 / 48	16 / 2
BMW F 800 ST	3 / 4		13 / 0	HONDA VFR 1200			2 / 0
BMW G 650 X	0 / 3		1 / 0	HONDA VFR 800	2 / 13	4 / 63	7 / 37
BMW K 1100 LT		4 / 0	9 / 0	HONDA XL 1000	2 / 16		5 / 17
BMW K 1200 GT	0 / 4	22 / 0	6 / 0	HONDA XL 700	5 / 40	11 / 10	3 / 0
BMW K 1200 LT		20 / 0	6 / 0	KAWASAKI ER-6 F/N	11 / 190	33 / 281	19 / 34
BMW K 1200 R	6 / 10		4 / 0	KAWASAKI GTR 1400			1 / 0
BMW K 1200 RS			22 / 6	KAWASAKI VERSYS 650	3 / 39		
BMW K 1200 S	1 / 6	34 / 0	9 / 0	KAWASAKI Z 1000	2 / 67	5 / 68	3 / 11
BMW K 1300 GT			2 / 0	KAWASAKI Z 750	4 / 288	23 / 561	4 / 20
BMW K 1300 R	0 / 1			KAWASAKI ZZR 1400			3 / 0
BMW R 1100 GS			3 / 0	MOTO GUZZI 1200 SPORT	2 / 0		
BMW R 1100 RT			6 / 2	MOTO GUZZI NORGE 1200	12 / 0	3 / 0	1 / 0
BMW R 1100 S			12 / 1	MOTO GUZZI STELVIO	2 / 0		
BMW R 1150 GS			15 / 0	PIAGGIO VESPA GTS 250	3 / 86	5 / 45	
BMW R 1150 R	1 / 9		7 / 0	PIAGGIO X9 EVO	4 / 18	13 / 56	
BMW R 1150 RT		27 / 0	17 / 2	SUZUKI AN 650		99 / 26	
BMW R 1200 CL			2 / 0	SUZUKI DL 650	3 / 105	47 / 249	
BMW R 1200 GS	61 / 57		36 / 0	SUZUKI GSF 1200		3 / 0	2 / 28
BMW R 1200 R	12 / 23		2 / 0	SUZUKI GSF 1250	4 / 0	8 / 0	2 / 2
BMW R 1200 RT	0 / 18	104 / 0	4 / 0	SUZUKI GSF 650	11 / 33	43 / 322	
BMW R 1200 S			1 / 0	SUZUKI GSR 600	1 / 150	20 / 533	1 / 6
BMW R 1200 ST	3 / 6		1 / 0	SUZUKI GSX 650		1 / 21	
BMW R 850 GS			1 / 1	SUZUKI SV 650			2 / 43
BMW R 850 R			8 / 2	TRIUMPH SPRINT ST	3 / 1		1 / 14
BMW S 1000 RR			7 / 0	TRIUMPH TIGER 1050	2 / 23		3 / 18
DUCATI MONSTER 1100			2 / 1	YAMAHA FJR 1300	1 / 0	20 / 4	18 / 20
DUCATI ST4	2 / 1		1 / 2	YAMAHA FZ-1		6 / 91	2 / 13
HARLEY DAVIDSON FLHRCI			5 / 29	YAMAHA FZ-6		1 / 1224	9 / 26
HARLEY DAVIDSON FLHRSI			0 / 2	YAMAHA TDM 900	5 / 8	4 / 6	
HARLEY DAVIDSON FLHTCU			3 / 14	YAMAHA V-MAX			1 / 7
HARLEY DAVIDSON FLHTCUI			0 / 11	YAMAHA XJ-6			3 / 2
HARLEY DAVIDSON FLHX			3 / 5	YAMAHA XP 500	102 / 336	91 / 354	
HONDA CB 1000 R	1 / 34		11 / 4	YAMAHA XT 1200			1 / 0
HONDA CB 1300		3 / 6	2 / 5	YAMAHA XT 660 TENERE			1 / 2
HONDA CB 600	3 / 295	4 / 515	2 / 27	YAMAHA YP 250		8 / 571	
HONDA CBF 1000	8 / 5	7 / 11	5 / 1	YAMAHA YP 400	21 / 185	6 / 217	
HONDA CBF 600		95 / 320	3 / 1	**TOTAL**	**377 / 2820**	**799 / 5814**	**420 / 470**

APPENDIX II

The table below shows a comparison of the share of non-sensitive crashes in each country with official statistics or previous studies.

	ITA	SPA	SWE
Present study	16%	10%	8%
2 Be Safe, 2010	17%	11%	-
STRADA 2008-2012	-	-	6%

The table below shows the sensitive to non-sensitive (head-on collisions) ratios in the Swedish non-ABS group, per driver age.

age groups	non-sensitive crashes	Sensitive crashes	ratio	% non-ABS group
18-24	0	72	∞	15%
35-34	8	118	15	27%
35-44	10	92	9	22%
45-54	7	95	14	22%
44-64	5	51	10	12%
65+	0	12	∞	3%
all age groups	**30**	**440**	**15**	**100%**

EXPLORATORY STUDY ON THE SUITABILITY OF AN AIRBAG FOR AN INDIAN MOTORCYCLE USING FINITE ELEMENT COMPUTER SIMULATIONS OF RIGID WALL BARRIER TESTS

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ABSTRACT

Airbag's feasibility for the large touring motorcycles in mitigating severe injuries or avoiding fatality to the rider in a fatal crash has been established. However, airbag's suitability is not yet established for the smaller motorcycles which are used in India and other South Asian Countries; as means of transport rather than amateur riding. The current study is a first of its kind to address an issue of safety of Indian motorcyclists in a fatal crash by airbag. Study was aimed at finding appropriate: triggering time of airbag inflation process, backing surface, location and orientation of airbag module, and size of the airbag; in restraining effectively and absorbing maximum kinetic energy of the rider in the primary fatal impact with the rigid wall barrier. The study undertaken was the great challenge in the developing country such as India where there is no facility to conduct an actual barrier test on a motorcycle with a dummy installed with all the instrumentations. It is also extremely difficult to get the data and design details of every object used in the actual crash tests conducted elsewhere in the world. As per ISO 13232 standards [6], rigid wall barrier test simulations of motorcycle with airbag and rider were performed to arrive onto any conclusions. A Finite Element (FE) model of a representative Indian motorcycle of 100cc was developed which behaved realistically in the barrier test simulation. The developed realistic models of folded airbag, MATD neck and helmet were used. MATD neck was integrated into the available ATD model. All the FE models of the components were integrated to have a complete system to conduct barrier test simulations in 90 degree and 45 degree angles of impact. Simulations were performed using nonlinear FE software Pamcrash^{TM}. It was found that the sensor time should be lowest possible for triggering airbag inflation process due to smaller space available with the motorcycle. A need of a backing surface was felt for properly restraining the rider by airbag. Different alternate arrangements were studied to find out proper location and orientation of the airbag module in the motorcycle. Effect of different sizes of airbag was studied in absorbing the kinetic energy of the rider during the crash. The study found out appropriate triggering time, backing surface, location and orientation of airbag module and airbag size in effectively restraining and absorbing maximum kinetic energy of the rider in the fatal crash. The scope of the study was the primary impact, where the rider's head impacts into the rigid wall barrier in the fatal crash. The study has not considered following: a scenario of fall of a rider on the ground, angular impact sensitivity analysis, presence of a pillion rider, and full scale crash tests mentioned in ISO 13232 standards. At the end of this study it can be said that the broader research question of suitability of the airbag in Indian motorcycle in mitigating injuries to the rider in the fatal crash is answered in affirmative.

INTRODUCTION

Airbag's feasibility for the large touring motorcycles in mitigating severe injuries or avoiding fatality to the rider in a fatal crash has been established. It has taken more than three decades of research to establish the feasibility of airbags at least for large touring motorcycles [7]. This is due to the complexities involved in motorcycle airbag research. However, airbag's suitability is not yet established for the smaller motorcycles which are used in India and other South Asian Countries; as means of transport rather than amateur riding. This could be because the issues of airbags for smaller motorcycle (~100cc) are of concern only to developing countries like India. In India, the vulnerable road users such as pedestrians, bicyclists and two wheeler riders account for 60-80% fatalities. The registered motorized two-wheelers, including motorcycles, mopeds and scooters, account for 70% of total vehicle population. The fatalities of motorized two wheelers in road accidents account for 20-30%, making it second largest after pedestrian fatalities 40-50% [1]. As reported [5], a typical scenario of a motorcycle crash is a frontal impact (65.2%) of a motorcycle with an opposing vehicle (45.8%) where the rider separates from the motorcycle and hits the opposing vehicle (45.8%) or ground (37.4%) resulting in fatality due to the severe injuries to upper body parts (84.4%). The rider's injury regions are head 48.6%, neck 9.1%, chest 18.3%, abdomen 8.4%, whole body 8.4% and other part 7.2%. Thus, to arrive on beneficial or harmful effect of an airbag into the motorcycle, it is important to monitor the kinetic energy of the rider's head during impact.

The study undertaken was the great challenge in the developing country such as India where there is no facility to conduct an actual barrier test on a motorcycle with a dummy installed with all the instrumentations. It is also extremely difficult to get the data and design details of every object used in the actual crash tests conducted elsewhere in the world. With these limitations, safety of motorcyclist was studied using Finite Element (FE) Analysis, and FE models of the objects under consideration were developed by reverse engineering technique wherever possible. The study has not considered following: a scenario of fall of a rider on the ground, angular impact sensitivity analysis, presence of a pillion rider, and full scale crash tests mentioned in ISO 13232 standards. The broad research question addressed in present work is that whether the airbag system is suitable for Indian motorcycles in mitigating severe injuries to its riders in the event of a fatal crash. The current exploratory study is a first of its kind to address an issue of safety of Indian motorcyclists in a fatal crash by airbag with detailed Finite Element Analysis. The study was aimed at finding appropriate: triggering time of airbag inflation process, backing surface, location and orientation of airbag module, and size of the airbag; in restraining effectively and absorbing maximum kinetic energy of the rider in the primary fatal impact with the rigid wall barrier.

MODEL DEVELOPMENT

The essential components of the motorcycle airbag research are a motorcycle, its rider, helmet and airbag. In order to investigate the suitability of airbags in Indian motorcycles using computer simulations, it is required to develop a motorcycle model of most representative motorcycle in India, develop a dummy model which can duplicate the rider behaviour, and develop an accurate helmet model. Also, to assess the rider interaction with the deploying airbag in realistic way, a neck model should be more biofidelic. According to ISO 13232 standards, Motorcycle Anthropometric Test Device (MATD) is meant to duplicate the rider in crash environment. The newly designed neck known as MATD neck is specially designed to handle airbag interaction.

Motorcycle Model

A typical motorcycle of 100cc engine capacity is taken as the representative Indian motorcycle. The motorcycle under study was selected and dimensional details of its individual parts were obtained. Considerable time was spent for this exercise with the available tools such as the vernier caliper, spirit level, rule, weight balance, camera etc. The weights of the parts were measured either using the spring balance or weighing machine depending on their weight. Some of the parts were hung on the hook and their period of oscillation was measured to know their moment of inertia and location of the center of gravity. To measure dimensions of the complex shapes, the arrangement of spirit level and scales was made in such a way that the unit became a small Co-ordinate Measuring Machine (CMM). The models of the individual parts were then developed using HYPERMESH™ software for the measured dimensions. The photographs were utilized to clarify the construction details of the motorcycle. There were some parts which were meant for the decoration purpose or were not contributing towards strength of the motorcycle during crash. Their dimensions were measured but their models were not made. During the measurements of the individual parts, at most care was taken of the attachment points. The individual parts were assembled by using the information of these attachment points. The models of the individual parts were assembled with each other by appropriately choosing the joints, nodal constraints or simply by the 'node merge' option. The subassemblies of the front tire, rear tire, front suspension, rear suspension, and the handle were assembled appropriately at the attachment points. Thus, the assembly of the individual parts and these subassemblies made the complete motorcycle unit. The following *Figure1* shows a photograph and FE model of the motorcycle.

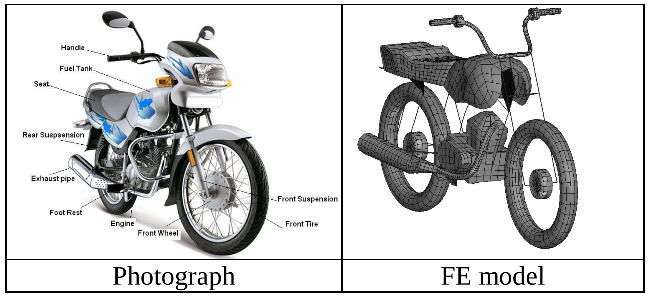


Figure 1 Indian Motorcycle

Motorcycle Barrier Test Any motorcycle model whether it is the Finite Element or Rigid Body is generally validated in a rigid wall barrier test. The purpose of the rigid wall barrier test is to make sure that the motorcycle model developed acts as a unit and produce reasonable wall forces by following proper dynamics. Also, in a barrier test, the motorcycle components' integrity is getting checked. Once it is ensured that the motorcycle act as a unit then it can be further subjected to Full-Scale-Tests where the dummy will be installed and it would be impacting into other opposing vehicle. The ISO 13232 standards specify the barrier force as one of the variables to be measured in a motorcycle dynamic testing. Thus, a barrier test of the motorcycle is must to evaluate the performance of any intended safety device into the motorcycle.

In present study, a FE model of a motorcycle was developed and validated by correlating its barrier test simulation results with the actual barrier test conducted by Mukherjee et al. [2002] [8]. As per ISO 13232 standards, the motorcycle model was simulated to impact into a rigid wall. The properties of the individual parts of the motorcycle were taken from authentic sources and input to corresponding models. The snapshots of the barrier test simulation are shown in Figure 2.

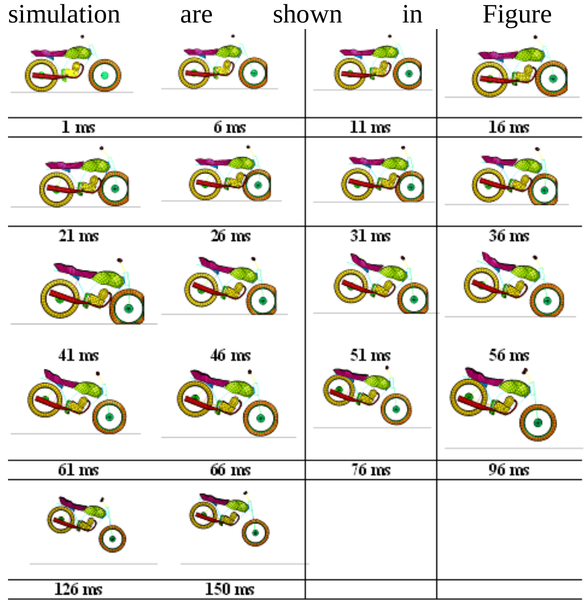
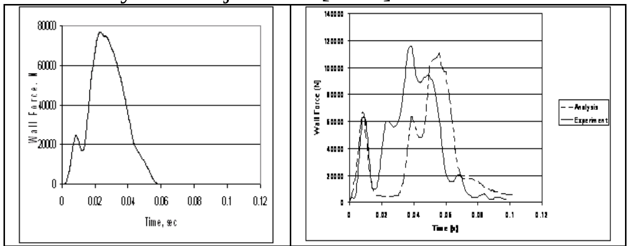


Figure 2 Simulation states for Motorcycle in Barrier Test

The results of the simulation were compared with Mukherjee et al. [2002]. It was observed that the wall forces curve of the barrier test simulation followed similar signature of the experimental curve of Mukherjee et al. [2002]. Figure 3 shows the comparison of the simulation results with the experimental and simulation curves observed by Mukherjee et al. [2002].



a) Present Simulation	b) [Mukherjee et al., 2002

Figure 3 Wall Forces comparison with [Mukherjee et al., 2002]

The magnitude of the wall forces was found to be proportionate to the motorcycles weights i.e. 100kg in present study and 218kg by Mukherjee et al. [2002]. It was concluded that the motorcycle model of present study could be used for further tests simulations.

Motorcycle Anthropometric Test Device (MATD) Neck

Depending on the crash scenario an unconstrained rider of a motorcycle can follow innumerable trajectories. The crash dummy mostly used in the automobile crashes is 50 percentile male Hybrid III dummy which was meant for frontal crashes. As per ISO 13232 standards, certain modifications are done in 50 percentile Hybrid III dummy to make it MATD. The MATD neck is specially designed to accommodate various postures of the rider and mimic the multi-directional impact scenarios. This is essential to arrive at any conclusion with reasonable accuracy on injury prediction for the motorcyclist. ISO13232 has given the construction details as well as performance criteria for the MATD neck. Figure 4 shows photographs of the actual MATD neck available to model MATD neck.

Front View	Side View

Figure 4 Photographs of MATD neck [2]

The MATD neck model should satisfy each and every corridor specified in ISO13232 for studying interaction with the deploying airbag in realistic sense. The tests specified in ISO13232 are the Frontal Flexion, Extension, Lateral Flexion and Torsion. For every test there are certain corridors of the angle and position of the neck to be satisfied. Dimensions of the each component of the MATD neck was estimated from the photographs. The MATD neck model was developed following the construction details specified in ISO 13232 standards and using estimated dimensions. The material properties were input to MATD neck model from authentic sources for simulating dynamic tests mentioned in ISO 13232 standards. The dimensions of the MATD neck were finalized by iterating on material properties of the mid-section rubber disks in dynamic tests simulations. Figure 5 shows MATD neck model.

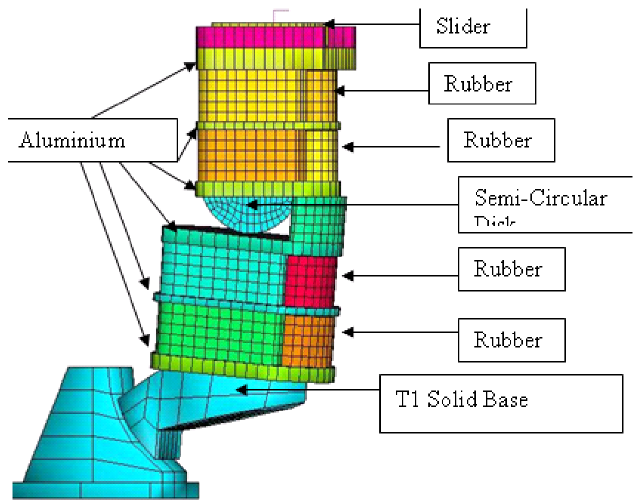


Figure 5 MATD Neck Model

The MATD neck model satisfied all the dynamic tests corridors of Frontal Flexion, Extension, Lateral Flexion and Torsion tests mentioned in ISO 13232 standards shown in appendix [2] .

Helmet

As shown in Figure 6, the FE mesh of the helmet model was available. The task at hand was to validate the model against the available experimental results for accommodating it in the crash simulations of the motorcycle.

Helmet Model [Kuroe et al., 2005]

Figure 6 FE Model of the Helmet and Photograph of the actual helmet used by Kuroe et al. [2005][7]

Helmet Drop Tests Helmets are impacted in drop tests to check their performance in a crash event or in a single fall scenario of the motorcycle rider. The helmet model and the actual helmet used by Kuroe et al. [2005] [7] looks similar in size and shape. The impact tests simulation results were compared with the experimental results reported by Kuroe et al. [2005] for different impact velocities of the helmet. It is reported that four impacting speeds of 5.94 m/s, 6.26 m/s, 7 m/s and 8 m/s. were used to test the actual helmet. It was reported that the actual test helmet was designed for maximum of 10m/s impact speed. So beyond this speed it would fail. Table 1 shows results of the helmet drop test simulations with the finalized inner foam properties as mentioned earlier. As shown in Table 1, the results of the helmet drop tests conducted by Kuroe et al. [2005] were reported in terms of the Head Injury Criteria (HIC) values. Last row of Table 1 shows that the helmet model was simulated for a higher impact speed of 13.4 m/s. In this case, the head form did touch the helmet outer shell. The helmet outer shell was in contact with the rigid plate which led to a higher acceleration peak and HIC value of the Head CG.

Table 1
Results of Helmet Impact tests simulations

Impacting Velocity in m/s	**Head form Center of Gravity (CG) Acceleration in G**	**Head Injury Criteria (HIC)**	**Head Injury Criteria (HIC) , Kuroe et al., 2005**
5.94	223.4	1436	1391
6.26	272.1	1888.4	1653
7	300.75	2562.8	2500
8	350.1	4584	4254
13.4	12587.4	2.37E+06	NA

Figure 7 is plotted from the results of Table 1. Figure 7 shows a close match between the simulation results of the helmet model under the study and the experimental results of Kuroe et al. [2005] with different impacting speeds in the helmet drop tests.

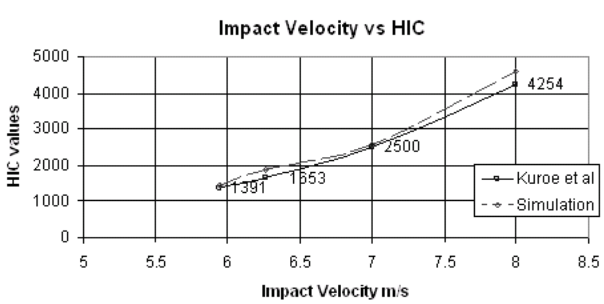


Figure 7 Comparisons of helmet impact simulations with [Kuroe et al., 2005]

The Finite Element helmet model thus can be said to be experimentally validated not only for the single impact speed but for four different impacting speeds. It may be noted that the helmet model would produce the HIC values as mentioned by Kuroe et al. [2005] for the impacting speeds lying in between the tested impacting speeds. Thus, in a crash simulation the helmet model would resemble the actual helmet used by Kuroe et al. [2005]. Moreover, the close match is for HIC values and not only for the head CG acceleration.

Airbag

The airbag as a passive safety device fitted in the automobiles is fast gaining public acceptance. The concept of the airbag in motorcycles is new compared to airbags for four wheeled vehicles. In this regard, currently passenger side airbags, which have a larger volume than the driver side airbags, are considered into the motorcycles.

Modeling of Folding of Airbag Mesh The rider's position varies with the motor cycle model and rider's style, and causes the rider to be often out-of-position i.e. rider comes in the trajectory zone of the inflating airbag. This is a dangerous situation as the airbag inflates within 40 ms and the speed of the airbag material coming out of the airbag module is around 200 mph (321 km/hr) [3, 9]. For this type of situation, the folding of the airbag is important which greatly influences the interaction between the rider and inflating airbag. Thus, to assess injuries of the rider reasonably in the simulations of the motorcycle crash, it is important to model the folded airbag in a realistic way. However, the modeling of the folding of the passenger side airbag is a time consuming and a tedious job. The commercial software tools used for modeling of the folding of the passenger side airbag do not give a realistic inflation process due to large distortion of airbag mesh elements and penetration problems.

In this work, new innovative method [3] is developed to model the folding of passenger side airbag mesh. Series of simulations were carried out for getting the folded passenger side airbag mesh. Initially, the undeformed mesh containing six layers of cloth was generated in the Finite Element software IDEAS™. For further folding simulations, the mesh was exported to PAM-CRASH™. The fold sequence was modeled using the simulations so as to duplicate the manual folding process in PAM-CRASH™. For each simulation of folding, the mesh was held between the rigid planes and these planes were given certain velocities corresponding to the folding process which gave folded airbag mesh of the complex shapes. The sequence of folding was similar to the manual folding of the airbag. Instead of hands, the rigid planes were used for the modeling of the folding on the passenger side airbag mesh. Figure 8 shows initial un-deformed mesh ready for series of folding simulations by rigid planes.

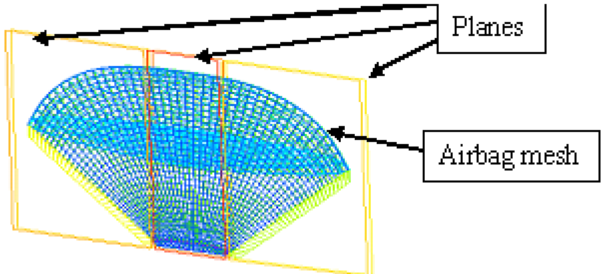


Figure 8 Initial Mesh and Rigid Planes

Annealing The appropriate state of *.DSY file from the previous simulation of the fold was selected. This file was opened in GENERIS™ and exported as mesh file *.unv. This *.unv file was again opened in GENERIS™ and saved as *.pc file by giving certain definitions. In this *.pc file the planes were defined as fixed rigid bodies and the airbag mesh was allowed to move inside the fixed planes. Thus, during the simulation, the contact forces between the airbag mesh, generated in the previous folding simulation, got reduced as it was allowed to relax inside the rigid planes. This simulation is called as annealing as it resembles the real annealing process in metallurgy. This simulation of the annealing was carried out after each simulation of the folding for reducing the contact forces between the airbag materials.
Figure 9 shows a simulation state after several folding and squeezing of the airbag mesh.

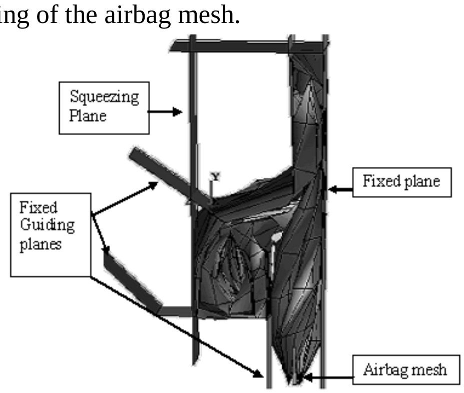


Figure 9 Arrangements of planes guiding the airbag mesh

Figure 10 shows the final state of the folded airbag mesh and surrounding rigid planes.

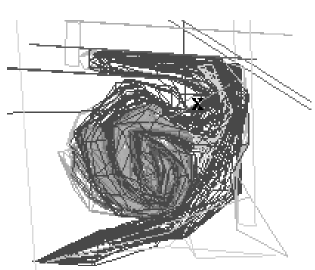


Figure 10 Side View of the final state of the folded airbag mesh

The properties related to airbag inflation process were taken from authentic sources. The inflation process of the folded airbag mesh was found to be in a better agreement with the inflation process of the unfolded airbag mesh. Figure 11 shows inflated folded airbag mesh.

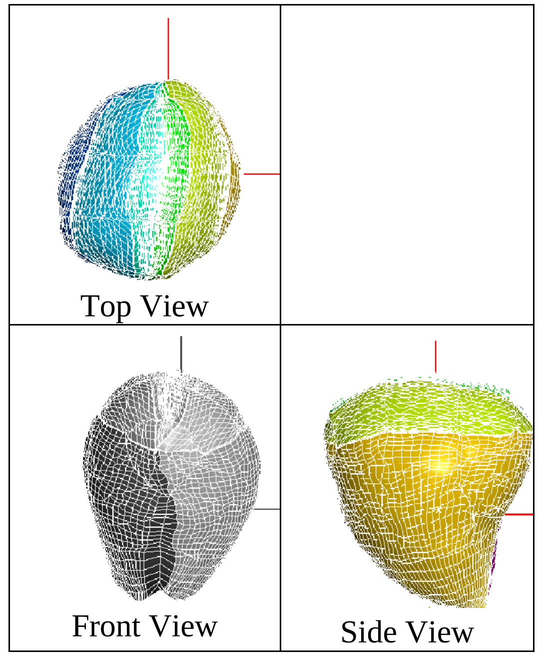


Figure 11 Inflated folded airbag mesh

Figure 12 shows simulation states of airbag inflation process. Airbag inflates within 40-50 ms as reported [5, 9].

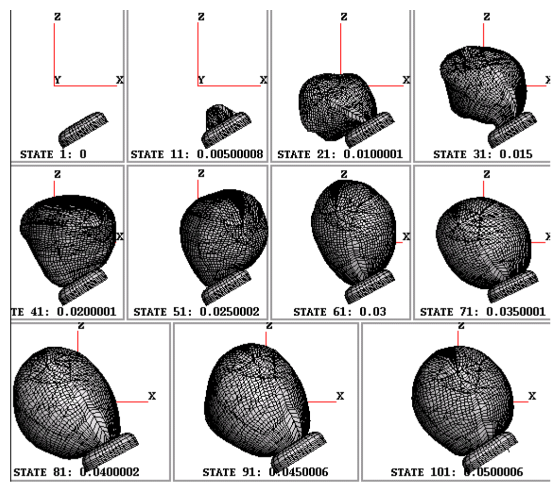


Figure 12 Simulation States of the inflation of the airbag

The operating pressure i.e. airbag internal pressure at which the occupant is intended to impact onto the airbag should be 50-60kPa as observed by Yamazaki et al. [2001] [9]. A very high internal operating pressure will lead to rebound of the occupant, whereas a small pressure will render the airbag ineffective in restraining the rider. The airbag mass flow and size of the airbag mesh was scaled appropriately to get the desired operating pressure 60kPa for each size of the airbag used. Figure 13 shows comparison of the internal pressure of the airbag with Yamazaki et al [2001].

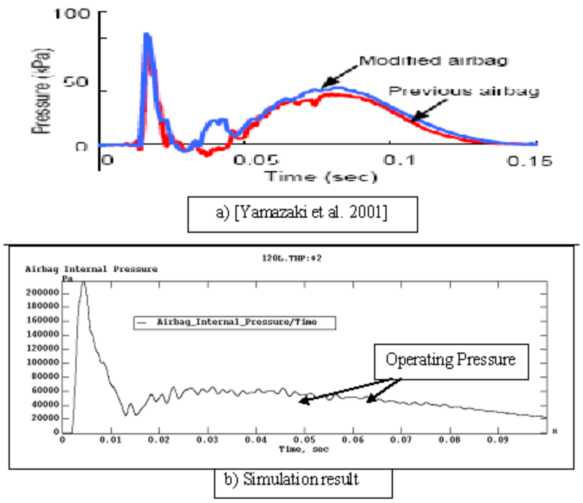


Figure 13 Airbag Internal Pressure curve compared with [Yamazaki et al., 2001]

The initial peak value of internal pressure of the airbag depends on the folding pattern of the airbag. The folding pattern of the airbag differs in both cases so the initial peak value differs as shown in Figure 13. Thus, it was concluded that the folded airbag mesh gave realistic inflation and could be used for further simulations for the motorcycle.

Airbag Mesh Sticking Phenomenon Generally, the airbag is stowed inside the airbag module i.e. casing. When gas starts filling the airbag, it's inside pressure increases sufficiently high to break open casing cover. Thus, the airbag fabric gets ejected out of its casing with high velocity. The inflation period of airbag was around 40 milliseconds (ms). The velocity at which airbag fabric gets ejected was reported between 200 to 300mph i.e. 320 to 480 kmph [(5)]. In reality it is observed that the airbag fabrics do not stick to casing of 8 to 20mm thickness during inflation. However in FE modeling, it was observed that airbag nodes got stuck with the casing (8.5mm thick) shell elements during the inflation as shown in Figure 14. This phenomenon of airbag elements getting trapped into the casing elements is termed as sticking. Due to this sticking phenomenon, the airbag could not be deployed as required to effectively absorb the kinetic energy of the passenger. The sticking phenomenon restricts smooth inflation of the airbag out of its casing.

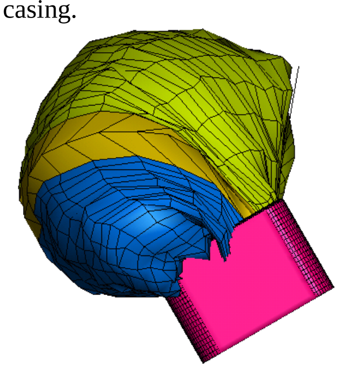


Figure 14 Airbag Penetrations with Casing

The following approaches were applied to avoid the sticking phenomenon between the airbag and its casing: i) Refinement of casing mesh and ii) Making casing with solid elements. Due to high velocity of the airbag nodes and size of airbag elements, the contact algorithm did not work with the refined mesh of the casing. Also, it was observed that the size of the airbag elements were more compared to the casing thickness. Thus, the refinement of the casing mesh did not solve the sticking phenomenon. It was thought that the solid elements of the casing may avoid penetration of the airbag mesh. The casing with larger thickness of 20mm was made with the hexahedron solid elements. The airbag elements of the bigger size easily crossed the casing thickness and remained there. Thus, there was no use of making the casing with solid elements to avoid sticking phenomenon of the airbag into its casing.

Last approach iii) Increasing thickness of casing was tried. It was observed that the airbag element length was bigger than casing thickness which caused nodes of the airbag element crossing over the casing elements and staying there. Thus to avoid penetration of the airbag nodes, the casing thickness was gradually increased. Figure 15 shows casings of various thicknesses. In all the cases, the height of the casing was kept same. Thickness of casing was increased by scaling the casing mesh in X-Y horizontal directions appropriately. It was observed that for 15mm to 50mm thickness of the casing, the sticking phenomenon gradually reduced but could not be avoided for a few elements particularly at the top edges of the airbag module.

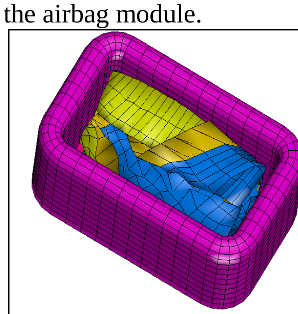
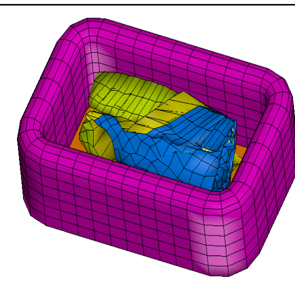
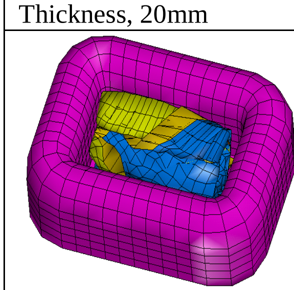
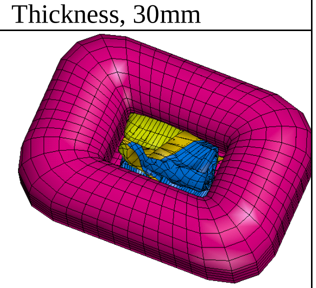
	
Solid elements with Thickness, 20mm	Shell elements with Thickness, 30mm
	
Shell elements with Thickness, 50mm	Shell elements with Thickness,75mm

Figure 15 Casing with varying thickness

As shown in Figure 16 it was observed that the penetration of the airbag nodes inside the casing elements was completely avoided when the casing thickness was

75mm. Thus, the airbag came out of the casing smoothly during inflation simulation.

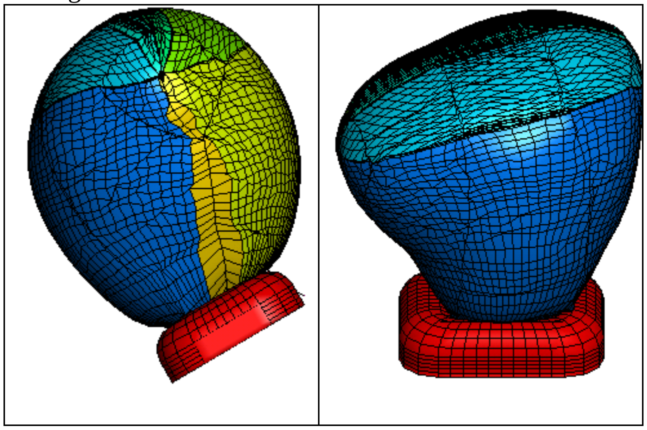


Figure 16 Inflated Airbag without any penetration in casing width 75mm

Although, in reality casing thickness is 8-20 mm but for simulation purpose it was taken as 75mm.

Selection of Airbag Sizes It was found that driver side airbags which are smaller in volume were too small to restrain a motorcycle rider by the airbag during a crash event. Therefore, larger volume airbags called as passenger side airbags were tried to restrain the motorcycle rider properly. Earlier, 65L driver side and passenger side 70L, 90L, 100L, 110L, 120L, 130L, 142L, 152L etc airbags were tried by the researchers for motorcycles. The choice of selecting a particular size of airbag for their motorcycle model was seemed to be dependent on their engineering judgment. In present case, the airbag sizes were selected based on the information available in literature. Finnis [1990] (4) found that 90L and 100L sizes airbags for 125cc motorcycle model were ineffective. Therefore higher size airbag of 110L is taken for the current study as a lower bench mark. Yamzaki et al [2001] (9) rectified the problem of increased injury level of rider with 140L size airbag from earlier 120L size airbag for their 1500cc motorcycle model (9). Therefore, 142L size airbag size is selected in this study in anticipation that it may give similar results as reported by Yamazaki et al [2001]. Further, Kuroe et al [2005] used 157L airbag for their 1800cc motorcycle. Therefore, 153L size airbag is considered in present study to verify effect of a larger size airbag on restraining the rider in a few cases. It may be noted that it is difficult to get an exact size of the airbag as required by scaling the mesh and airbag parameters because of stretching of the airbag fabric elements.
Finally, the airbags chosen in present study are categorized as 110L small airbag, 142L midsize airbag and 153L as large airbag.

Triggering Time for Airbag Inflation The triggering time of airbag inflation is crucial to evaluate an overall performance of the airbag in a crash event. An ideal scenario of a dummy getting impacted into an airbag after it gets fully inflated could not be achieved in the initial configuration (described in next sections) of the airbag because of the constraints such as the early dummy movements and the space available for the airbag inflation.
As reported by Iijima et al. [1998], the accelerometers were used as sensors to detect the crash event and accordingly trigger the airbag inflation mechanism. The firing time calculation method was mentioned as follows : If sensed acceleration (rearward/downward) exceeds 9g (g=9.81 m/s^2) start "velocity change" calculation; if "velocity change" exceeds 2.4 m/s, send trigger signal; if "velocity change" does not exceed 2.4 m/s and acceleration becomes less than 9g, stop "velocity change" calculation, and reset to zero. It was observed that the sensor system took 10 to 12 ms time to calculate velocity change exceeding 5.7 m/s value in the crash configurations as mentioned in ISO 13232 standards, where a motorcycle with 30 mph i.e. 13.4 m/s velocity impacted into a Corolla passenger car. Similarly, it took 15 to 21 ms time to calculate the velocity change in crash events where a motorcycle with 20 mph impacted into a Corolla passenger car. Thus, a typical time to make judgment about the crash event is in the range of 10 to 21 ms.
In the present study it was assumed that similar sensor system was installed to detect the crash event. According to ISO 13232 standards, in the rigid wall barrier tests, 13.4 m/s i.e. 30 mph impacting velocity of the motorcycle is considered. For 13.4 m/s impacting velocity, the judgment time mentioned is 10 to 12ms. However, in this study the rigid wall barrier was considered instead of passenger car so the judgment time was further reduced to 9ms. Thus, the minimum possible delay time to trigger the airbag inflation was considered.

BARRIER TESTS

In barrier tests, the rigid wall or flexible wall can be moving or fixed. According to ISO13232 standards, in the barrier test with the fixed rigid wall, the impacting velocity of the motorcycle is fixed to 13.4 m/s i.e. 48.24 kmph. The barrier tests are primary requirements of the motorcycle airbag research. The motorcycle components are tested in a barrier test for their integrity. The motorcycle is subjected to a barrier test with a dummy installed onto the motorcycle with all the instrumentations. Further, it can be subjected to duplicate an actual crash event in which it gets impacted into the opposing vehicle. This test is known as Full Scale crash Test (FST) which is out of scope of this study. A motorcycle is pulled by the guided trolley release system and after getting required velocity of the impact just before the rigid wall or the opposing vehicle it can be released. This arrangement makes sure that the motorcycle does not have constraint before and after the impact as observed in an actual crash event. The dummy installed on to the motorcycle for these studies is kept at the desired position by the arrangement of the supports so that just before the impact, the dummy's movement becomes unconstrained. The instruments are placed at the appropriate places to measure the crash variables in a barrier test and FST. The details of the crash test procedures are given in ISO 13232 [2005] standards. The scope of this thesis is restricted to the fixed rigid wall barrier tests only. The essential components of the barrier tests are a motorcycle with/without safety device installed, rider with helmet and rigid wall.

All the models of individual components of the motorcycle airbag system were assembled in the Pam-Generis™ platform and the airbag inflation simulations were carried out in the Pam-Safe™. A uniform strategy was applied to assemble various models from different *.pc files. In *.pc file of a base component another model file was merged. Then, the appropriate transformations were applied to the model so that the model gets placed at the desired location. The file of these transformation was saved with another name *.pc. In this file, another model file was merged. Then again appropriate transformations were applied to newly merged model so that it gets placed at the desired location. This sequence was continued for positioning the models with respect to each other appropriately. The barrier tests simulations of the assembled models were run with the appropriate contact definitions, initial and boundary conditions.

The MATD neck was properly positioned into available ATD model. Helmet was positioned onto MATD head. Airbag was installed into the motorcycle. Overall performance of the airbag installed was studied in the rigid wall barrier tests simulations. There were two objectives defined for this study, first one to evaluate the performance of the airbag at the back drop that there is no backing surface to support the reaction forces of the airbag when the rider impacts into the airbag. Second, if there is any need of such backing surface then to find the alternate arrangement within a domain or provide the backing surface in terms of a windshield by appropriately designing it.

Base Simulation

The base simulations without the airbag inflation process were run. In first case, the angle of impact was 90^0 and in second case the angle of impact was 45^0. The results of these simulations were plotted by assigning the Node number 8001 for the Head CG, 8004 for the Chest center and 8007 for the Pelvis CG. All the airbag simulations of the rigid wall were compared with these base simulations. Figure 17 shows the snapshots of various simulation states where the motorcycle hits the rigid wall barrier at right angle i.e. at 90^0.

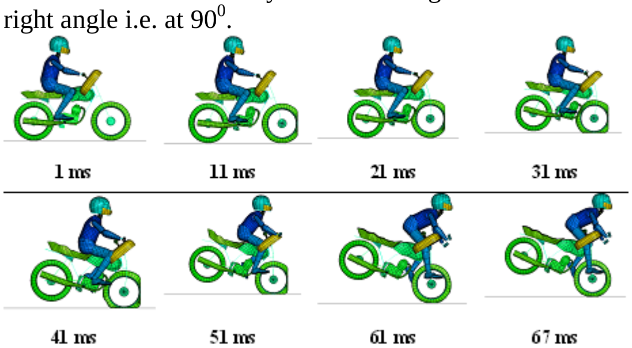


Figure 17 Motorcycle with 90^0 impacts- Base simulation

It can be seen from Figure 17 that after 21ms the dummy's legs got off the foot rest and the pelvis moved forward. At 31ms the motorcycle started to have pitching motion. Its rear tire started loosing the contact with the road. After 31 ms the hand got off the handle and it came out fully at 41ms as shown. After 41ms the pelvis came into contact with the fuel tank. That resulted in the dummy gaining some height and moving forward. At 51ms it shows that the dummy left the motorcycle. There was no contact defined between the legs and the airbag casing in this base simulation. In the base simulation there was no role of the airbag inflation. Moreover, there was no contact defined between the airbag casing and the dummy parts in any simulations. This is because the casing width was 75mm which was more than the realistic one. The casing width was kept more just to avoid the airbag inflation problems with the casing. After 51ms, the dummy's legs got straight and the head started moving towards the wall. At 61ms it shows that the pelvis gained certain height making the legs straight due to the gravitational field. Also, the motorcycle started moving backward from the wall and moving upward from the road. However, the dummy kept on moving in a forward direction. After 67ms its helmet first hit the rigid wall.

Figure 18 shows a velocity profile of the dummy's various parts such as the Head CG, Chest Center and Pelvis CG. The head velocity increased before its impact into the rigid wall due to momentum transfer phenomenon. This phenomenon can be explained using three rigid links connected with each other by revolute joints. Let us take the pelvis as a bottom link, chest as a middle link and neck as a top link. When we try to stop moving links at the bottom most end of the pelvis, then due to momentum transfer the chest link imparts linear as well as rotational motion to the neck link. Then the neck link transfers additional kinetic energy from its bottom end to its other end at the top. Thus, although all links are moving with certain velocity but due to stoppage of the bottom most links at its bottom end; greater velocity is imparted to the loose end of the neck link where the head gets placed.

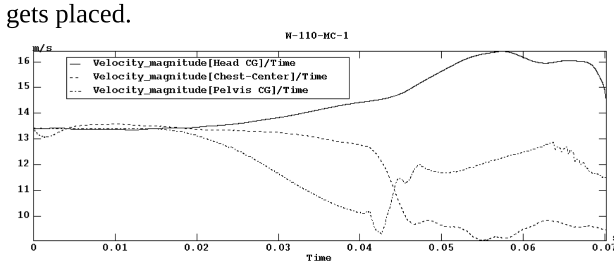


Figure 18 Motorcycle with 90^0 impacts - Velocity profile of MATD parts

Figure 19 shows the snapshots of the simulation states for 45 degree angle of impact. For more clarity, the snapshots are placed such that the first row shows the front view and second row (below the first row) shows its top view at every time step of 10ms. In the front view one can not get clear idea about the crash event. It is seen from Figure 19 that although the motorcycle handle got titled due to impact of the rigid wall, the dummy head continues to move forward towards the rigid wall due to its inertia. It is seen from Figure 19 that the hands got off the handle at

20ms. At 30ms the motorcycle got titled along with the 45^0 inclined rigid wall. As shown in Figure 19, the right leg of the dummy got lifted during 40 to 50ms period. The seat and the fuel tank offered resistance to the right leg and the pelvis after 40ms. Due to this the pelvis velocity got reduced suddenly as shown in Figure 20. But due to sliding of the motorcycle along the rigid wall, the resistance from the fuel tank and seat to the pelvis got released. This resulted in spike in the velocity curve of the pelvis which continued to move forward steadily after 50ms. The chest continues to move forward with a reduced velocity due to reduction in velocity of the pelvis. However, the head continued to move forward with a slightly increased velocity. At around 80ms it got impacted into the rigid wall.

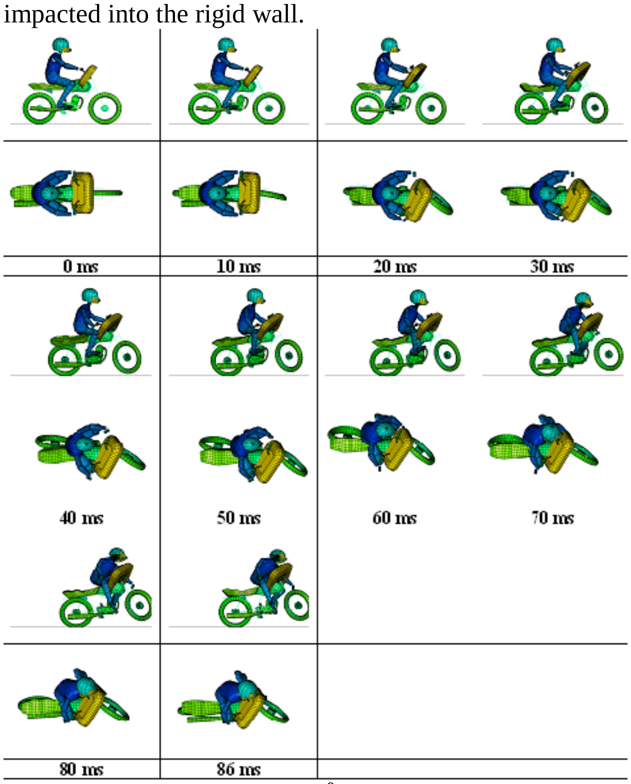


Figure 19 Motorcycle with 45^0 impacts - Base simulation

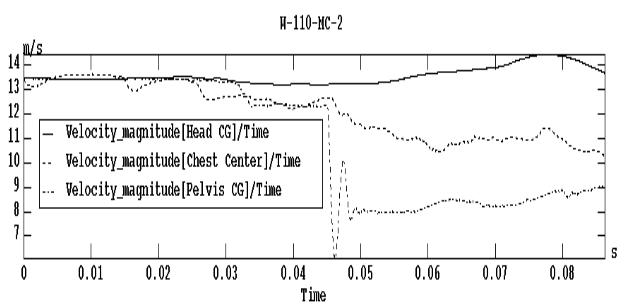


Figure 20 Motorcycle with 45^0 impacts - Velocity profile of MATD parts

As shown in Figure 18 and Figure 20, in both the cases of 90^0 and 45^0 angle of impacts respectively, the head CG velocity increased from the initial velocity due to the momentum transfer phenomenon. The pelvis velocity got reduced in both the cases because of its contact with the fuel tank and seat. The result of the chest slowing down was due to the reduction in the velocity of the pelvis.

Evaluation of a Backing Surface Effect

Initially, the airbag module was placed in between the handle bars. The base of the airbag was centered on the steering triangular member. Thus, the base of the airbag was kept parallel to the plane passing through the beams of the steering triangular member. The handle connected to the steering triangular member beams was passing below the airbag casing. This position of the airbag module was called as initial configuration shown in Figure 21. Two test runs were simulated to find out the effect of a backing surface. In first run the airbag was not included in the rigid wall definition and thus allowed to move beyond the rigid wall; while in second run, the airbag was included in the rigid wall definition so that it would not move beyond the rigid wall.

Effect of various sizes of airbags was studied in both the test runs. Mainly, there were two sizes of the airbags considered in this study. Those were smaller airbag of 110L and medium airbag of 142L size. In following section, 110L and 142L airbags results are given to highlight the backing surface effect. The airbag module was placed on the steering frame at the mid centre of the handle i.e. initial configuration. In both the test runs, the motorcycle was impacted into the rigid wall with 13.4m/s speed at right angle.

Without backing surface In this case, the velocity of the head CG of the rider just before impacting the rigid wall was not much reduced as compared to the base line simulation.

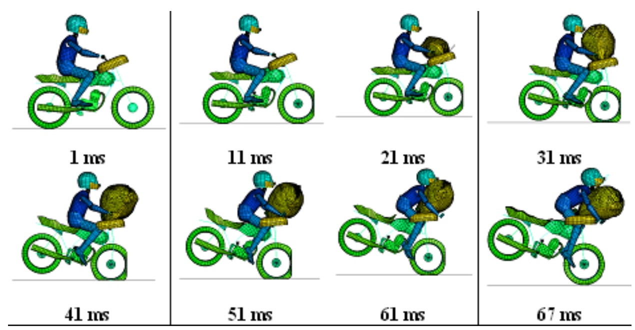


Figure 21 Barrier test simulation without backing surface for 110L airbag

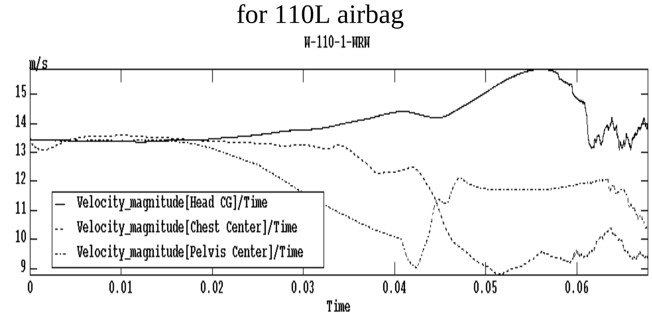


Figure 22 Barrier test simulation without backing surface for 110L airbag: Velocity profiles

Figure 21 shows that the dummy just rolled over the airbag for smaller airbag of 110L size at 67ms. As shown in Figure 22, the velocity of the Head CG just before impacting into the barrier was 13.8 m/s. It was observed that the reduction in Kinetic energy of the Head CG was 13.75%. As seen in Figure 21, the airbag could not restrain the rider due to lack of support in terms of a backing surface. Thus, the purpose of mounting the airbag into the motorcycle got defeated due to lack of proper backing surface. In this case, a need of a backing surface for the airbag was felt to restrain the rider.

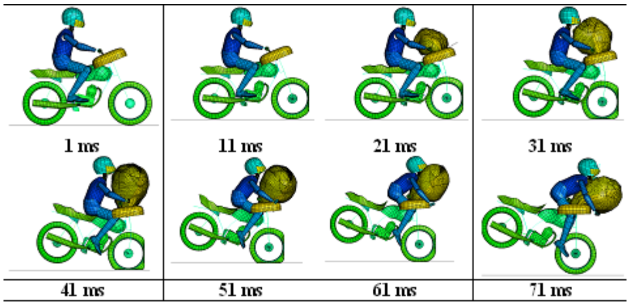


Figure 23 Barrier test simulation without backing surface for 142L airbag

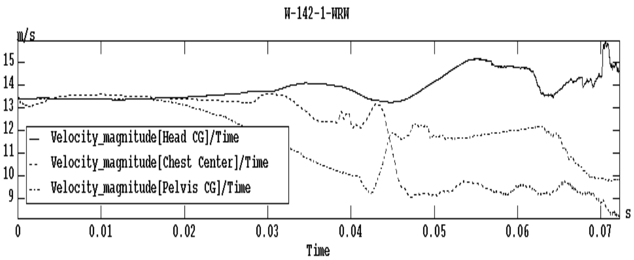


Figure 24 Barrier test simulation without backing surface for 142L airbag: Velocity profiles of MATD parts

As shown in Figure 23, it was observed that for 142L size airbag, the dummy just rolled over the airbag. Figure 24 shows, the velocity of the Head CG just before impacting into the rigid wall was 14.2 m/s. The reduction in kinetic energy of the Head CG was 11.21%. Likewise as in the earlier case with 110L size airbag; in this case also a need of a backing surface was felt to restrain the rider properly. Thus, without a backing surface the airbag did not provide the cushioning and restraining effect to the rider as required.

With a backing surface It was observed that a backing surface provided by the rigid wall led to the reduction in kinetic energy of the rider's head to some extent for all sizes of airbags considered.

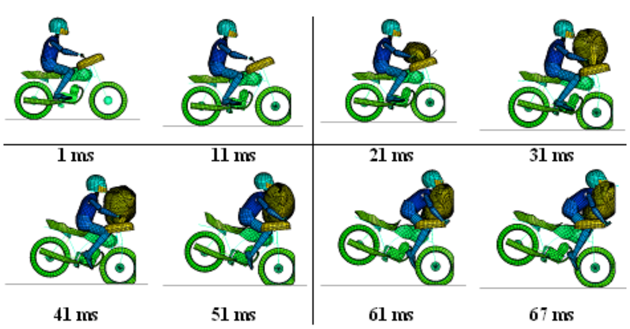


Figure 25 Barrier test simulation with backing surface-110L airbag-Simulations states

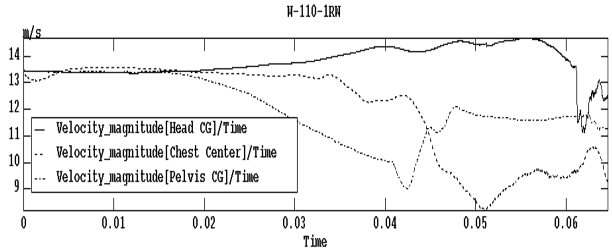


Figure 26 Barrier test simulation with backing surface-110L airbag- Velocity profiles

Figure 25 shows the snapshots of the simulation states for 110L size airbag. It shows that in the initial configuration the airbag got ejected upwards. The restrain type airbag became the trajectory type due to the pitching movement of the motorcycle as shown in Figure 25. The airbag got trapped in between the rider and the rigid wall. Thus, the rigid wall provided the backing surface in restraining the rider to some extent. At 67ms it shows that the rider was restrained from further moving forward. Figure 26 shows the velocity of the Head CG just before impacting into the barrier was 12.5 m/s. For smaller airbag of 110L size, it was observed that the reduction in kinetic Energy of the Head CG was 21.87 %. In this case, a need of a backing surface for the airbag was felt to restrain the rider properly in better way.

Figure 27 shows the snapshots of the simulation states for 142L size airbag. Here also, the airbag got trapped in between the rider and the rigid wall.

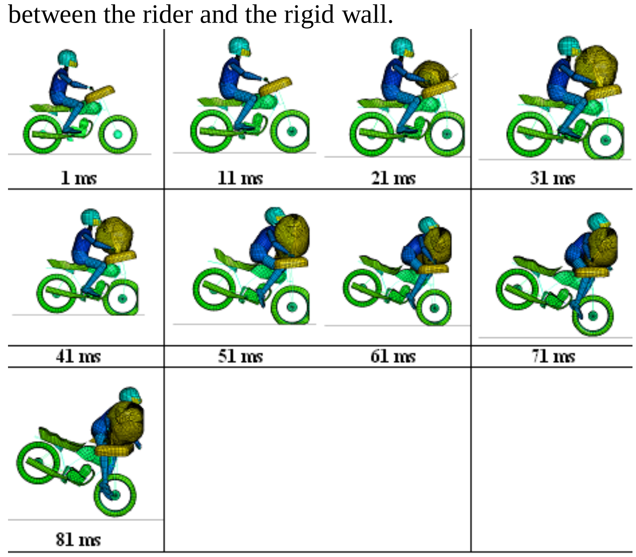


Figure 27 Barrier test simulation with backing surface for 142L size airbag

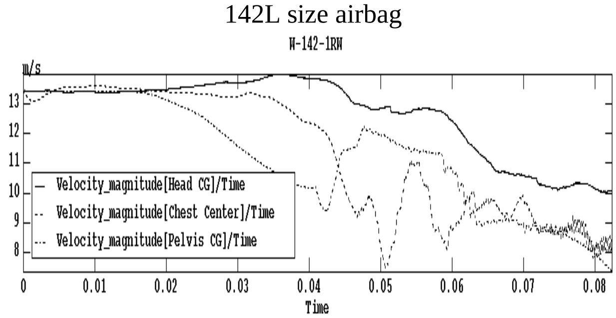


Figure 28 with backing surface for 142L size airbag

It is seen from Figure 28 that the velocity of the Head CG just before impacting into the barrier was 10.3 m/s. The reduction in kinetic energy of the Head CG was found to be 35.62 %. A need of backing surface within a motorcycle was felt, to restrain the rider effectively.

Alternate Arrangement

As discussed in earlier sections, it was felt that the airbag was not that much effective to restrain the rider with the initial configuration of the airbag module. Moreover, it was felt that it would be better to make use of a backing surface within the motorcycle itself rather than taking it from the opposing vehicle or the barrier. It was decided to use the airbag support base as a backing surface. Three options were tried for this arrangement called as alternate arrangement 1, 2 and 3. In the first case the airbag module was tilted such that the airbag inflation axis gets directed toward the dummy chest centre. In second case, the airbag module was shifted at the front by 200mm and upward by 50mm and tilted such that its inflation axis gets directed towards the neck./chin of the rider. In third Alternate arrangement, the axis of inflation of airbag was directed towards the chest center.

<u>Alternate arrangement 1</u> The axis of airbag inflation was calculated by selecting a mid node of the casing box at the bottom side and a mid node at the top side of inflated airbag mesh directly coming out of the casing. A node at the middle of the chest and sternum facing the airbag called as chest center was selected as the point towards which axis of airbag inflation was directed. It was done by tilting appropriately the airbag with its casing relative to the top base frame of the front suspension. As shown in Figure 29, the airbag casing was allowed to overlap the fuel tank. As discussed earlier, although the thickness of the airbag casing in reality is 8-20mm but for the modeling purpose it was taken as 75mm. It was observed that after deployment of the airbag, the fuel tank also acted as a backing surface in the alternate arrangement of tilting the airbag module. Also the velocity and thus kinetic energy of the rider got reduced significantly due to the airbag restraining effect. Figure 29 shows the snap shots of the simulation states for 110L airbag in Alternate arrangement 1 configuration. It is seen that the rider got slid on the airbag pushing it towards left hand side. As shown in Figure 30, for 110L airbag, the velocity of the Head CG just before impacting into the barrier was 10 m/s. The fluctuations in velocity profile of the Head CG were due to sliding of the dummy on the airbag. Thus, the reduction in kinetic energy of the Head CG was found to be 37.5%. The results were encouraging compared to the initial configuration of the airbag module.

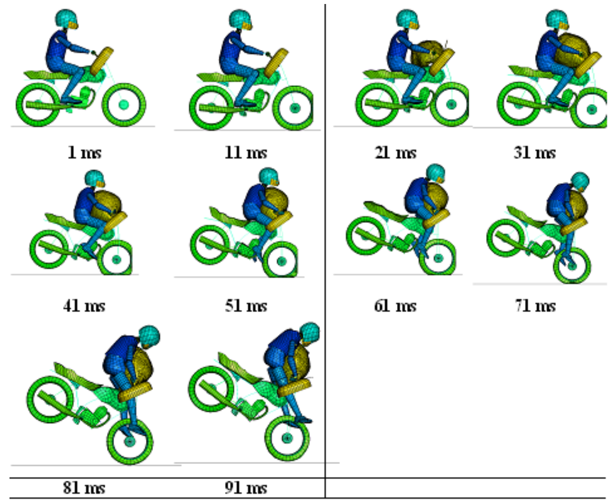


Figure 29 Alternate arrangement 1- 110L airbag – Simulation states

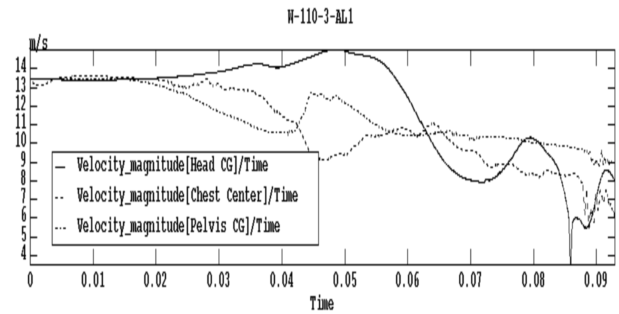


Figure 30 Alternate arrangement 1- 110L airbag- Velocity profiles

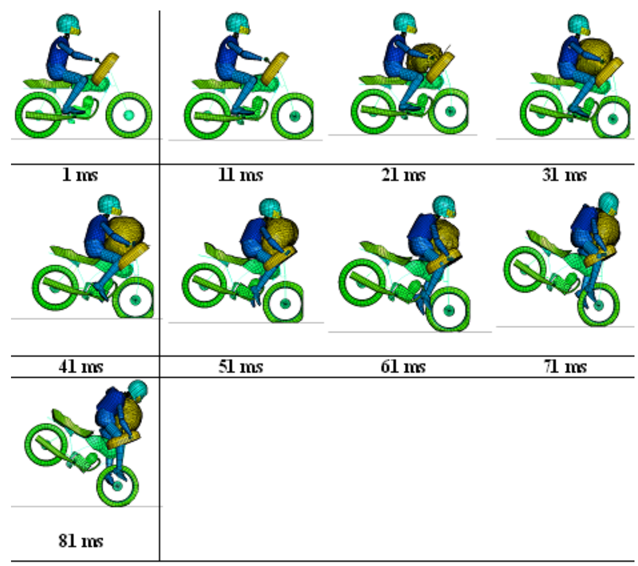


Figure 31 Alternate arrangement 1- 142L airbag – Simulation states

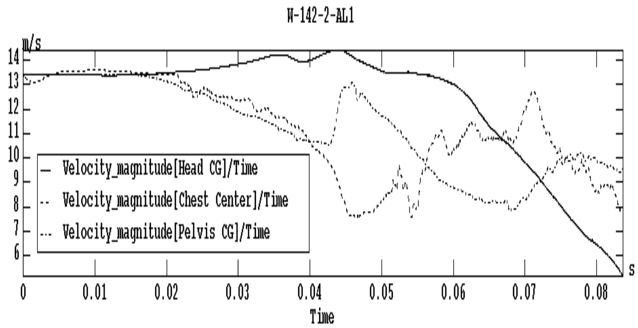


Figure 32 Alternate arrangement 1- 142L airbag- Velocity profiles

Figure 31 shows the snap shots of the simulation states for 142L airbag in Alternate arrangement 1 configuration. Here also, the rider tried to slide on the airbag. The airbag could not open properly due to smaller space available for its deployment. However, as seen in Figure 31, at 71 to 81 ms the rider was restrained by the airbag properly. Figure 32 shows, for 142L airbag, the velocity of the Head CG got reduced smoothly as compared to 110L size airbag. The velocity of the Head CG just before impacting into the barrier was 5 m/s. Thus, the reduction in kinetic energy of the Head CG was found to be 68.75%. The results were encouraging for 142L airbag as compared to the initial configuration of the airbag module in reducing kinetic energy of the Head.

In this case Neck Injury Criteria was calculated as per ISO 13232 standards. Table 2 shows relation between Abbreviated Injury Scale (AIS) and Maximum Neck Injury Index (NII)max.

Table 2
Neck combined loading injury severity probability as a function of *NII* [ISO 13232, 2005]

Severity Level	AIS≥ 1	AIS≥ 2	AIS≥ 3	AIS ≥4	AIS≥ 5
Minimum NII_{max}	1.06	1.86	2.29	4.73	4.73

Further, 153L and 180L sizes airbag were tested in Alternate Arrangement 1.

Table 3
Results for Alternate Arrangement-1

Alternate Arrangement -1

Neck Injury Criteria (NIC) for MATD Neck				90 degree Impact		
Constants Value	**Parameter**	**110L**	**142L**	**153L**	**180L**	**MC-Only**
Fc* = 6.53kN	Fc	-3.305	-2.5	-4.04	-2.52	-1.48
Ft* = 3.34 kN	Ft	1.79	2.08	9.2	3.896	0.617
Mx*=62.66Nm	Mx	43.5	42.6	99	29.2	21
Me*= 58Nm	Me	-83.25	-60.4	-119.4	-78	-75
Mf*=204.2Nm	Mf	23	24	49.5	50	40.8
Mz*=47.1 Nm	Mz	18.3	17.6	13.95	10.8	2.7
NIC	NII_{max}	**1.788354**	**1.706905**	**3.028836**	**2.000728**	**1.485423**
File Name		W-110-3.pc	W-142-2.pc	W-160-32.pc	W-160-1.pc	W-110-MC.pc
Simulation end time, T		82ms	83ms	150ms	78	70ms
Head Velocity, m/s		10	5	5.4	8.1	16
% Reduction in KE		**37.5**	**68.75**	**66.25**	**49.375**	**0**
Base File		W-110-2.pc	W-142-1.pc	W-160-31.pc	W-110-3.pc	W-110-3.pc
AIS		**1**	**1**	**3**	**2**	**1**

As shown in Table 3, AIS value for 153L and 180Lsize airbag was 3 and 2 respectively. Therefore for the larger airbags of 153L and 180L size, the snap shots of the simulation states and the velocity profiles are not given here. However, their results in terms of the Neck Injury and reduction in kinetic energy are given in Table 3. It is observed that the 142L airbag reduced kinetic energy of the head CG by 68.75%. Also, in this case the NIC gave injury index of Abbreviated Injury Scale (AIS) 1 i.e. minor injury. The Neck Injury Criteria was given for the Alternate Arrangement 1 since the space available between the airbag and dummy was small. Therefore there was possibility of neck injury by deploying airbags of various sizes. It was found that 153L and 180L sizes airbag increased neck injury level to AIS 3 and 2 respectively.

Alternate arrangement 2 It was found that the airbag could not get sufficient space to inflate properly in the Alternate arrangement 1. The airbag module was moved forward by 200mm and upward by 50mm in this configuration. It was placed on the top of the head light of the motorcycle. The airbag inflation axis was directed towards neck/chin of the dummy. Table 4 shows results of Alternate Arrangement 2.

Table 4
Results for Alternate Arrangement-2

Alternate arrangement 2- Airbag Inflation axis towards neck/chin

90 Degree with Alternate Arrangement 2- Airbag Inflation axis towards neck/chin

Constants Value	**Parameter**	**110L**	**142L**	**153L**	**Motorcycle Only**
Fc* = 6.53kN	Fc	-4.58	-6.2	-5.8	-1.48
Ft* = 3.34kN	Ft	0.516	2.49	3.48	0.617
Mx* = 62.66Nm	Mx	50.2	52.4	96.4	21
Me* = 58Nm	Me	-71	-108.2	-107.6	-75
Mf* = 204.2Nm	Mf	54	40.7	12	40.8
Mz* = 47.1Nm	Mz	4.92	16.5	36.4	2.7
Neck Injury Critera	**NII**	**1.190552**	**1.855636**	**2.37381**	**1.485423**
File Name		W-110-5-1.pc	W-142-4-1.pc	W-160-35.pc	W-110-MC.pc
Simulation end time T, ms		96	79	107	70ms
Head Velocity, m/s		4.32	4.58	3.4	16
% Reduction in KE		**73**	**71.375**	**78.75**	**0**
Base File		W-110-5.pc	W-142-2.pc	W-160-34.pc	W-110-3.pc
AIS		1	1	2	1

As compared to Alternate arrangement 1, the Alternate Arrangement 2 showed encouraging results in reducing kinetic energy of the rider's head. It was found that the velocity of the Head just before impacting into the barrier was 4.32 m/s for 110L size airbag. Thus, the reduction in kinetic energy of the Head CG was 73%. It was found that the velocity of the Head just before impacting into the barrier was 4.5 m/s for 142L size airbag. Thus, the reduction in kinetic energy of the Head CG was 71.37%. Moreover, it was found that the head did not move forward to impact into the rigid wall, but moved upwards along with the motorcycle. Also for the airbag size of 153L, the head CG velocity reduced to 3.4 m/s. Thus, the total reduction in kinetic energy of the head was found to be 78.25%. However, the neck injury increased to AIS 2 with 153L.

Alternate arrangement 3 In this arrangement the airbag inflation axis was directed towards the dummy chest center for a better restraint of the rider.

Alternate Arrangement 3 configuration for 110L size airbag Figure 33 shows the snap shots of the Alternate Arrangement -3 simulation states for 110L size airbag. It can be seen from the snap shots that the airbag got sufficient space to inflate properly. To get more clarity of the crash event, the front and top views of snap shots are shown in Figure 33.

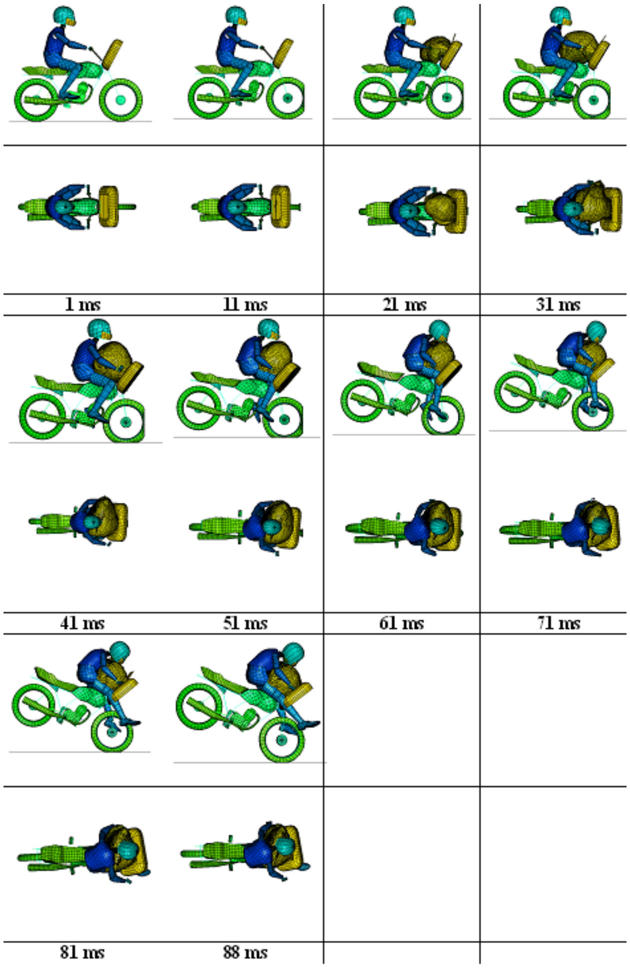


Figure 33 Alternate arrangement 3- 110L airbag- Simulation states

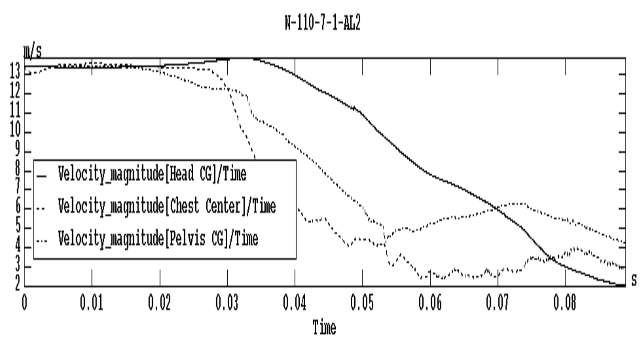


Figure 34 Alternate arrangement 3- 110L airbag- Velocity profiles

As shown in Figure 33, at 31 ms, the airbag almost got fully inflated. As it is directed towards the chest center so it restrained the chest and the pelvis up to the maximum extent. It is seen that the rider got bent above the airbag, thus its height of ejection got reduced. At 88ms, Figure 33 shows that the dummy was in the air and had no contact with the motorcycle. However, it rested on the deflating airbag as shown. This configuration of the airbag module provided the maximum restrain for the rider.

Figure 34 shows the velocity profile of the dummy parts. The dummy did not come in contact with the rigid wall till more than 88 ms. It was found that the velocity of the Head just before impacting into the barrier was 1.98 m/s for 110L size airbag. Thus, the reduction in kinetic energy of the Head CG was 87%.

Alternate Arrangement 3 configuration for 142L size airbag The following Figure 35 shows the snap shot of the simulations states for 142L size airbag. At 31 ms the airbag got sufficiently inflated when it hit the rider's chest and pelvis. At that time the rider was sliding on the seat and fuel tank. However, the airbag did not allow it to gain certain height due to the fuel tank.

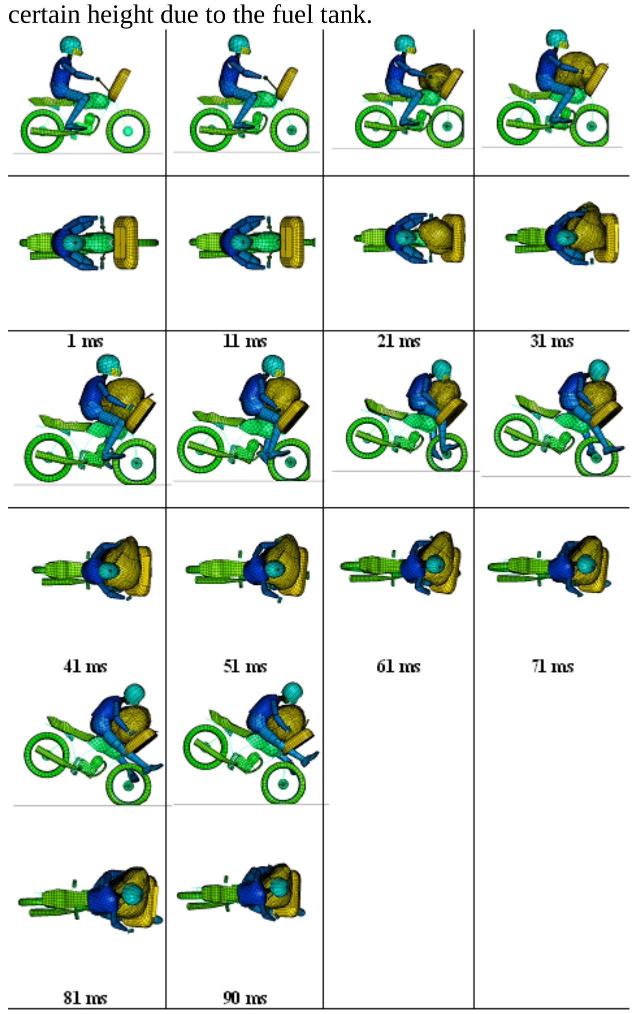


Figure 35 Alternate arrangement 3- 142L airbag- Simulation states

As shown in Figure 35, the rider after 41ms left the motorcycle and was completely restrained by the airbag. At 90ms the pelvis touched the fuel tank again. As shown, the rider did not touch the rigid wall up to 90ms. It is seen that the airbag tried to slip from the left hand side of the rider. But the rider's movement restricted the airbag from slipping further. The front tire did not leave the road as found in the base simulation. This is due to the dummy's entire weight falling on the airbag, which got transmitted to the front wheel. Figure 36 shows the velocity profiles of the dummy parts. It was found that the velocity of the head just before its contact with the rigid wall was 2.4m/s. Thus, the reduction in kinetic energy of the rider's head was 85%. Also, the pelvis and chest velocity reduced gradually along with the head velocity.

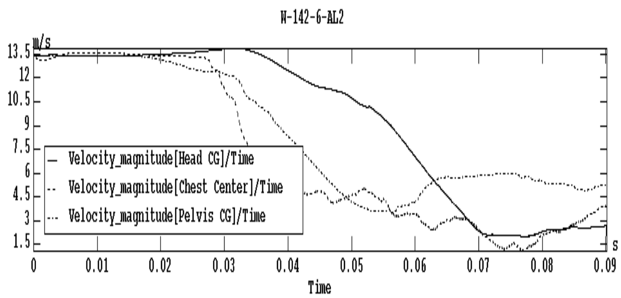


Figure 36 Alternate arrangement 3- 142L airbag- Velocity profiles

Table 5
Results of simulation for Alternate Arrangement 3

90 Degree with Alternate Arrangement -3					
Constants Value	**Parameter**	**110L**	**142L**	**153L**	**Motorcycle Only**
Fc* = 6.53 kN	Fc	-3.15	-3.675	-5.85	-1.48
Ft* = 3.34 kN	Ft	0.56	0.78	0.212	0.617
Mx* = 62.66 Nm	Mx	60	56.25	64	21
Me* = 58 Nm	Me	-64.5	-78	-71	-75
Mf* = 204.2 Nm	Mf	14.7	56	32	40.8
Mz* = 47.1 Nm	Mz	11.92	12.72	14.45	2.7
Neck Injury Criteria	NII	1.504023	1.486177	1.176471	1.485423
File Name		W-110-7-1.pc	W-142-6.pc	W-160-36.pc	W-110-MC.pc
Simulation end time T, ms		89	83	80	70ms
Head Velocity, m/s		1.98	2.4	7.4	16
% Reduction in KE		**87.625**	**85**	**53.75**	**0**
Base File		W-110-5.pc	W-142-4-1.pc	W-160-35.pc	W-110-3.pc
AIS		1	1	1	1

Table 5 shows that the 110L size airbag absorbed maximum of 87% kinetic energy of the rider's head whereas 142L airbag absorbed 85% and 153L airbag absorbed only 53%. It was found that 153L airbag could not provide proper restraining effect to the rider. Due to its larger volume the airbag got bent at its base and the dummy rolled over it. However, it was found that the NIC gave AIS value of 1 for all sizes of airbags in Alternate Arrangement 3.

Angular Impact

To study the effect of an angular impact, the rigid wall was titled to 45 degree with respect to the direction of motion of the motorcycle. The initial velocity of the motorcycle was kept at 13.4 m/s. The angular impact test simulations were carried out to find out the angular impact sensitivity on the airbags under the study. It was found that the motorcycle slid along the wall. Due to the sliding motion of the motorcycle, the airbag tries to push the rider further to leave the motorcycle. The left side of the rider slid along the inclined rigid wall. The rider tried to fall on the left side in between the motorcycle and the inclined rigid wall. The right leg got lifted due to this tendency of the rider. However, the head continued to move forward although its pelvis got resistance from the seat and the fuel tank. Kinetic energy of the head somewhat got reduced due to the airbag restraining. Its value was not as much as observed in the frontal impact scenario. The snapshots of the simulation states for the Alternate Arrangement 1 are not given for all the sizes of the airbags since the rider motion was more or less similar as discussed earlier. Table 6 shows the results of Alternate Arrangement 1 in 45 degree angular impacts.

Table 6
Angular Impact- 45 degree- Alternate Arrangement 1

45 degree Impact- Alternate Arrangement -1					
Constants Value	**Parameter**	**110L**	**142L**	**153L**	**Motorcycle Only**
Fc* =6.53 kN	Fc	-2.375	-4.75	-4.36	-2.39
Ft* = 3.34 kN	Ft	0.855	0.51	0.848	0.78
Mx* = 62.66 Nm	Mx	52.2	61.45	52.8	51.6
Me* = 58 Nm	Me	-33	-49.3	-48.2	-37.73
Mf* = 204.2 Nm	Mf	24.6	30.345	36.6	10.05
Mz* = 47.1 Nm	Mz	11.36	17.5	13.65	6.6
Neck Injury Criteria for MATD Neck	NII	1.317187	1.18322	1.177719	1.339407
File Name		W-110-4.pc	W-142-3-1.pc	W-160-33.pc	W-110-MC-2.pc
Simulation end time T, ms		104	62	78	86
Head Velocity, m/s		6.9	5.1	8.6	13.67
% Reduction in KE		**49.52451**	**62.69203**	**37.08851**	**0**
Base File		W-110-3.pc	W-142-2.pc	W-160-32.pc	W-110-MC-1.pc
AIS		1	1	1	1

As shown in Table 6 the velocities of the Head CG just before impacting into the barrier were 6.9, 5.1 and 8.6 m/s for 110L, 142L and 153L size airbags respectively. Thus the reduction in kinetic Energy of the Head CG was 49.52%, 62.69% and 37.08 % for 110L, 142L and 153L size airbags respectively. In this case since the airbag came into the contact with the dummy from the initial stages of the airbag inflation, so in angular impact the airbag provided some restrain to the rider. However, this restraining was not as effective as observed in the frontal impact scenario. The reason was that, in angular impact the dummy tried to move straight forward whereas the airbag got titled along with the handle. So the backing surface in terms of the airbag base as envisaged could not be utilized due to turning of the handle. Thus there was no proper restraining of the dummy in angular impact of 45 degree.

In the Alternate Arrangement 2, the reduction in kinetic energy of rider's head was not that much as observed with the Alternate Arrangement 3. Therefore, the angular impact simulations were not carried out for Alternate Arrangement 2.

The following Figure 37 shows the snap shots of the simulation states for 110L size airbag in the Alternate Arrangement 3. As shown in Figure 37 at 20ms the hands got of the handle due to titling of the handle in 45^0angular impact. At 30ms the airbag got sufficiently inflated and came in between the hands of the dummy. At 40ms, the pelvis tried to leave the seat and right leg got lifted. At 50ms the dummy leant on the airbag and right leg left the foot rest. At 60ms motorcycle slid along the inclined wall and the dummy tried to get down from left side in between the motorcycle and wall. However, the head continued to move forward towards the wall with very less restraining from the airbag. At 67ms the head touched the wall.

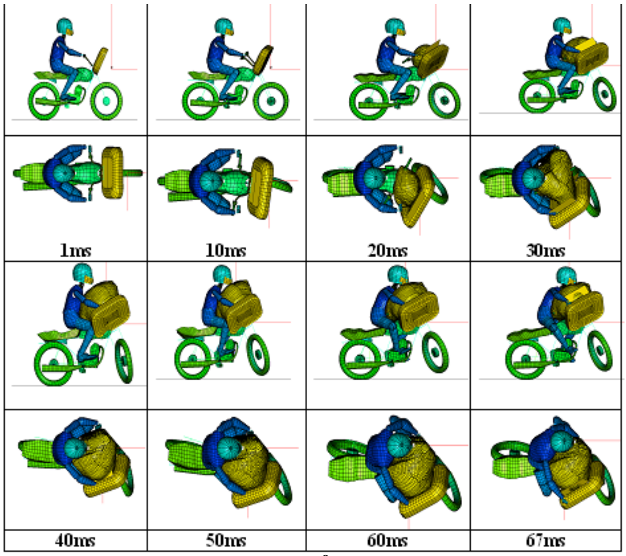


Figure 37 Angular impact-45^0: Alternate arrangement 3 - 110L airbag- Simulation states

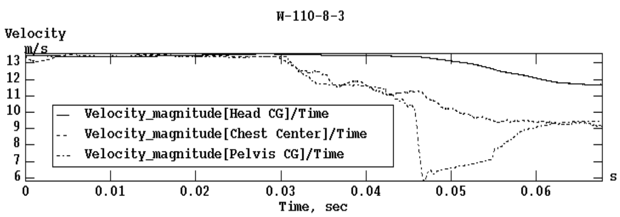


Figure 38 Angular impact-45^0: Alternate arrangement 3 - 110L airbag- Velocity Profiles

Figure 38 shows that the velocity of the head before its impact into the rigid wall was 11.8m/s. Thus, the reduction in kinetic Energy of the head was just 13.6%. The chest velocity was also not reduced much in this case. Thus, the smaller size of 110L airbag could not provide restraining in angular impact of 45^0 as observed in frontal impact.

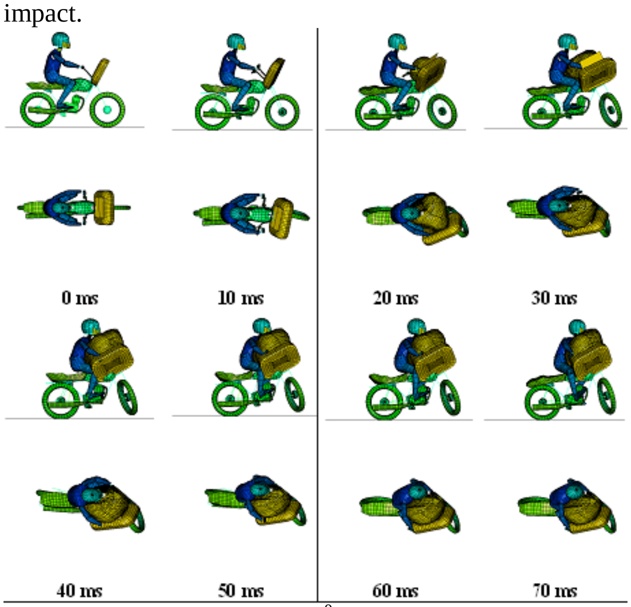


Figure 39 Angular impact-45^0: Alternate arrangement 3 - 142L airbag- Simulation states

Figure 39 shows that at 20ms the hand got off the handle. At 30ms the airbag got fairly inflated in between the hands of the dummy. At 40ms the airbag tried to provide restraining due to its larger size. At this time the right leg got lifted. The dummy continued to move forward. It touched the wall at 70ms.

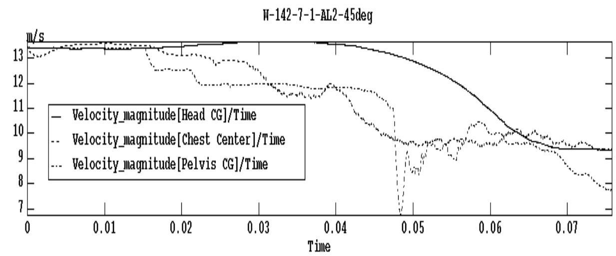


Figure 40 Angular impact-45^0: Alternate arrangement 3 - 142L airbag- Velocity profiles

As shown in Figure 40, the velocity of the Head CG just before impacting into the barrier was 9.2 m/s. Thus, the reduction in kinetic Energy of the Head CG was 32.69 %. This is better than that observed with the 110L size airbag.

Table 7
Percentage Reduction in kinetic Energy of Rider's Head in Barrier Test Simulations

Barrier Test Simulation	90^0 angle of impact			45^0 angle of impact		
Airbag Size	110L	142L	153L	110L	142L	153L
Initial Configuration	21.87	35.62	-	-	-	-
Alternate Arrangement 1	37.5	68.75	66.25	49.52	62.69	37.08
Alternate Arrangement 2 (Airbag axis towards neck/chin)	73	71.37	78.75	-	-	-
Alternate Arrangement 3 (Airbag axis towards chest)	87.62	**85**	53.75	13.6	**32.69**	-

Table 7 shows that in Alternate Arrangement 3 configuration the reduction in kinetic energy of the rider's head were 87.62% and 13.6% for 110L size airbag in 90^0 and 45^0 angles of impact respectively. This was the maximum reduction in kinetic energy of the rider's head that could be achieved. Due to smaller size it could not restrain the rider properly in angular impact. The airbag of 142L size could reduce kinetic energy of the rider's head by 85% and 32.6% in the frontal and angular impact simulations respectively as shown in Table 7. The large airbag of 153L size did not show positive results in the frontal impact barrier tests simulations. As shown in Table 7 it could reduce kinetic energy of the rider's head by 53.57%. Thus, the airbag of 142L size shows the promising results in mitigating the severe injuries or avoiding fatalities to the motorcycle rider in the frontal as well as angular impacts.

CONCLUSIONS

To evaluate the performance of the installed airbags into the Indian motorcycle, the barrier tests simulations of 90^0 and 45^0 angles of impact were run using PAM-CRASH™. The need of a backing surface in effectively restraining the rider by the airbag was investigated. It was found that the airbag module base can provide the required backing surface. The Alternate Arrangements of placement of the airbag module were investigated. It is concluded that the airbag of 142L size is most promising in reducing kinetic energy of the rider's head in 90^0 and 45^0 angles of impacts by 85% and 32.69% respectively, when placed at the top of the head light of the motorcycle and its axis of inflation directing towards the chest center. The broad research question of suitability of an airbag in Indian motorcycle can be answered in affirmative.

REFERENCES

[1]. Annual Report- 2004. Ministry of Transport and Highways, Govt. of India, Annual Report 2004.

[2]. Bhosale, P., 2008. "Modeling of MATD Neck using Reverse Engineering Technique" Paper No.66891, American Society of Mechanical Engineers' 2008 International Mechanical Engineering Congress and Exposition, Boston, USA, 30 October-5 November 2008.

[3]. Chawla A. Bhosale P., Mukherjee S., 2005. "Modeling of Folding of Passenger Side Airbag Mesh", Paper No. SAE 2005-26-059, SIAT and SAE Conference, Pune, India, 25-29 January 2005.

[4]. Finnis M. P., 1990. "Airbags and Motorcycles: Are They Compatible?", SAE 900744, 1990

[5]. Iijima, S, Hosono S, Ota A, Yamamoto T., 1998. "Exploratory Study of an Airbag Concept for a Large Touring Motorcycle" Paper No. 98-S10-O-14, Sixteenth International Technical Conference on the Enhanced Safety of Vehicles, Windsor, Canada, 1-4 June 1998.

[6]. International Standard ISO13232:2005 Motorcycles Test and Analysis Procedures for Research Evaluation of Rider Crash Protective Devices Fitted to Motorcycles.

[7]. Kuroe T., Iijima S., Namiki H., 2005. "Exploratory Study of an Airbag Concept for a Large Touring Motorcycle: Further Research Second Report", Paper Number 05-0316, 19th Enhanced Safety of Vehicles 2005.

[8]. Mukherjee S., Chawla A, Mohan D., Singh M, Sakurai M. and Nakatani T., 2002. "Motorcycle-Wall Crash: Simulation and Validation", PAM-CRASH™ Users Conference Assembly, China, 2002.

[9] Yamazaki T., Iijima S. and Yamamoto T., "Exploratory Study of an Airbag Concept for a Large Touring Motorcycle: further research" Paper No. 01-S9-O-240, Seventeenth International Technical Conference on the Enhanced Safety of Vehicles, Amsterdam, Netherlands, 4-7 June 2001.

APPENDIX 1: MATD Neck Dynamic Tests (2)

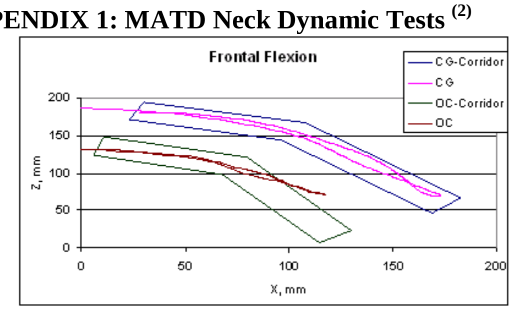


Figure 1-1 Frontal flexion Test- Trajectories of head CG and occipital condoyle

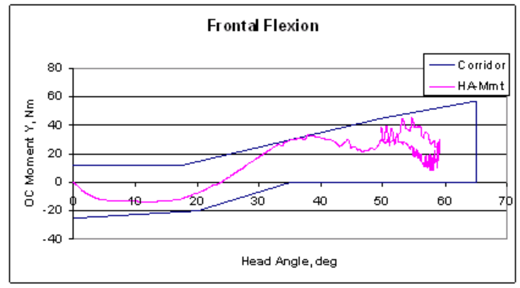


Figure 1-2 Frontal flexion Test- OC moment in Y-direction vs. Head angle

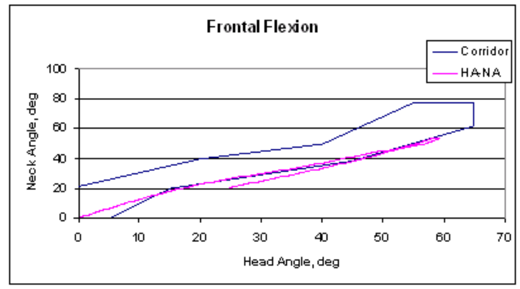


Figure 1-3 Frontal flexion Test- Head angle vs. Neck angle

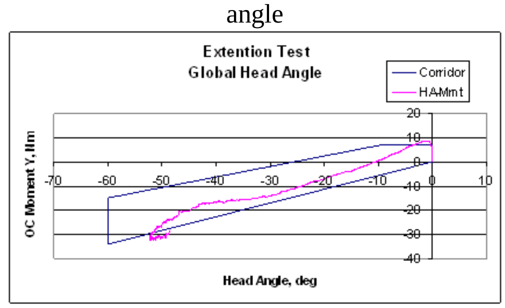


Figure 1-4 Frontal Extension Test: OC moment in Y-direction vs. Head angle

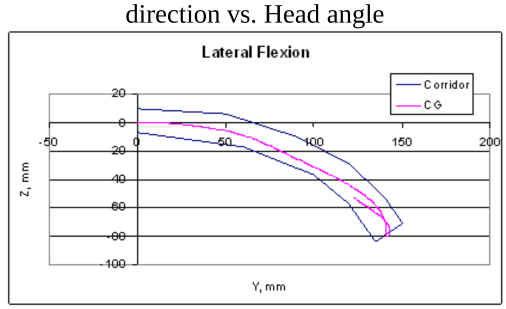


Figure 1-5 Lateral Flexion Test: Head CG Trajectory in Y-Z plane

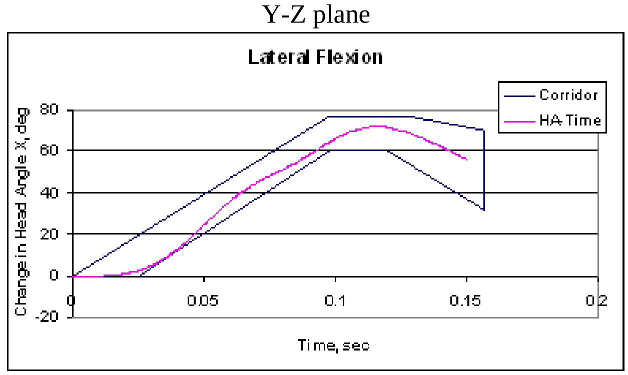


Figure 1-6 Lateral flexion Test: Time history of change of head angle

DISTRIBUTION AND TYPE OF DAMAGE TO CLOTHING WORN BY MOTORCYCLISTS: VALIDATION OF THE PRINCIPALS OF EN13595

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ABSTRACT

While the use of protective clothing has been shown to reduce the risk of injury for motorcycle riders, not all protective clothing performs the same in crashes. A European standard for motorcycle protective clothing (EN13595) was released in 2002. Riders that use clothing approved to this Standard should expect good protection. This standard specifies four zones in motorcycle clothing with different levels of protective qualities and four different test methods for assessing abrasion, burst, cut and tear damage resistance. High frequency impact areas are labelled zone 1 and include the elbows, knees, hips and shoulders. Zone 4 has the lowest expected frequency of impact.

This project examined damage location and type in clothing worn by riders following a crash to establish the distribution of impact points and validate the principals indicated in EN13595.

Data from 117 crashed motorcycle riders collected during crash investigation were examined. This data included medical data and clothing inspections, and contained 576 cases of clothing damage. To ensure the impact point distribution included all possible contact locations, an additional 433 distinct injury locations were examined where injury had occurred but no damage was observed or no clothing was present at that location. Descriptive techniques were used in the analysis.

The majority of damage occurred in areas covering the extremities or pelvic girdle (93%) with most occurring on the wrists and hands (18%) and the ankles and feet (18%). Clothing regions covering the shoulder (10%), forearm (10%), elbow (9%), thigh (7%), lower leg (6%) and pelvic-hip (5%) were also frequently damaged. Other body regions contributed only 8% of damage seen. Analysis of the injury where no damage occurred demonstrated a similar distribution of impact. The most common types of clothing damage were abrasion, accounting for 69% and torn material which accounted for 26% of all damage. Further, the majority of material abrasion and tearing occurred in regions corresponding to zone 1, followed by zone 2, 3 and then 4. There were very few instances (3%) of burst and cut damage.

The results are in agreement with the general concept of the zoning used in the European standard. However, these results indicate that minor adjustments may be warranted. In particular, the number of impacts to the forearm and lower leg suggest that these regions might be better protected by considering the whole regions as Zone 1or 2 rather than the multiple regions as currently indicated in the Standard. However the subjective nature of determining the zone in which damage (and/or injury) occurred limits these findings and any others that attempt to validate the zone principals using real world data. Further validation requires consideration of the severity of impact at different zones.

This work confirms the validity of the principals of EN13595 but indicates room for modification, and will be of interest to those developing regulatory and consumer assessment protocols for motorcycle protective clothing.

INTRODUCTION

Motorcyclists face a higher relative risk of serious injury than car occupants despite the fact that motorcycle usage only accounts for one per cent of vehicle kilometres travelled. These figures have been steadily increasing in recent years and may be linked to the increase in sales growth for motorcycles [1-4]. Motorcycle injuries as a result of a crash have been reported to cause a significant cost to the public health system [5].

The most common form of injury in motorcycle crashes has been shown to be skin abrasions, lacerations and contusions [6-8] and are primarily due to contact with the roadway or road side [6]. Additionally, it has been shown that the majority of injuries involve sliding, being dragged, tumbling or rolling to the final position. Protective clothing is suitable to provide protection for these types of movements [9].

The use of protective clothing to reduce soft tissue injuries for motorcycle riders has been the subject of scientific discussion at least since 1976, when Feldkamp and Junghanns [10] reported on protective clothing being associated with a reduction of serious injuries in motorcycle crashes. Since then, there has been increasing evidence of the benefits of protective clothing, particularly in low-impact (<50km/h) crashes [6, 7, 11-21], which are the most frequent type of motorcycle crash [6, 15, 22].

The European standard for motorcycle protective clothing (jackets, trousers and one piece or divided suits), EN13595 [23], was released in 2002 and established the broad technical requirements and performance criteria for motorcycle protective clothing.

The technical basis for EN13595 is largely work conducted by R.I. Woods. Woods examined the location and type of damage seen to 100 motorcycle suits following a crash [24] as well as observing the type of damage seen in samples of clothing on different road surfaces using dummy simulation of motorcyclists impacting the ground following a crash [25].

Four different zones with different levels of protective capabilities were created based on the distribution of damage observed to the damaged motorcycle suits. Zone 1 has the highest expected frequency of impact and hence these areas require impact protectors. Zone 1 regions include the knees, elbows, shoulders and hips. Zone 4 has the lowest frequency of impact and the material in these regions can be used to provide ventilation. The different types of damage to the clothing were observed to be abrasion, cut, tear and burst damage. Based on these results, machines were developed to recreate these types of damage in a laboratory environment [26]. The performance criteria for burst, cut, tear and abrasion resistance were developed from these laboratory studies.

Despite the limited review of real world data and the non-biofidelic dummy simulations conducted by Woods, this work was used to design the test methods and performance criteria included in the European Standard. This project examines the distribution of impact locations to motorcyclists from a sample of real world motorcycle crashes. It compares this impact distribution, and the types of damage seen in their clothing, to the principles incorporated in EN13595.

METHODS

The Gear study [7] involved a 12 month prospective cohort of motorcycle crashes on public roads within the Australian Capital Territory (ACT) and was conducted from June 2008. Eligible participants were residents of the study area, aged 17-70 years who had sustained an injury or required repair of damage to their motorcycle following a crash. Motorcyclists were excluded if they scored <13 on the Glasgow Coma Scale (GCS), sustained severe head (3+) or spinal injuries (4+) on the Abbreviated Injury Scale (AIS), or were otherwise unable to provide informed consent [27, 28]. The 117 cases examined for this analysis included only the cases from the GEAR study in which the participant had been injured and medical records were available.

Potential participants were identified through the two hospitals servicing the study area and participants were interviewed face-face approximately two weeks after their crash. The interview format was based on the OECD methodology for motorcycle crash investigation [29] and information collected included the self-reported type and speed of impact, clothing worn and injury details. The damage and injury details, including location, type of damage and dimensions, were recorded on body outline diagram by the interviewer. The medical records of participants who attended hospital were used to corroborate interview reports on injuries and admissions details. Where possible, photographs were taken of the clothing worn by participants during the crash and compared to interview reports.

From this data, the type of clothing and impact protection worn by the motorcyclists was analysed. Clothing type was classified by whether it was specifically designed for motorcycle use, not designed for motorcycle use or not present at all. Clothing items which were specified as a jacket not designed for motorcycle use included any type of upper garment (e.g. jackets, jumpers and shirts) and was classified by degree of coverage (long or short sleeves). Pants specified as not designed for motorcycle use were classified as long, short or calf length pants. Gloves were classified into whether they covered the wrists or didn't cover the wrists. Information was additionally collected on whether gloves and footwear remained on the riders' hands and feet during the crash. Information was recorded on whether impact protection was worn by the riders on the shoulders, back, elbows, hips and knees; whether this impact protection worn was certified to the European Standard for impact protectors; and whether the impact protector remained in the appropriate position during the crash. The type of clothing material was also analysed and was classified into nine groups: light-weight material (e.g. shirt/t-shirt); waterproof material; medium weight (e.g. denim, cotton knit); abrasion resistant fabric (e.g. Cordura, Kevlar reinforced); leather; a combination of leather and abrasion resistant fabrics; unknown; none; and other.

Areas of damage to each riders clothing were recorded and analysed. Areas of injury resulting from an impact to the body where clothing was either not present or not damaged were also recorded and analysed to ensure all areas of impact were included. Fractures, sprains, dislocations and avulsions were not included as they are not necessarily representative of the exact location of impact. Skin injuries were classified as abrasions, lacerations, contusions and burns.

Injury details were coded using the National Sampling System (NASS) Occupant Injury Classification (OIC) scheme [30]. The OIC categorizes injury by body region using both the Injury Severity Score (ISS) and OIC regions, and by the aspect of injury, type of injury, Abbreviated Injury Scale (AIS) severity of the injury, organ or system injured, injury source and source of data.

A similar coding method was developed for the purposes of classifying the clothing damage location and type of damage. This included relating the damage location to OIC and ISS body regions, aspect of damage, type of damage (abrasion, burst, cut or tear), depth of damage, clothing system damaged, source of damage and source of information. The type of damage seen to the different clothing items was also analysed.

Impact locations were classified in terms of their relation to the clothing zones as specified by the European Standard. Impact locations were only included if they occurred to the clothing, not to the footwear or gloves and if they had sufficient positional information to classify into a zone.

Descriptive analysis was used to determine the distribution of impact locations with respect to the ISS body regions, OIC body regions and clothing zones. Additionally, descriptive techniques were used to determine the major forms of clothing damage observed and the main forms of skin injury at distinct injury locations. Analysis was conducted using IBM SPSS Statistics 20 [31].

Ethical approval for the Gear study was obtained from the Human Research Ethics Committees (HREC) for ACT Health and Calvary Health Care.

RESULTS

Table 1 summarises the type of clothing worn by the 117 crashed motorcycle riders.

The results indicated that the majority of riders wore jackets which were designed for motorcycle use (76%) as well as gloves designed for motorcycle use (80%). Riders were not as likely to be wearing pants designed for motorcycle use (27%) or footwear designed for motorcycle use (31%).

The majority of the clothing worn was not approved to the EN13595 standard. None of the pants or jackets worn by the motorcyclists were approved to this standard. However, 3% of footwear and 2% of gloves were CE certified.

A majority of riders wore long sleeved upper garments (90%), long pants (96%) and gloves which covered the wrists (66%) while only 20% of gloves worn by riders did not cover the wrists.

Table 2 presents information on the amount and type of impact protection worn by the riders. More than half of the jackets contained impact protection at the shoulders (63%), back (55%) and elbows (62%). Only a minority of the pants contained impact protectors at the hips (9%) and the knees (11%).

Almost half of the shoulder impact protectors (48%) and elbow impact protectors (47%), and almost two thirds of the knee impact protectors (62%) were approved to the European Standard for impact protectors. However, less than 10% of back impact protectors (6%) and hip impact protectors (9%) were approved to the Standard.

The majority of impact protectors were reported by the riders to have remained in place during the crash: shoulders (77%), back (75%), elbows (81%), hips (64%) and knees (77%).

Table 3 illustrates the types and frequency of materials observed in the clothing worn by the 117 motorcycle riders. Abrasion resistant fabric jackets (54%) were more popular than leather jackets (23%) and 15% of motorcyclists wore upper garments made from other light-weight materials. The majority of pants were manufactured from medium weight materials (54%) followed by abrasion resistant fabrics (21%). Most of the footwear (82%) and the gloves (55%) were made from leather.

Table1.
Clothing worn by motorcycle riders during the crash (sample size is n=117 for each clothing type).

	Designed for motorcycle use (%)			CE approved (%)			Length (%)				Remained on (%)		
	yes	no	none	yes	no	unknown	short	calf	long	unknown	yes	no	unknown
jacket	76	24	0	0	92	8	9	n/a	91	0	n/a	n/a	n/a
pants	27	74	0	0	96	4	3	2	96	0	n/a	n/a	n/a
footwear	31	69	0	3	90	7	n/a	n/a	n/a	n/a	87	11	2
gloves	80	10	9	2	80	9	20	n/a	66	5	83	0	8

Table2.
Impact protection worn by motorcycle riders during the crash.
Note: The first column displays the percentage of clothing in which impact protectors were present. Of the impact protectors which were present, the second column displays the percentage of impact protector types worn, and the third column describes whether these protectors remained in position.

	Present (%) n=117			Type (%)				Position remained (%)		
	yes	no	unknown	CE certified	comfort	other	unknown	yes	no	unknown
shoulders	62	37	1	48	21	29	4	77	16	8
back	55	45	0	6	66	23	5	75	3	22
elbows	62	38	0	47	21	28	6	81	11	8
hips	9	91	0	9	55	27	9	64	9	27
knees	11	89	0	62	23	8	8	77	15	8

Table3.
Types of material worn (sample size is n=117 for each clothing type).

Material	Jacket n=117	Pants n=117	Footwear n=117	Gloves n=117	Total
light-weight material (e.g. shirt/t-shirt)	18	19	1	0	38
waterproof only	1	2	0	0	3
medium weight (e.g. denim, cotton knit)	7	63	5	6	81
abrasion resistant fabric (e.g. Cordura, Kevlar reinforced)	63	25	4	6	98
leather	27	6	96	64	193
combination of leather and abrasion resistant fabrics	0	1	9	21	31
unknown	1	1	2	8	12
none	0	0	0	11	11
other	0	0	0	1	1

Table4.
Type of clothing worn at the location of the clothing damage and skin injury

Designed for motorcycle use	Damage (%) n=576	Skin injury (%) n=433
yes	63	37
no	37	54
none	n/a	9
unknown	0.2	0.2

Among the 117 crashed motorcycle riders there were 576 distinct areas of clothing damage and an additional 433 areas of distinct skin injury (see Table 4). This is an average of four skin injuries and five clothing damage locations per rider with a range of 0-22 for both skin injury and clothing damage locations.

Most of the clothing damage (63%) was observed in clothing that had been designed for motorcycle use. Most of the skin injuries observed, where no clothing damage was present, were to body regions where the rider wore clothing not designed for motorcycle use (54%). Only a small amount of skin injuries actually occurred where no clothing was present at the site of the injury (9%).

The distribution of impact locations with respect to the ISS body regions is shown in Figure 1. Clothing damage occurred most frequently on the extremities and pelvic girdle (93%), with only a small amount of clothing damage seen to the abdominal or pelvic contents (4%), the chest (3%) and the head or neck (0.2%).

Investigation into the predominant impact locations (including both clothing damage and skin injury) in terms of the ISS body regions showed a similar distribution to that of just clothing damage. Most impacts still occurred to the extremities or pelvic girdle (90%), followed by the abdominal or pelvic contents (5%) and the chest (4%).

Figure 2 presents the distribution of impact locations according to the OIC body region in which the impact occurred. Wrists and hands (18%) and the ankles and feet (18%) contributed the most to the total amount of clothing damage observed. Clothing regions covering the shoulders (10%), the forearms (10%), the knees (10%) and the elbows (8%) were also damaged frequently. Other regions which had a large number of impacts were the thighs (7%), the lower legs (6%) and the pelvic-hip (5%). Clothing damage covering other body regions contributed only 8% of the total damage observed.

The distribution of all impact locations, including both skin injury and clothing damage locations, was similar to that of just clothing damage locations (see Figure 2). Most of the impacts occurred to the wrists and hands (17%), followed by the ankles and feet (13%) and the knees (12%). Other body regions contributing to the total number of impacts observed were the thighs (9%), the shoulders (8%), the lower legs (8%), the forearms (8%), the pelvic-hip (7%) and the elbows (6%). Impacts in other body regions only contributed 14% to the number of impacts observed.

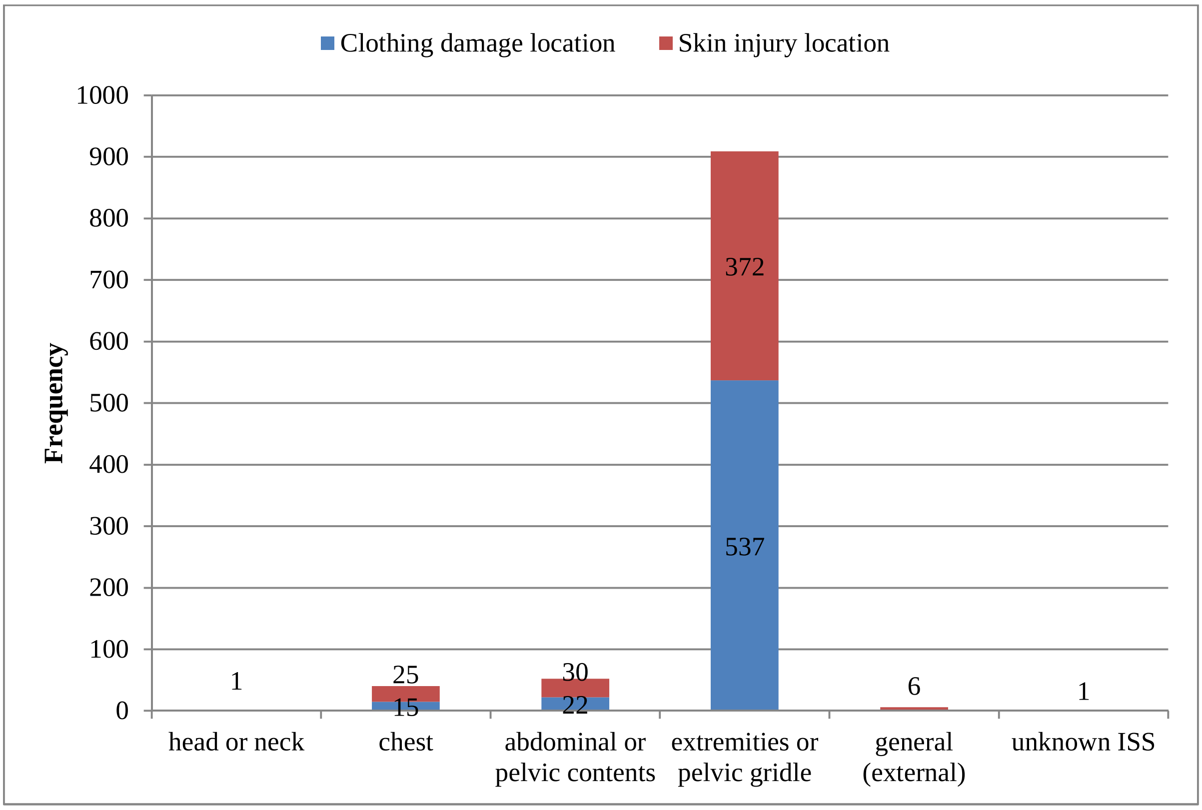

Figure1. ISS body region of all impact locations.

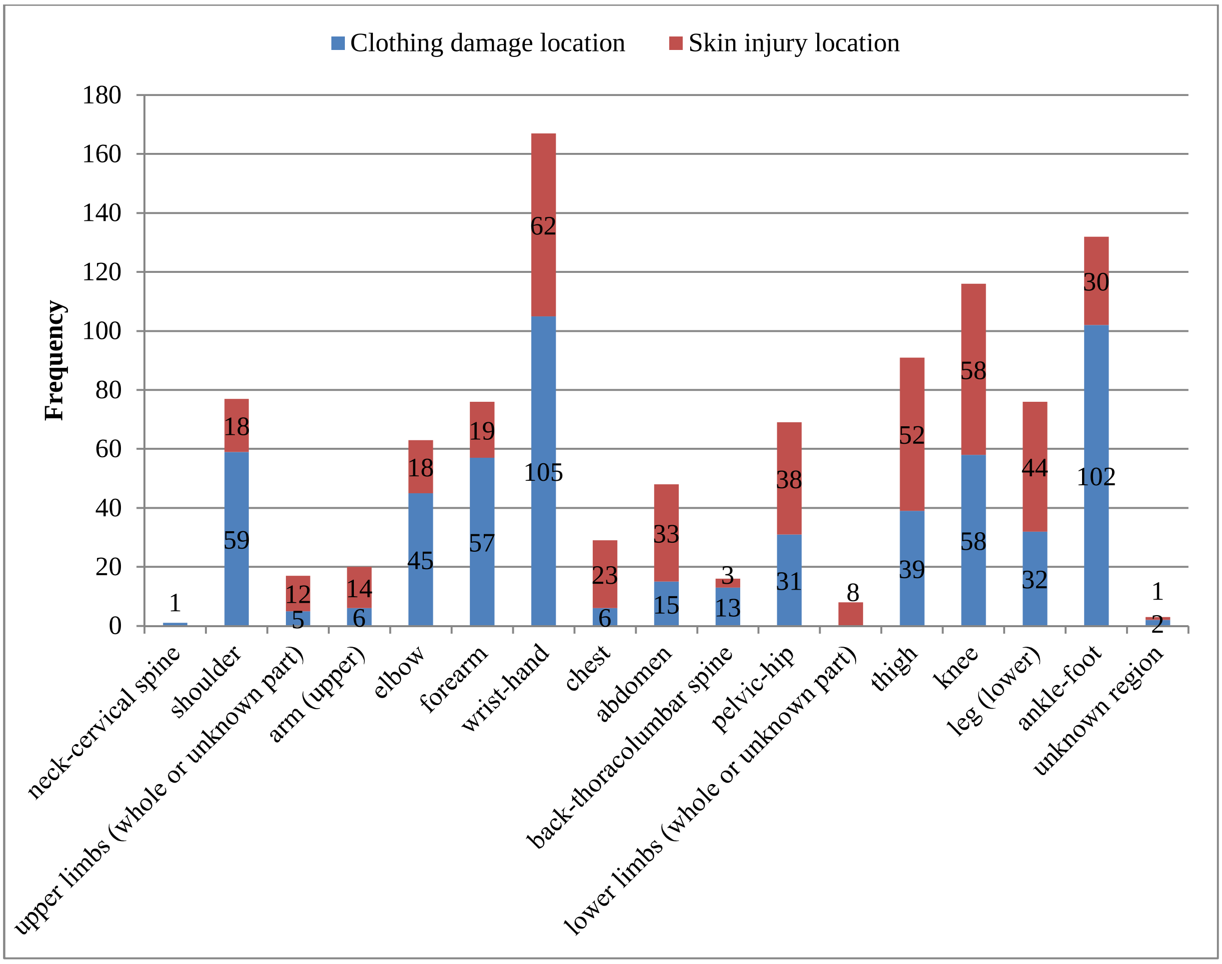

Figure2. OIC body region for all impact points.

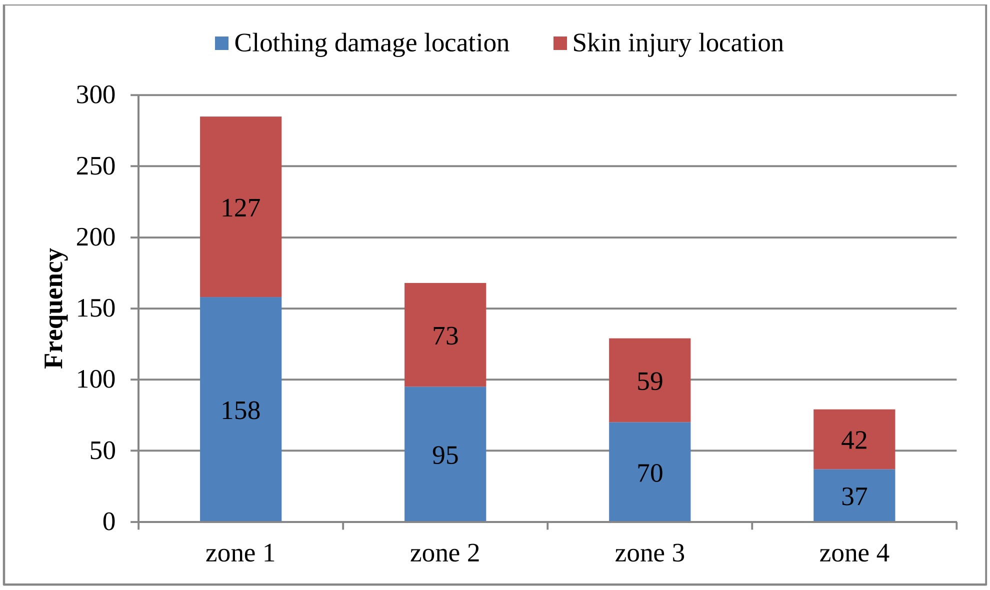

Figure3. Frequency of impacts to the different clothing zones

Figure 3 presents the frequency of impacts to each of the four different clothing zones. There were 661 cases of impact locations (360 clothing damage locations; 301 skin injury locations) which were investigated for the zone location. Impacts occurred mostly to zone 1clothing regions (43%), followed by zone 2 (25%), zone 3(20%) and zone 4 clothing regions (12%).

The distribution of the impact locations with respect to both the OIC body locations and the clothing zones was examined. This impact distribution is shown in Figure 4.

A large number of the forearm impact locations (36) occurred in zone 3 and 30 impacts occurred in zone 2. Most of the impacts to the thigh occurred in zone 2 (64) with a reasonable amount occurring to zone 3 (13) and zone 4 (14). The lower leg impacts occurred mostly to zone 1 (29) and zone 2 (17). There were seven impacts to both the front and the back of the lower leg in zone 4, one impact to the ankle and four impacts behind the knee. Zone 3 of the upper arm also had a large number of impacts with 10 impacts on the front and 6 impacts on the back of the upper arm. The chest and abdomen both had a large number of impacts with 17 impacts occurring in both body regions.

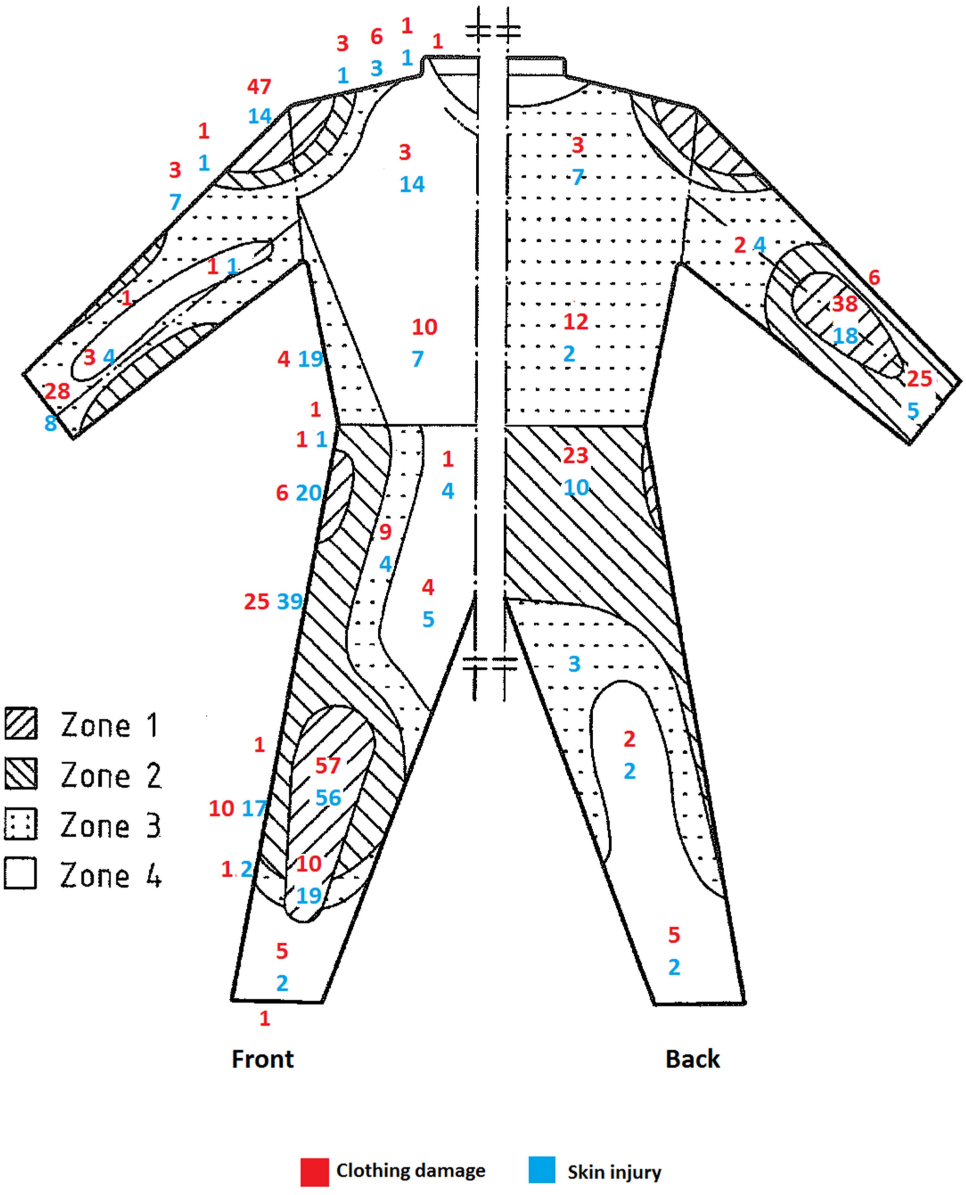

Figure4. Distribution of damage with respect to zones as specified in EN13595.

Clothing damage was classified as one of the four different types of damage specified in the European Standard. These types of damage were: abrasion/erosion of the material, burst-failure of the seams or fastenings, penetration or cutting by a sharp object and torn material.

Figure 5 presents the frequency of the different types of damage which occurred to the clothing. The most common types of damage observed were abrasion, accounting for 69% of the total amount of damage observed, and torn material which accounted for 26% of the total damage. There was little evidence of cut or burst damage to the clothing which accounted for only 3% of the total damage observed.

The frequency of the different types of damage in each of the four clothing zones is presented in Figure 6. The majority of abrasion and tear damage was seen in clothing region zone 1 followed by zones 2, 3 and 4. This was not the case for burst and cut damage, which was more randomly distributed. However, there were not enough cases of burst and cut damage to obtain a clear pattern of which clothing zones these types of damage were occurring in.

The type of damage seen to different items of clothing which were CE marked clothing as compared to clothing items which were not approved to the European Standard is shown in Table 5. There were seven cases of damage to clothing which were CE marked. All seven points of damage were abrasion damage occurring to the footwear and gloves as footwear and gloves were the only CE marked clothing worn. Majority of abrasion occurred to upper garments (36%), followed by pants (25%), gloves (20%) and footwear (19%). Torn material occurred frequently to both pants and jackets. Upper garments were damaged the most (36%), followed by pants (28%). Footwear (18%) and gloves (18%) were damaged less frequently.

There was no CE marked jackets or pants worn. Of the 208 cases of damage seen to jackets, 70% was abrasion damage, and 27% was tear damage. There were 162 cases of damage to the pants, with 61% being abrasion damage and 36% being tear damage.

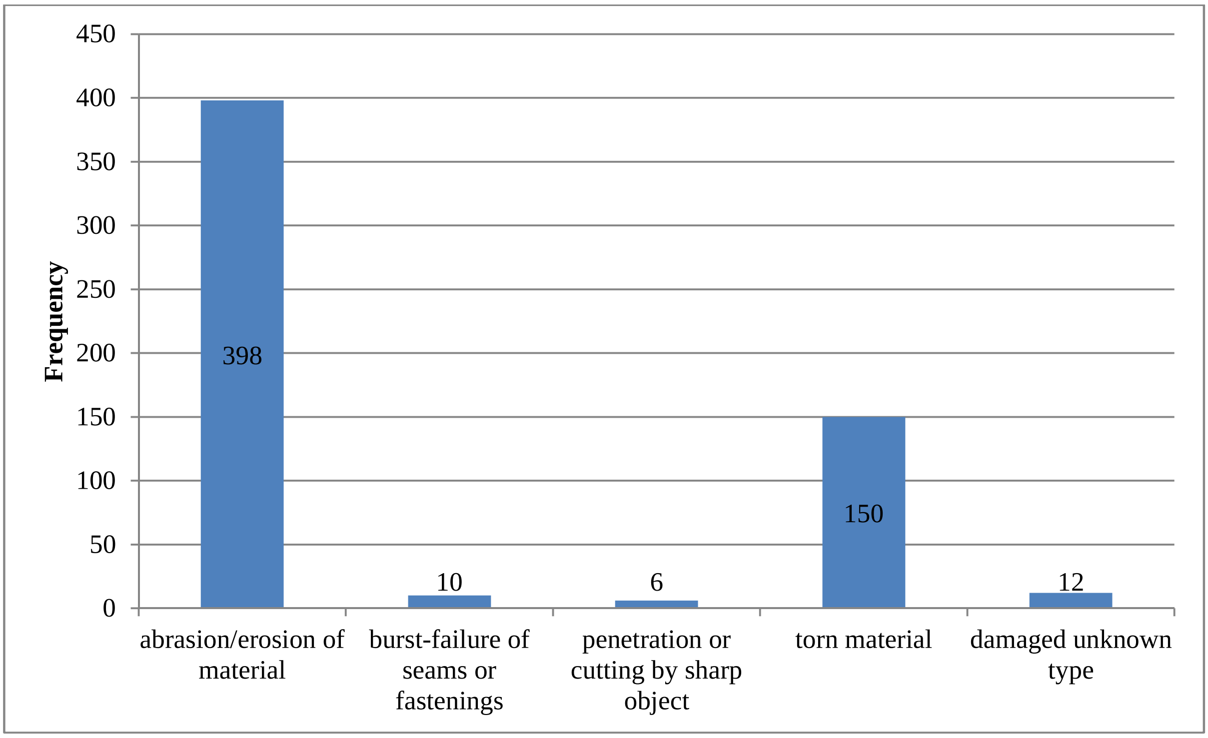

Figure5. Type of damage seen to the clothing

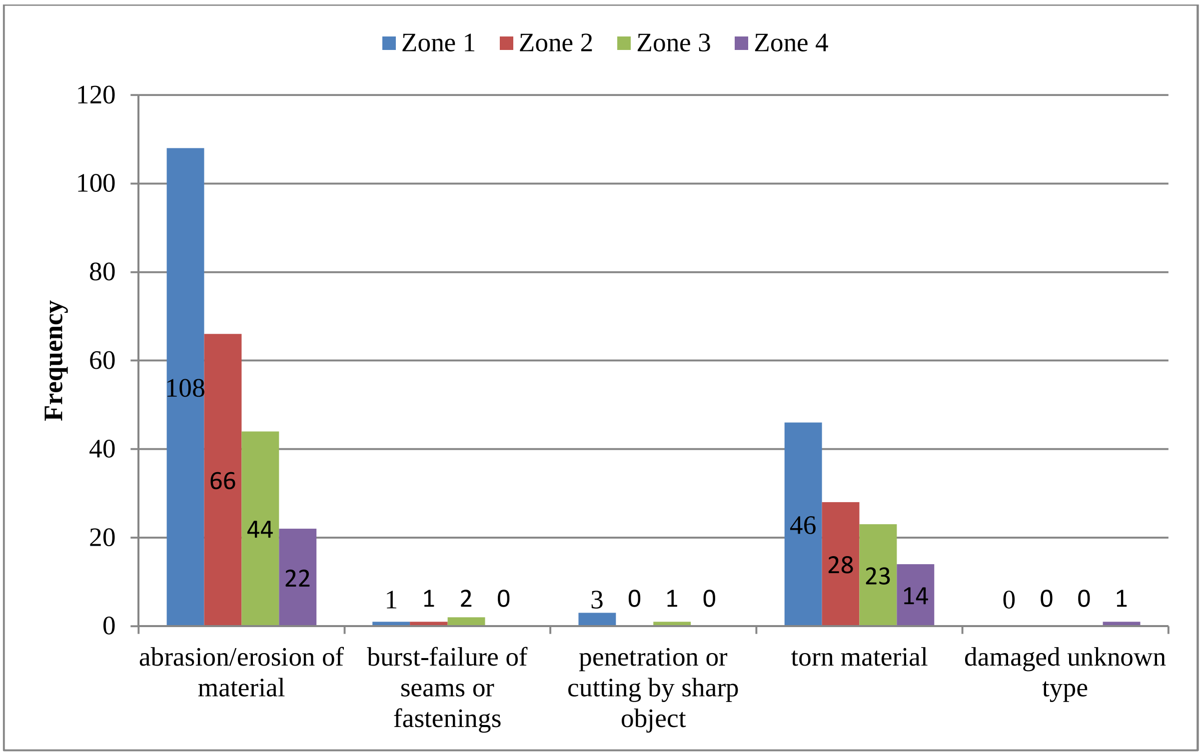

Figure6. Distribution of the different types of damage for the different clothing zones.

Table5.
Distribution of the different types of clothing damage seen to CE approved clothing.

		Clothing type (%) (total number of damage n=576)			
CE marked	**Damage type**	**jacket**	**pants**	**footwear**	**gloves**
yes	abrasion	0	0	1	0.3
	burst	0	0	0	0
	cut	0	0	0	0
	tear	0	0	0	0
	unknown	0	0	0	0
no	abrasion	23	17	11	13
	burst	1	0.2	1	1
	cut	0.2	1	0.3	0
	tear	10	10	3	3
	unknown	0.3	0.2	1	1
unknown	abrasion	2	0.2	1	1
	burst	0	0	0	0
	cut	0	0	0	0
	tear	0.2	0	0.2	0.2
	unknown	0	0	0.2	0
total		36	28	18	18

The frequency of the different types of skin injury occurring to the motorcyclists is shown in Figure 7. The most frequent injury type was contusions (54%) followed by abrasions (31%), lacerations (14%) and burns (1%).

The frequency of the different types of skin injury occurring in the four different clothing zones is displayed in Figure 8. The majority of laceration, contusion and abrasion injury was to zone 1 followed by zones 2, 3 and 4. Burn injuries did not follow this pattern.

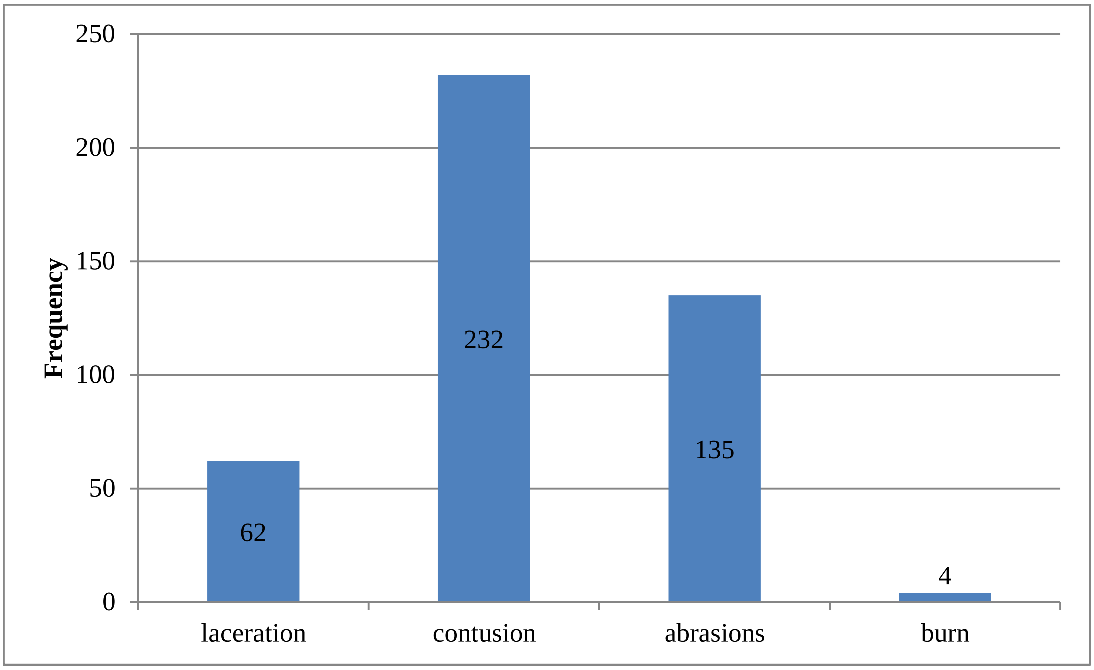

Figure7. Types of skin injuries occurring to motorcyclists.

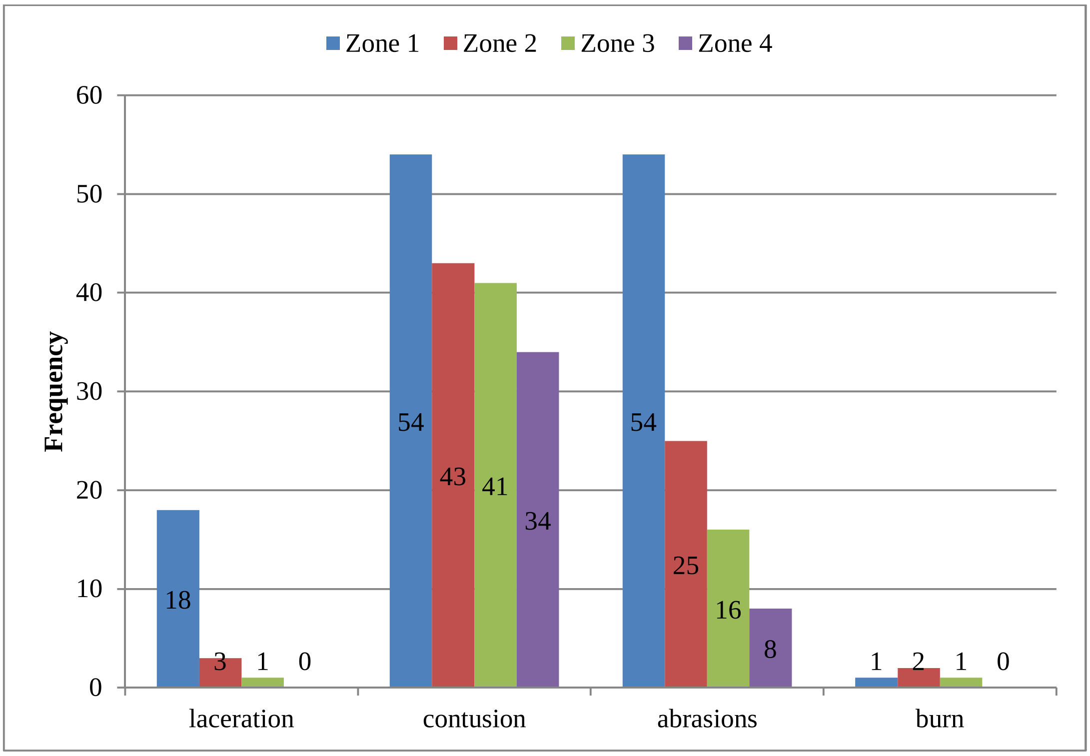

Figure8. Distribution of skin injury to the four clothing zones.

DISCUSSION AND LIMITATIONS

This study has provided a detailed examination of the distribution of impact locations to motorcycle riders during a crash as well as investigating the type of damage observed to the motorcycle clothing. The impact distribution to motorcycle riders and type of damage to motorcycle clothing during a crash have not been investigated since the study by Woods in 1996 from which the standards were developed [24].

Preliminary categorization of impact locations indicated that the results from this study were consistent with the European standard, with the majority of impacts occurring in zone 1 regions, and the least in zone 4. Abrasion and burst damage as well as contusions, abrasions and laceration injuries also followed this pattern. Burn injuries, cut damage and burst damage did not follow this pattern; however, the lack of an apparent pattern may be due to the small number of cases where this type of damage occurred.

Categorization of the impact locations into the OIC body regions demonstrated that the impact distribution differed slightly to that predicted by the principles of the European Standard. Body regions such as the forearms, lower leg and thigh suffered a large number of impacts. These regions are not zone 1 regions according to the European Standard; however, they experienced a similar number of impacts then some Zone 1regions.

The distribution diagram was used to observe which zone the impacts were occurring in for each body region. Impacts to the thigh occurred mostly to the zone 2 clothing region covering the thigh which already intends to protect riders from a high-risk of impact. However, 13 impacts still occurred to zone 3 covering the front of the thigh. This zone only protects a small body surface area and therefore this is a large number of impacts for the size of the area. Zone 2 could be extended to cover this area, eliminating the zone 3 region at this location.

The majority of impacts to the forearm occurred in zone 3, located at the anterior of the forearm. A large number of impacts were also seen to zone 3 upper arm, with 10 impacts to the anterior and six to the posterior of the upper arm in zone 3. Zone 2 could also be extended here to so that there would be no zone 3 region in the arm.

A large number of the impacts occurred to zone 4 of the lower leg with 8 impacts to the anterior and 7 impacts to the posterior of the lower leg. However, if appropriate motorcycle footwear was worn, this region of the lower leg would be covered by an additional layer of protection and no changes may need to be made to this area of the clothing.

The chest and abdomen experienced a larger number of impacts than the upper and lower back. The chest and abdomen are zone 4 regions, while the upper and lower back are zone 3 regions. It may therefore be justified to change the chest from a zone 4 to a zone 3 region.

These changes would greatly simplify the template for motorcycle clothing. However, it potentially decreases the number of zone 3 and 4 regions which may reduce the ability of manufacturers to provide ventilation and comfort in motorcycle clothing. This might have an overall detrimental effect as it could reduce the likelihood of motorcyclists wearing protective clothing in hot weather. Advances in materials technology might be able to address this issue by providing materials with high resistance to impact damage while still proving enough ventilation for rider comfort.

This study also investigated the different types of clothing damage seen to motorcycle suits following a crash. The most common forms of clothing damage were abrasion and tear damage, with little evidence of burst and cut damage. This suggests that tests for abrasion and tear resistance could be given a higher priority than burst or cut tests. It also indicates a need for research into abrasion and tear resistant materials and better understanding of which material properties effect abrasion and tear resistance.

Only a small amount of burst damage to the seams of clothing was observed in this study. Performance and manufacturing production methods of seams appear to have improved substantially over the years, as initially burst failure of clothing seams was the most common cause of garment failure [32].

Standards approved clothing is required to have multiple layers of stitching, including a layer which must be protected within the seams. None of the standard approved clothing in this study displayed any evidence of burst damage to the seams, and hence this multiple layer of stitching may be adequate to protect from burst damage. However, the sample of standards approved clothing in this study was small, so further examination of the performance of approved clothing in the real world is necessary.

An attempt was made to look at the effect of different road surfaces on the different types of clothing and the clothing abrasion sustained. However, the limited sample size of participants who crashed on unsealed roads (3/117) made any statistical analysis void. Additionally, road surfaces were only classified in terms of whether they were sealed or unsealed. Analysis of the effect of the road surface on the amount and severity of abrasion occurring would benefit from further characterisation of the road surfaces in terms of its roughness or coefficient of friction.

The absolute number of clothing items certified to the Standard observed in this study was very low. It was therefore impossible to draw any conclusions about the performance of standards approved clothing versus clothing that was not approved to the Standard. It was also not possible to determine the level of performance of non-standards approved clothing i.e. whether or not it may have passed the Standard's tests. It was therefore not possible to investigate in this study whether the damage resistance requirements specified in the European Standard are appropriate or whether adjustments should be made. However it is worth noting that clothing designed for motorcycle use, regardless of certification or not, appeared to be effective in preventing skin injury as most skin injuries to protected skin occurred when the clothing was not specifically designed for motorcycle use. While earlier studies primarily looked at leather clothing, these findings support reports of the protective effect of motorcycle clothing even though most of the clothing in this study was made from other fabrics [6, 7, 21]. Moreover, clothing damage was seen predominantly among clothing designed for motorcycle use whereas skin injury without overlying clothing damage occurred mostly among clothing not designed for motorcycle use. This further indicates the protective effect of the specifically designed clothing.

A limitation to these results is the subjective nature of determining the exact location of where damage and injury locations occurred related to standardized clothing and body diagrams defining the zones used in the Standard. The accuracy of the distribution of impact locations by zones may have been affected by this subjectivity. Currently, there is no other method for determining accurate locations of clothing damage. Further work will investigate potential methods for increasing the accuracy such as using computer modelling from photographs taken of the clothing, or creating a grid over the clothing such as that commonly used in studying the distribution of impacts on helmets. This analysis did not examine the severity of the abrasion and tear resistance and what injuries occurred as a result of the different impacts and different damage types. Future research will aim to examine the link between different damage types and resulting injuries as well as how the severity of damage affects the injury outcome. Further research will also focus on whether current materials offer suitable abrasion and tear resistance and which material types offer the best protection.

CONCLUSION

This study provides a confirmation of the general principles of the European Standard for motorcycle protective clothing. However, some minor changes to the zones may still be of benefit to the protective effect of motorcycle clothing. The results also indicate that more research into material abrasion may be required as this is the most common form of damage seen to motorcycle clothing.

These findings have implications for regulatory and consumer assessment protocols for motorcycle protective clothing and are useful for the development of these protocols.

REFERENCES

1. WHO, *World Report on Road Traffic Injury Prevention*, M. Peden, et al., Editors. 2004, World Health Organisation: Geneva.
2. ATC, *National Road Safety Action Plan 2009 and 2010*, 2008, Australian Transport Coucil.
3. ATC, *National Road Safety Strategy 2011-2020*, 2011, Australian Transport Coucil.
4. AIHW, *Trends in serious injury due to land transport accidents, Australia 2000-01 to 2007-08*, in *Injury Research Statistics Series: No. 56*2011, Australian Institute of Health and Welfare: Canberra.
5. BITRE, *Road crash costs in Australia 2006, Report 118*, 2009, Bureau of Infrastructure, Transport and Regional Economics: Canberra.
6. ACEM, *MAIDS in-depth investigation of accidents involving powered two wheelers: Final report 1.2*, 2004, Association of European Motorcycle Manufacturers.
7. de Rome, L., et al., *Motorcycle protective clothing: protection from injury or just the weather?* Accid Anal Prev, 2011. **43**(6): p. 1893-900.
8. Cawich, S.O., et al., *Strategies for secondary prevention of motorcycle road traffic accident injuries: Time for policy re-evaluation in Jamaica.* The Internet Journal of Emergency and Intensive Care Medicine, 2010. **12**(1).
9. Baldock, M.R.J., J.A.L. Grigo, and S.J. Raftery, *Protective clothing and motorcyclists in South Australia*, 2011, Centre for Automotive Safety Rseaecrg (CASR): Adelaide, Australia.
10. Feldkamp, G. and K. Junghanns. *The typical traffic accident in adolescents: The motorcycle accident- some epidemiologic features and the effectiveness of safety helmets and clothing*. in *IRCOBI*. 1976. Amsterdam.
11. Hell, W. and G. Lob. *Typical injury patterns of motorcyclists in different crash types-effectiveness and improvements of countermeasures*. in *Proceedings of the 37th Annual Conference of the American Association for the Advancement of Automotive Medicine. AAAM*. 1993. San Antonio.
12. Engström, A., *Causes and consequences of moped and motor-cycle accidents. A prospective and retrospective study of*

clinical series. Scandinavian Journal of Social Medicine, Supplement, 1980. **15**: p. 1-88.
13. Hurt, H.H., J.V. Ouellet, and D.R. Thom, *Motorcycle accident cause factors and identification of countermeasures. University of Southern California Traffic Safety Centre Technical Report*, 1981, National Highway Traffic Safety Administration: Washington, DC.
14. Hurt, H.H., J.V. Ouellet, and I.J. Wagar. *Effectiveness of motorcycle safety helmets and protective clothing*. in *Proceedings of the 25th Annual Conference of the American Associaion for the Advancement of Automotive Medicine. AAAM*. 1981. San Francisco.
15. Aldman, B., et al. *The protective effect of different kinds of protective clothing worn by motorcyclists*. in *Proceeding of the 6th International Conference of the Research Council on the Biomechanics of Impact. IRCOBI*. 1981. Salon-de-Provence, France.
16. Kalbe, P., E.G. Suren, and D. Otte. *Trauma assessment of injuries and their consequences in accidents with two-wheelers*. in *Proceedings of the 6th International Conference of the Research Council on the Biomechanics of Impact. IRCOBI*. 1981. Salon de Provence, France.
17. Schuller, E., G. Beier, and W. Spann. *EFFECTIVENESS OF PROTECTIVE CLOTHING IN MUNICH AREA MOTORCYCLE ACCIDENTS*. 1982.
18. Danner, M., et al., *Protective clothing for riders*, in *Buro fur KFZ*1984, Federal Highway Research Institute: Bergish, Gladbach.
19. Schuller, E., G. Beier, and W. Spann. *DISABILITY AND IMPAIRMENT OF PROTECTED AND UNPROTECTED MOTORCYCLE RIDERS*. 1986.
20. Otte, D. and V. Middlehauve. *Quantification of protective effects of special synthetic protectors in clothing for motorcyclists*. in *Proceeding of the International Conference of the Research Coucil on the Biomechanics of Impact. IRCOBI*. 1987. Birmingham, UK.
21. Otte, D., G. Schroeder, and M. Richter, *Possibilities for load reductions using garment leg protectors for motorcyclists -- a technical, medical and biomechanical approach.* Annual proceedings / Association for the Advancement of Automotive Medicine. Association for the Advancement of Automotive Medicine, 2002. **46**: p. 367-385.
22. MCC, *Positioned for safety 2010: A motorcycle safety strategic plan 2007-2010*, 2010, Motorcycle Council of NSW.
23. NSAI, *EN 13595-1:2002 Protective clothing for professional motorcycle riders- jackets, trousers and one piece or divided suits- Part 1: General requirements*, 2002, National Standards Authority of Ireland: Dublin, Ireland.
24. Woods, R.I., *Specification of motorcyclists' protective clothing designed to reduce road surface impact injuries*, in *Performance of Protective Clothing: Fifth Volume ASTM STP 1237*, J. Johnson and S.Z. Mansdorf, Editors. 1996, American Society for Testing Materials: Philadelphia. p. 3-22.
25. Woods, R.I. and D.M. Prime, *Tests on the protection afforded by various fabrics and leathers in a simulated impact of a motocyclist on a road surface*, in *IRCOBI*1984: Bron, France.
26. Woods, R.I., *Testing of protective clothing for motorcyclists: validation of laboratory tests by accident studies*, in *Performance of Protective Clothing: Fifth Volume ASTM STP 1237*, J. Johnson and S.Z. Mansdorf, Editors. 1996, American Society for Testing and Materials: Philadelphia. p. 43-56.
27. AAAM, *Abreviated Injury Scale*, T.A. Genanarelli and E. Wodsin, Editors. 2005, Association for the Advancement of Automotive Medicine: Barrington, IL, USA.
28. Teasdale, G. and B. Jennett, *Assessment of coma and impaired consciousness: a practical scale.* Lancet 1974. **2**(42): p. 81-84.
29. OECD, *Motorcycles: common international methodology for on-scene, indepth accident investigation*. Development, O.F.E.C.A., ed. T.E.G.o.t.C.G.f.M.A. Investigations2001, Paris: Road Transport Research Program of the Directorate for Science, Technology and Industry, OECD.
30. Transportation, U.S.D.o., *National Accident Sampling System (NASS)*, N.H.S. Administration and N.C.f.S.a. Analysis, Editors. 1981, U.S. Department of Transportation: Washington, D.C.
31. IBM, *SPSS Statistics 20*, 2011: United States.
32. de Rome, L., *The injury reduction benefits of motorcycle protective clothing*, in *NTSB Public Forum on Motorcycle Safety* September 12-13 2006, National Transport Safety Board: Washington DC.

EVALUATING DRIVER ACCEPTANCE OF HEAVY TRUCK VEHICLE-TO-VEHICLE SAFETY APPLICATIONS

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ABSTRACT

This paper describes the results of a study to determine the acceptance of drivers of vehicle-to-vehicle (V2V) safety applications in Class 8 heavy trucks. This study was conducted to provide some of the information and data needed to assess heavy truck V2V safety benefits. Driver Clinics were conducted in two locations in the U.S. to evaluate acceptance of the connected vehicle technology and safety applications by volunteers with Commercial Driver's Licenses (CDL) who were previously unfamiliar with the technology. Two heavy truck tractors with integrated V2V Safety applications were developed and used for this study.

The V2V safety applications tested included a Forward Collision Warning (FCW), Blind Spot/Lane Change Warning (BSW/LCW), Emergency Electronic Brake Lights (EEBL), and an Intersection Movement Assist (IMA). Warnings were presented to drivers in the form of a visual display mounted in the cab and also audio warnings. Driving scenarios were developed to demonstrate each V2V safety application. Drivers were recruited for this study from local trucking fleets, independent owner-operators, and respondents to advertisements both online and in local truck stops. After an initial briefing and practice drive time in the truck, participants completed a series of scenarios and were given in-vehicle questionnaires after each scenario and a final questionnaire at the end. Approximately half of the drivers were selected for in-depth interviews following the drive. In addition, the vehicles were instrumented with a data acquisition system (DAS) that collected engineering and video data from each drive. As V2V safety systems are further refined for all vehicle types, understanding the acceptance by commercial vehicle drivers of this new technology is important so that anticipated safety benefits for heavy trucks can be fully achieved.

INTRODUCTION

Two driver acceptance clinics (DACs) were conducted to determine heavy-truck driver acceptance of collision-warning systems based on vehicle-to-vehicle (V2V) technology. In short, V2V technology involves the transmission of vehicle information between vehicles via Dedicated Short Range Communications (DSRC) at 5.9 GHz radio frequency. Specifically, onboard computers broadcast information such as current vehicle location, size, speed, and path history. Using that same information received from other vehicles, the system can predict impending collisions and provide a warning to the driver.

This paper begins with a brief overview of the DACs and the safety applications that comprise the V2V-based collision-warning system. Following that are the aims and results of the analysis of the results of the DACs, as conducted by the Volpe National Transportation Systems Center.

Overview of Heavy Truck DACs

The DACs are part of a series of tests of V2V technology conducted by the U.S. Department of Transportation known as Safety Pilot [1]. The Safety Pilot consists of two parts, Driver Acceptance Clinics and the Model Deployment. The Model Deployment, which is a large-scale field test being conducted on the streets of Ann Arbor, Michigan, in which volunteer participant drivers use vehicles with fully-integrated V2V systems in their regular day-to-day driving. The DACs were conducted before the Model Deployment began and provided initial data on driver acceptance as well as an opportunity to further refine the V2V technology before the Model Deployment. Both the Driver Acceptance Clinics and Model Deployment generate data that will be used by the National Highway Traffic Safety Administration for potential agency decisions related to V2V technology.

Driver Acceptance Clinics for passenger vehicles were held from August 2011 to January 2012 to test V2V safety applications with volunteer participant drivers in controlled roadway situations. The evaluations explored driver reactions to safety applications using a variety of cars in six locations in the U.S. The driver clinics were designed to identify how drivers respond to the V2V safety applications and assess drivers' response to and benefits from in-vehicle alerts and warnings and not other issues such as security and privacy. Over 600 drivers in total experienced the technology with generally positive responses from drivers [2].

In order to support potential agency decisions on heavy vehicles, the U.S. DOT has contracted with a Connected Commercial Vehicle (CCV) Team led by Battelle that includes Mercedes-Benz Research and Development North America, Daimler Trucks North America, Denso, Meritor WABCO, and the University of Michigan Transportation Research Institute, to develop connected vehicle on-board equipment (OBE) and safety applications on selected Class 8 commercial vehicles and to build vehicles for research and testing activities to provide information and data needed to assess safety benefits and support NHTSA agency decisions. The Heavy Vehicle Driver Acceptance Clinics are some of the many tests and demonstrations of heavy vehicle connected vehicle technology during this project.

The heavy-truck driver clinics were conducted by the Battelle team in 2012 at two separate test tracks: at the Transportation Research Center in East Liberty, Ohio, from July 10-26, and at the former Alameda Naval Air Station in Alameda, California, from August 22-23. In both clinics, volunteers were asked to drive V2V-equipped vehicles through scripted interactions with other vehicles that were driven by professional drivers. These interactions were designed to demonstrate different types of collision warnings. For each warning, a test conductor sitting in the passenger seat described to the volunteer how to drive and what would happen before the demonstration was conducted.

A total of 112 participants from local trucking fleets, independent owner-operators, and respondents to advertisements both online and in local truck stops volunteered, of which 64 were in the Ohio clinic and 48 in the California clinic. Among other criteria, volunteers had to be at least 21 years of age, possess a valid Class-A Commercial Driver License (CDL-A), currently drive a tractor trailer, and not have had more than two moving violations in the last three years or to have caused an injury or crash in the last three years. Subjects were not equally balanced by gender (most were male) or age, but were meant to be representative of the demographic of professional truck drivers currently on the road.

The two vehicles demonstrating the V2V technology are shown in Figure 1. Both were Freightliner Cascadia Class 8 heavy trucks. The white truck had a high-roof sleeper body and the red truck was a mid-roof sleeper. Both towed empty 53-foot van semitrailers and were purchased specifically for the DACs.

Figure 1. **The demonstration trucks used in the DACs.**

V2V-Based Safety Applications

Trucks were equipped with four different safety applications, each designed to warn against a different type of collision scenario. In all cases, visual warnings were displayed on an iPad mounted on the center of the dashboard (Figure 2). Warnings to the driver consisted of both visual icons displayed on the screen and auditory beeps emitted from speakers mounted at roof height on both sides of the interior of the truck cab.

The four safety applications and their accompanying visual icons are shown below in the order in which they were demonstrated to drivers. The auditory warnings did not differ between safety applications, but were different for "cautionary" and "imminent" warnings.

***Figure 2*. Placement of the display in the truck cab.**

<u>Intersection Movement Assist (IMA) -</u> Warns drivers of a vehicle approaching from the side while entering an intersection (Figure 3). In this case, the subject was instructed to release the brakes and roll into an intersection as a passenger vehicle approached from the left at a constant speed. In all scenarios, the participant drove the tractor-trailer (illustrated in blue in the figure). A single-unit truck (illustrated in green) was parked at the corner in order to obstruct the participant's view of the approaching passenger car (illustrated in red), which comprised the threat. On the right side of Figure 3 are the visual icons displayed to the driver: on top is the cautionary warning and below is the imminent warning. . The system first issued a cautionary alert followed by an "imminent" alert.

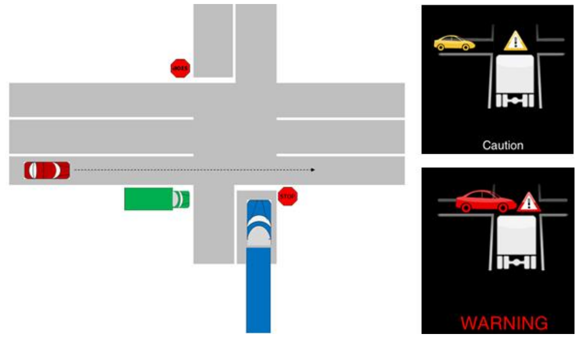

***Figure 3.* Intersection Movement Assist scenario and associated cautionary and imminent warnings displayed to driver.**

<u>Forward Collision Warning (FCW)</u> Warns the driver if they are approaching a stopped or slower lead vehicle (Figure 4). In this scenario, the system issued a cautionary and then imminent alert as the participant's vehicle approached a stopped passenger vehicle. The participant drove the blue truck toward a stopped passenger car, shown in red. Below Figure 4 are the visual icons displayed to the driver: on the left is the caution and on the right is the imminent warning.

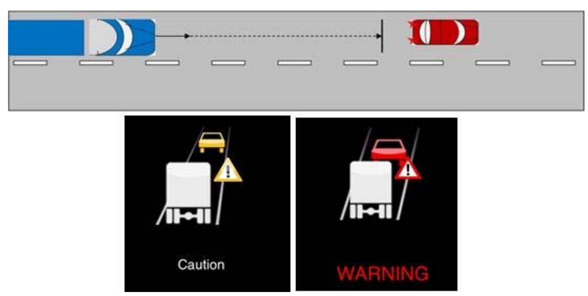

***Figure 4.* Forward Collision Warning scenario and associated cautionary and imminent warnings displayed to driver.**

<u>Emergency Electronic Brake Lights (EEBL)</u> - Warns the driver if there is hard braking one or more vehicles ahead in the traffic queue (Figure 5). In this scenario, the participant drove behind two vehicles, including a single-unit truck directly in front of the participant's truck that blocked the participant's view of a passenger car farther ahead. The driver of the passenger car then abruptly applied its brakes. If the vehicles were in an adjacent lane, the system would issue a cautionary warning. If they were in the same lane, an imminent warning would be issued. This alert was not dependent upon the intermediate vehicle braking (single-unit truck in this scenario), but instead was intended to provide information on traffic farther ahead. For this safety application only, there was no audio for the cautionary warning (but there was for the imminent warning). In this scenario the participant drove the blue truck. The red passenger car braked but was obscured from the view of the blue truck by the green truck, which did not brake. Below are the visual icons displayed to the driver: on the left is the caution and on the right is the imminent warning.

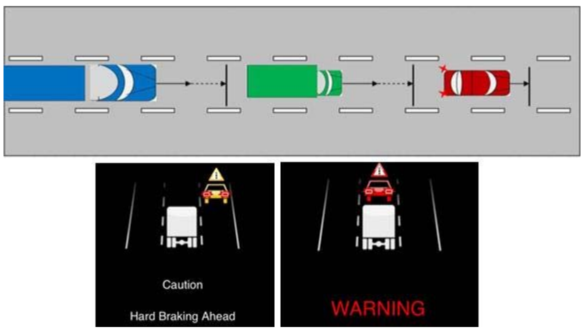

Figure 5. **Emergency Electronic Brake Lights scenario and associated cautionary and imminent warnings displayed to driver.**

<u>Blind Spot/Lane Change Warning (BSW/LCW) -</u> Indicates to the driver that there is a vehicle in their blind spot (Figure 6). In this scenario, the participant was driving down a road at a constant speed of 35 mph. When a passenger car entered the participant's blind spot in the adjacent lane, the system issued a cautionary alert (the BSW). When the participant activated their turning indicator in the direction of the lane in which the passenger car was driving, the system issued an imminent alert (the LCW).

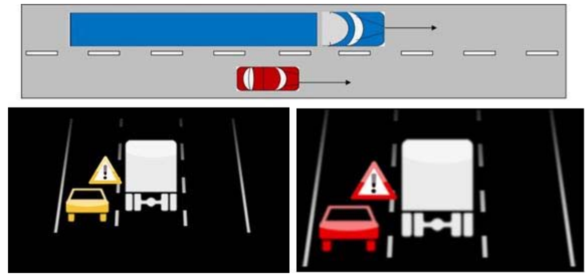

Figure 6. **Blind Spot Warning scenario and associated cautionary and imminent warnings displayed to driver.**

After the IMA demonstration and before the FCW demonstration, participants were asked to accelerate and to practice hard braking.

In total, participants spent approximately 90 minutes in the vehicle, a third of which was spent driving in the scenarios with the remaining time being used to explain each scenario and complete questionnaires. After checking in, participants were first given an overview of the study, an orientation of the vehicle and course, and then sat behind the wheel and took part in the demonstrations. Their participation ended when they were debriefed and paid.

Data Collection

Participants filled out three different surveys, each at a different time: "pre-drive" surveys before the demonstrations; "in-vehicle" surveys for each safety application immediately after experiencing it; and "post-drive" surveys after the demonstrations were complete and participants had left the vehicle. Additionally, half of drivers participated in a verbal post-demonstration interview in which they were asked to further explain their impressions and concerns regarding the V2V technology.

The surveys themselves consisted of both open-ended questions (*e.g.*, "Do you have any concerns, ideas for improvement, or other comments for the blind spot warning?") and questions to be answered on a Likert scale. The Likert-scale items consisted either of questions or statements that participants rated their agreement with (Figure 7).

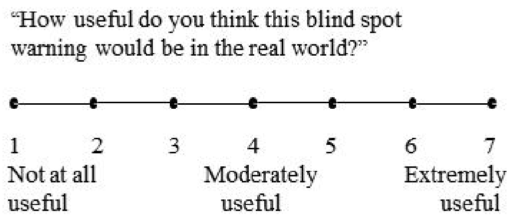

***Figure 7*. Example of Likert scale used in questions.**

A more detailed description of the experimental design can be found in the DAC test report prepared by the Battelle CCV Team [3].

ANALYSIS METHODOLOGY

Objectives

The aim of this analysis is to assess driver acceptance in terms of both the compatibility between participants' expectations of the technology and its performance, as well as in terms of the degree to which participants express interest in having the technology in their vehicles. "Driver acceptance" is a complex combination of several different factors that influence whether drivers will want the technology and how well it will work for them. These factors may vary independently of one another and it is therefore useful to analyze them separately in order to gain a more nuanced understanding of why and how drivers do or do not accept a technology. In this study, acceptance is defined in terms of five criteria that comprise the objectives of the analysis:

1. **Usability:** Do participants think that the V2V safety applications are easy to use?
2. **Perceived Safety Benefits:** Do participants think that V2V technology will contribute to their driving safety?
3. **Understandability:** Are the V2V safety applications easy to understand and learn to use?
4. **Desirability:** Do participants want to have and use V2V safety applications in their truck?
5. **Security and Privacy:** How do participants feel about the security and privacy issues raised by V2V technologies?

Of particular interest is the risk of unintended consequences, including overreliance or distraction caused by the V2V technology, which falls under the second objective above.

METHODS

Non-parametric tests, such as Mann-Whitney and Kruskal-Wallis tests, were used since data collected on a Likert scale cannot be assumed to be on an interval scale (the magnitude of the difference between a response of, for example, a four and a five, cannot be assumed to be the same as the magnitude of the difference between a five and a six). Medians were used instead of means for the same reason.

One of the downsides of having participants answer survey questions on a scale of one to seven is its inherent subjectivity: one participant's five might be equivalent to another's seven. In order to remove some of that subjectivity, for the analysis scores were converted to one of three bins: "negative," "neutral," or "positive" (the actual names of these bins varied from question to question depending on the wording of the question at hand). The bins were divided according to a system of 12-345-67, i.e., with scores of one and two as "negative," three through five as "neutral," and six and seven as "positive." This 12-345-67 breakdown was used instead of a 123-4-567 breakdown because it is more conservative and because so many of the responses were strongly positive and the chance of finding meaningful changes in the results is higher if the upper responses are separated from the middling ones—otherwise the results would likely be almost exclusively "positive."

Open-ended responses were summarized in terms of the overarching or dominant concerns or issues raised. They were also used to clarify unusual responses (such as outliers) and to illustrate concerns or trends seen in the numerical Likert-scale responses. Finally, all responses were checked for anything related to security and privacy to determine whether participants raised concerns about those issues. An analysis of the post-drive verbal interview sessions is not presented here.

RESULTS

What follows are the results of the analyses conducted by the Volpe Center and outlined in the preceding section. The total number of participants (*n*) answering each question varies in some cases because participants occasionally left questions blank.

Effect of Driver Clinic

Before pooling the data from the two clinics, one in Ohio and one in California, the results from each were compared to rule out an effect on driver acceptance of some variable, such as scenery, track layout, or weather conditions that varied between them (the staff that administered the tests were the same for both clinics). For each question answered on a Likert scale (a total of 26 questions), the percent of scores that were positive (a score of six or seven) were compared between clinics. No significant difference was seen between clinics: the pattern of the scores was similar, as indicated by a significant positive correlation between both clinics (*Pearson's r* = 0.9, n = 26, p < 0.001, two-tailed); and the magnitude of the scores was similar, as indicated by a small mean difference (1.4 percentage points, 95-percent confidence interval between 1.0 and 3.8 percentage points) and no significant difference between clinics (*paired* t-*test*, t = 1.2, df = 25, p = 0.24, two-tailed). The responses from the two clinics were therefore pooled for all subsequent analyses.

Responses Grouped by Objective

The following stacked bar charts show the results from all three surveys (pre-drive, in-vehicle, and post-drive), grouped by analysis objective. The charts illustrate the percentage of responses that fell into each of the three score bins (split according to 12-345-67). The number of respondents in each bin is written over the bars.

Usability. All safety applications were rated on the in-vehicle survey as effective by the majority of participants (Figure 8). There may have been an order effect, though, as the order in which participants experienced the safety applications was the same for all participants and corresponds with the relative effectiveness rating below, with the last-experienced safety application (BSW/LCW) being rated highest and the first-experienced safety application (IMA) being rated lowest.

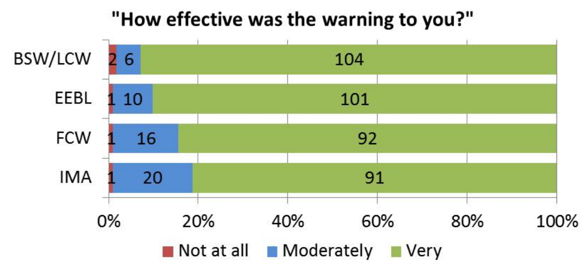

***Figure 8*. The effectiveness of the different safety applications.**

One factor that plays a role in effectiveness is whether alerts are auditory only, visual only, or both. For each safety application, participants were asked which type of alert was the most useful. In the demonstration, all participants experienced simultaneous auditory and visual warnings (though they may not have always noticed both). The results showed most thought that having both a visual and an auditory component to the alerts was most useful (Figure 9), and considered the visual warnings to be "clear and obvious" (in-vehicle survey; Figure 10—unlike the other questions on a seven-point scale, this question allowed an answer of zero for those who did not notice a visual warning at all). Of those who preferred to receive only an auditory warning, most expressed a desire not to take one's eyes off the road during an emergency situation in order to look at the display. This concern was raised in the open-ended answers multiple times, with drivers stating a preference for a heads-up display, one on the windshield, or simply stating their unease with looking away from the road.

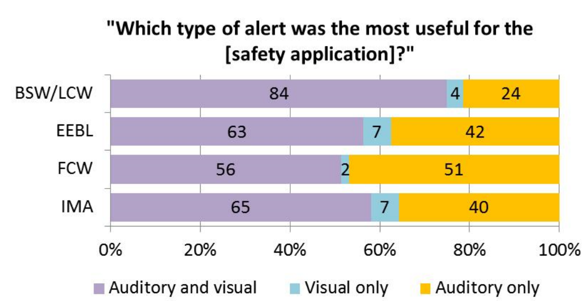

***Figure 9*. Usefulness of alerts presented only as auditory, visual, or as both, for each safety application.**

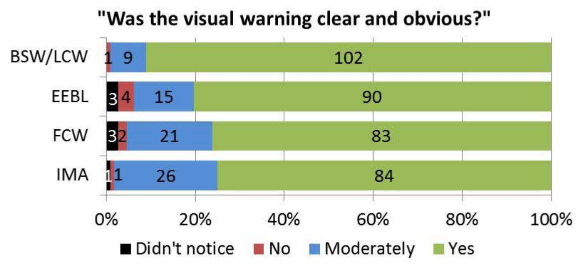

***Figure 10.* Clarity of visual warnings for each safety application.**

<u>Perceived safety benefits</u>. Participants gave very high approval rates to the perceived safety benefits conferred by each safety application overall during the in-vehicle surveys (Figure 11). Of those applications, the BSW/LCW received higher ratings of usefulness than the EEBL, which received higher ratings than the FCW. The IMA received the lowest number of high ratings (though it also received no "not useful" ratings).

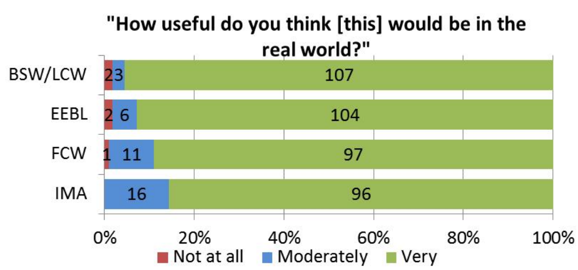

***Figure 11.* Rated "real world" usefulness for each safety application.**

Again, the above relative preferences between safety applications may be affected by the order in which the applications were experienced, since the order is the same as the inverse of the order of preference, with the application rated most useful being experienced last and the least useful being experienced first. That this may be an order effect is addressed by responses to a question on the post-drive survey: "rank in order of usefulness of each application, starting with 1 being the MOST useful to 4 being the LEAST useful." Here the mean ranks were different: BSW/LCW (2.1), EEBL (2.2), IMA (2.7), and FCW (3.0).

The following two questions from the post-drive survey concerned participants' opinion of the potential for driver distraction as caused by the safety applications. These questions reveal an overall perception that, although 75 percent of participants estimate the degree of distraction caused by the applications to be comparable to operating the truck's stereo system (the same percentage was found in the report on the light-vehicle DACs [4]) (Figure 12), nonetheless 81 percent believed there was some likelihood of drivers becoming dependent upon the warning systems to alert them to danger (Figure 13).

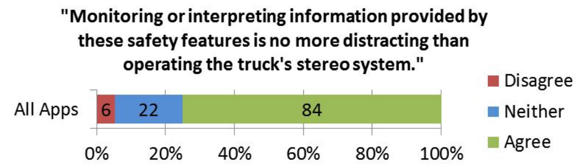

***Figure 12.* Distraction potential.**

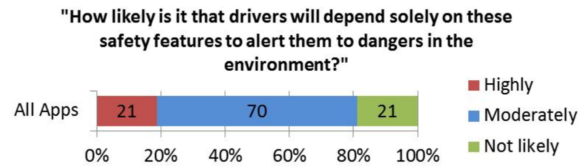

***Figure 13.* Likelihood of overreliance on safety applications.**

Several drivers expressed further concern for unintended consequences in question 21 of the post-drive survey: "Each driver must learn not to rely on these safety devices. Still no substitute for driver looking and staying alert;"

"The only con of all these things that I can see in the future is that some of the future drivers may begin to rely on this technology too much and pay less attention to the actual road;"

"Warning not to depend on system. Must be used with SAFE driving practices. There are (maybe) legal implications for ignoring warning system. Driver should be made aware;" and

"I think this is helpful and useful. My only reservation is that I believe these systems would hamper drivers in developing instincts. I am a million-mile safe driver and I feel the instincts I have built over the years have been good to me. But if I had the choice in a vehicle with or without this system, I would use the warning system."

Another survey question pertains to the issue of overreliance indirectly. Participants were told, "It is possible that the Vehicle-to-Vehicle Communication safety application may become temporarily unavailable, and not warn you when it otherwise would. With that in mind, please answer the following." Participants were then asked whether or not they would want to receive notification of system unavailability. The overwhelming majority answered affirmatively (Figure 184). This question pertains to overreliance since desiring to know when the system is online implies that drivers may act differently with the system on or off.

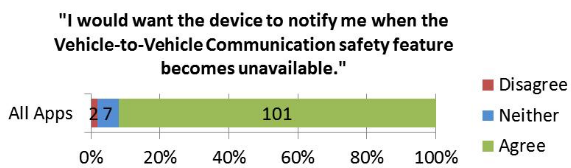

Figure 14. **Desire for being notified when the system becomes unavailable.**

<u>Understandability</u>. When asked during the in-vehicle survey to rate agreement with the statement that a given safety application was easy to understand, the large majority of participants rated their understanding as high for each application (Figure 15).

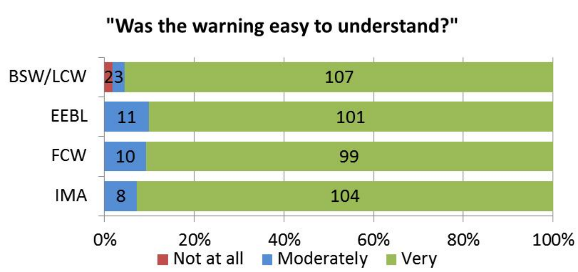

Figure 15. **Rated understanding of the safety applications.**

In the post-drive survey, a large number of participants reported feeling that there would be some confusion in interpreting which warnings were provided by which safety applications (Figure 16).

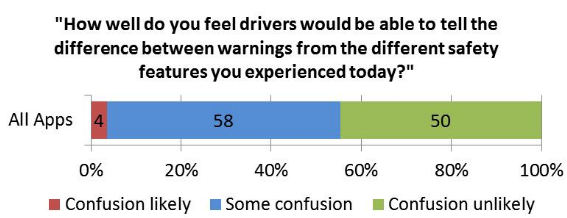

Figure 16. **Rated potential for confusing the safety applications.**

Participants were asked after completion of the demonstrations how well they understand the technology and how it works. From the wording of the question, it is unclear whether positive responses indicate an understanding for the basic logic of the system, e.g., "the system beeps when I'm in danger of hitting someone," or how the technology works on a more fundamental level, with vehicle information being broadcast and received via DSRC, etc. Most participants stated "full comprehension" of the technology, with only one driver saying they don't understand (Figure 17).

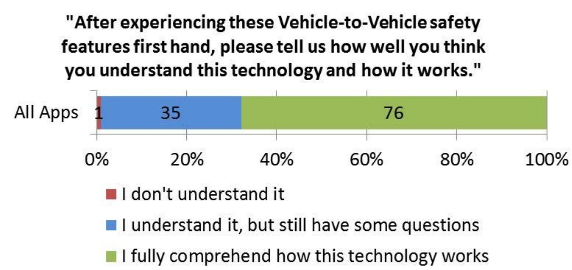

Figure 17. **Reported understanding of "how [V2V] technology works." The question was multiple choice and participants were asked to check only one of the three options.**

<u>Desirability</u>. The following questions from the post-drive survey indicate that the vast majority of participants would like to have V2V technology (Figure 18).

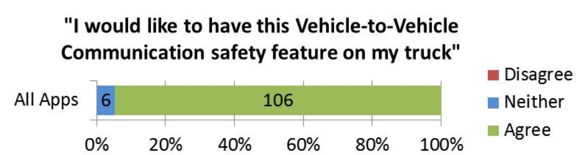

Figure 18. **Desirability of the combined package of all four safety applications.**

When broken down by individual safety application in the in-vehicle surveys, the IMA was again the least strongly rated—but as before, even it was still rated overwhelmingly positive, with over 87 percent of respondents giving it a six or seven (Figure 19).

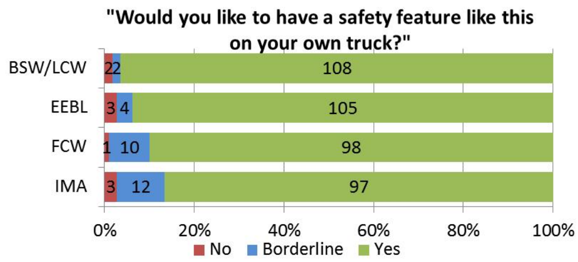

Figure 19. **Desirability of the individual safety applications.**

When compared with other options for vehicle systems, desire for V2V technology was highest: in order from most to least desirable, participants ranked the options first V2V, then FCW (via Eaton Vorad or Meritor OnGuard), then Adaptive Cruise Control, then stability control systems, then GPS, and finally tire-pressure monitoring systems. Table 1 shows the mean rankings for different vehicle systems in response to the question, "Please rank the following options in terms of overall desirability, with 1 being the MOST preferred and 6 being the LEAST. Use numbers 1-6 only once." Row order is the same as it was in the survey.

Table 1.
Mean rankings for different vehicle systems.

Available Option	Mean Rank
Adaptive Cruise Control (slows down when somebody is in front of you)	3.8
Forward Collision Warning System (Eaton Vorad or Meritor OnGuard)	2.7
GPS Navigation System	4.2
Roll Stability Control or Electric Stability Control	4.0
Tire Pressure Monitoring System	4.5
Vehicle-to-Vehicle Warnings (All of the safety applications you experienced today)	1.8

Security and privacy. There were no questions asking participants directly about security and privacy concerns (it could be argued that to ask about such concerns directly is to ask a leading question, thus creating the concerns in drivers' minds, rather than checking to see if they initially had them). Consequently, the responses to the open-ended questions were checked for anything related to security or privacy that drivers raised on their own. Of most relevance was question 21 of the post-vehicle survey, which asked, "any final thoughts or comments on your overall experience today that you would like to provide?" Only one out of the 112 participants raised an issue that pertained to either security or privacy, namely, "can someone rig something to send false info to mess with a driver?"

Environmental Conditions

For each safety application, participants were asked in the post-drive survey, "under what environments and conditions do you feel the safety application would provide the most benefit? (Circle all that apply)." The possible answers included: nighttime driving, daytime driving, slippery roads, poor visibility, unfamiliar roadways, obscured views, and "other." Overall, participants picked all options with high frequency for each safety application. For the IMA warning, poor visibility and obstructed views were the most widely chosen. For FCW, all options except daytime driving were commonly picked. The responses for EEBL and BSW/LCW were similar. Representative written-in responses to the "other" option are provided below each chart. "Heavy traffic," "rush hour," and "distracted/tired" drivers were common answers for all safety applications. Situations obstructing views were listed for the IMA, and factors causing vehicles to suddenly stop were listed for the FCW and EEBL alerts. Several drivers cited "motorcycles passing on the right" as a use for the BSW/LCW safety application.

For the IMA, participants wrote the following under the option for "other": "city driving;" "when pulling from driveways or blind intersection;" "tired drivers / distracted drivers;" "could save a tired driver from making a mistake he wouldn't normally make;" "heavy traffic;" "trees and signs block trucks a lot;" "over the hill;" "a stoplight on a four-lane highway. The light changes for you, but the driver in the outside lane doesn't stop. This warning would be very helpful."

For the FCW, participants wrote the following under the option for "other": "stop-and-go traffic," "heavy traffic conditions," "during rush-hour traffic in large cities;" "two-lane country roads;" "tired drivers / distracted drivers," "when thinking or daydreaming;" "cars stopped due to an accident or break down."

For the EEBL, participants wrote the following under the option for "other": "commuter traffic, heavy;" "stop-and-go traffic, like rush hour traffic when vehicles are close together;" "freeway or highway driving;" "stalled vehicles in lane;" "tired drivers / distracted drivers;" "heavy traffic / downhill;" "animals running across the road causing a car to slam on the brakes;" "a warning for stopped traffic that might be on the other side of a hill such as mountain back-up going down the other side."

Lastly, for the BSW/LCW, participants wrote the following under the option for "other": "making right turns;" "motorcycle riders that pass on right;" "rush-hour traffic;" "when driving in lots;" "tired drivers / distracted drivers;" "when driver's been on the road for a while;" "leaving or entering toll booth."

Effect of Age

Of the 112 volunteers who took part in the clinics, the age ranged from 28 to 66 years old. The mean age was 47.2 years old, with a standard deviation of 9.3 years.

Correlation analyses. Spearman correlation tests were conducted to test for relationships between responses to Likert-scale survey questions and years of age. There were a couple statistically significant correlations (p-values < 0.05), which is no surprise given the large sample sizes, which ranged from 108 to 111. However, the important measure in such correlations is not the degree of significance but the magnitude of the correlations, and in that case nothing was found: all of the correlation coefficients (r_s) were between 0.2 and -0.1 and were therefore very weak or non-existent. In other words, there did not appear to be any non-weak linear relationships between survey responses and age. This was true both for the safety applications individually, as well as for the combined system.

Analysis comparing "age bins." Age was also analyzed by dividing the subjects into subgroups ("bins") by age and comparing the ratings given by those groups using non-parametric between-subject tests. The analysis focused on Likert-scale questions related to driver acceptance. Three groups were used: 28-39, 40-49, and 50-66. Kruskal-Wallis omnibus tests were used to compare all three age bins between subjects. No significant differences were found between age groups (in all cases $p > 0.05$).

Effect of Previous Driving Route Experience

When asked to report the number of years with a CDL-A license, the mean response was 18.6 years, with a standard deviation of 11.7 years. The least amount of time was five months and the longest 41 years. With regard to the number of years of experience driving a tractor trailer, the mean response was 17.7 years, with a standard deviation of 11.8 years. The least amount of time was again five months and the longest 41 years.

To determine whether there is a difference in the acceptance of V2V technology between route types, subjects were divided into three groups: those who have driven only local "pick-up & delivery" (P&D), those who have driven only line haul and those who have driven both (those who have driven neither should, and was, and empty group). This division was based on the survey question in which drivers were asked, "What types of routes do you have experience driving?" Participants were provided with five choices of answers:

a. Local
b. Over the road
c. City driving
d. Truckload
e. Less than truckload

In this case, answers to (a) and (c) were considered P&D, and (b) was considered line haul. The vast majority of drivers have experience with both types of routes and no drivers had experience with neither. See Figure 20.

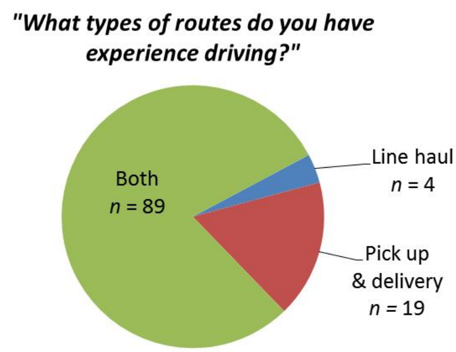

Figure 20. **Reported route experience in terms of line haul, pick up & delivery, or both.**

Effect of Previous Experience with Safety Applications

Although collision-warning systems based on V2V communication are a new technology, collision-warning systems based on other technologies, such as onboard radar or cameras, are already in use. To determine whether prior experience with other types of warning systems may have affected subjects' acceptance of V2V-based technology, the pre-drive survey included two questions regarding other types of systems. The first asked drivers, "Which of the following devices are installed or available to you in your primary truck?" (question 9). The second asked, "which devices would you like to have installed or available in your truck?" (question 10). For both questions a range of devices were then listed, next to which participants could check one of three columns: for question 9, "installed" / "don't know" / "not installed"; and for question 10, "desirable" / "don't know" / "not desirable." Of the 21 devices listed, six were identified as including capabilities similar to the V2V safety applications used in the DACs, namely audio or visual warnings for impending collisions. Those six included Cadec, Eaton Vorad, Forward Collision Warning (FCW), Lane Departure Warning (LDW), OnGuard, and Wingman.

Table 2 shows the responses to device possession and desire, grouped by device. There was a large degree of uncertainty in terms of what devices drivers had in their vehicles, although most drivers had none of them. The type of device known to be in the vehicle most frequently was Cadec. The devices with the least uncertainty regarding possession were the LDW and FCW warnings. These were also the two most desired devices—the rest had a large degree of uncertainty regarding desirability. They are also the two devices with descriptive rather than brand names. For the most part, the devices all received very few "not desirable" ratings.

Table 2.
Number of drivers that reported having a given collision-warning device on their vehicle and the number of drivers that reported desiring a given device on their vehicle.

	Installed in primary truck?		
Device	**Not installed**	**Don't know**	**Installed**
Cadec	37	39	9
Eaton Vorad	48	30	4
FCW	71	9	8
LDW	72	9	3
OnGuard	64	14	5
Wingman	62	17	2

	Like to have?		
Device	**Not desirable**	**Don't know**	**Desirable**
Cadec	8	59	12
Eaton Vorad	11	60	13
FCW	3	7	89
LDW	4	18	76
OnGuard	8	51	31
Wingman	6	64	18

The data in Table 2 are broken down by driver rather than by device type as in Table 3. In total, 25 drivers gave no answer for any of these six devices for either the "do you have it installed?" or the "do you want it installed?" questions, and were dropped from the table. Only 22 percent of drivers (19 drivers) had at least one warning device already, and of them 89 percent wanted at least one of them. Of the 78 percent of drivers that had none of the devices in their primary trucks, 90 percent wanted to have at least one of them.

Table 3.
Number of drivers who have and want at least one of the six devices (listed in Table 2) that provide some form of collision warning

		Want installed?		
		At least one	None	Total
Have installed?	At least one	17	2	19
	None	61	7	68
	Total	78	9	87

Outlier Analysis

Overall, the participants had a very clear positive response to V2V technology. As reported above, when asked in the post-drive survey to report their agreement with the statement, “I would like to have this Vehicle-to-Vehicle Communication safety application on my truck” (Figure 18), responses were strongly positive. As in the light-vehicle DAC [4], the median response was the maximum response, a seven. In the analysis of the light-vehicle DACs, this question was used to identify negative outliers, which were defined as those who rated agreement three or less (out of 406 drivers, nine qualified as negative). However, in the heavy truck DACs no drivers gave ratings less than five, meaning *all* responses were at least somewhat positive. Consequently, outliers were identified based on their scores rating the safety applications individually: subjects were deemed outliers when for at least one safety application they gave a response of less than four to the question, “would you like to have a safety application like this on your own truck?” To explore these outliers, Table 4 shows how those individuals responded to other questions. Note: the column labeled “ALL” is neither the mean nor the sums of the other columns, but rather the answer to a separate question referring to the suite of safety applications combined. Scores below four are shaded red. Dashes indicate that no answer was recorded for that run.

Table 4.
Outlier analysis listing responses to several questions by participants who rated at least one individual safety application as undesirable by giving a less-than-neutral score (less than four).

		Would you like to have it?					How useful would it be?			
ID	Age	IMA	FCW	EEBL	BSW/ LCW	ALL	IMA	FCW	EEBL	BSW/ LCW
19	58	3	4	1	6	4	4	5	2	5
20	60	7	7	7	1	7	7	7	7	1
36	35	7	-	1	7	7	7	-	2	7
40	29	6	5	2	7	5	6	6	4	7
42	47	6	2	7	7	7	6	7	7	7
50	50	3	7	6	7	7	4	6	7	7
54	30	3	7	5	7	5	4	2	5	7
55	48	1	4	7	7	6	4	5	7	7
67	44	2	7	7	7	6	4	7	7	7
85	56	7	7	7	1	7	7	7	7	1
89	35	1	7	6	7	6	4	7	4	7

Overall, it appears that, for a given safety application, participants rated usefulness slightly higher than desirability, a finding consistent with the light-vehicle DAC outlier analysis (the only internally inconsistent answer in this regard is Participant 54, who strongly desired the FCW alert in spite of giving it a very low rating of usefulness). Likewise, even though participants may have rated a given safety application undesirable, they tended to rate other safety applications highly, indicating that their aversion is specific to the warning rather than to the idea of warning systems or V2V technology in general.

These outlier participants made comments in the open-ended questions that can explain why they gave low ratings for some systems. Representative comments include: “bigger graphics on screen” (Participant 20); “more audio than visual [to] keep your eyes on the road” (Participant 42); “it’s better to keep a driver’s eyes in the direction of the danger rather than pulling his vision and attention to the dashboard” (Participant 50); “most would be useful but must be able to adjust. If these are on all the time, driver will not pay attention” (Participant 55);

"the alerts shouldn't sound the same, try to add voices on lane change blind spot" (Participant 89). With regard to the IMA: "my experience was beneficial because I don't believe I had actually moved prior to the warning going off. So the system was extremely effective in that scenario. I like how I just had to let off the brake" (Participant 36); "as a local T/T driver (city), this application would not be useful. Due to high traffic conditions, alerts would be too common" (Participant 55). With regard to the BSW/LCW: the most beneficial aspect was "the visual display because it forced me to look in the direction of my mirror" (Participant 50); and "blind spot alert very useful but in city use this would be on all the time" (Participant 55).

CONCLUSIONS

Overall, driver acceptance of the V2V system in heavy trucks was very high, with the vast majority of drivers giving the maximum rating to most safety applications. The following are the key findings (the five objectives are in bold):

- There was no detectable effect of clinic location, with both those who experienced the Ohio clinics and those who experienced the California clinics giving similar responses.
- **Usability** was rated very high, with at least 81 percent giving strongly positive ratings. However, there appeared to be an order effect, since acceptance of each safety application increased with the order in which it was demonstrated.
- The **perceived safety benefits** were also rated high, with at least 86 percent giving strongly positive scores, although the relative preferences among the different safety applications again appeared to vary with the same order effect. The presence of an order effect was supported by the fact that, when asked afterwards to think back on their ranking of the usefulness of each application, they gave a different order, ranking the IMA above the FCW safety application.
- At least 90 percent of participants gave the highest rating for **understandability**, although 55 percent said there was chance for at least some confusion in differentiating the various safety applications.
- **Desirability** was high, with 95 percent of participants wanting a V2V system on their truck (when safety applications were rated individually, the lowest-rated safety application, the IMA, was still desired by 87 percent of participants, with an additional 11 percent saying they were borderline). Compared to several other available options, including adaptive cruise control and GPS, participants rated V2V the highest.
- Only one participant out of 112 raised the issue of **security and privacy**.
- Between 50 and 75 percent of subjects wanted alerts to have both a visual and an auditory component. Although at least 75 percent thought the visual displays were "clear and obvious," some expressed concern that they draw one's eyes inside the cabin exactly when attention is most strongly needed outside of it. Others voiced concern that audio alerts could be drowned out by the radio.
- Although 75 percent of participants rated the distraction potential of the V2V system on par with their radio system, 81 percent said there was at least some risk that drivers will depend "solely" on the safety applications to alert them to dangers on the road. Relatedly, the fact that 92 percent of drivers would want to be notified when the system becomes unavailable raises the concern that drivers might behave differently with the system on.
- No age effects were observed. This is of little surprise given the relatively narrow age range of participants, which included few very young or very old drivers.

There were very few outliers at the negative end of the spectrum, with not a single driver expressing a negative (less than four) rating of agreement with the statement, "I would like to have this Vehicle-to-Vehicle Communication safety application on my truck," when referring to the combined suite of safety applications. Outliers therefore had to be identified by negative ratings of individual safety applications, of which there were very few. As was the case with the light-vehicle DACs, outliers rated usefulness slightly higher than desirability. That participants who rated a given safety application low tended to rate the other safety applications high suggests that their aversions are specific to the warning and not to the idea of V2V-based warning systems in general.

Regarding an understanding of the underlying technology, although 68 percent said they "fully comprehend how this technology works," it is unclear what level of understanding participants thought the question referred to—whether it meant just an understanding that alerts would be provided when another vehicle got too close, or whether it referred to principles of the underlying technology. This is important because a good understanding of the underlying principles, especially the fact that V2V technology will be constantly broadcasting your vehicle information to others and receiving information that could be falsified, are both central to whether or not one will have concerns with regard to security and privacy. Given the reaction truck drivers have had to devices that monitor their activity, this is likely to be an important factor in fleet acceptance, even if was not raised here.

The experimental design did not control for the order in which participants experienced the different safety applications, as this appears to have affected their relative impressions of the individual systems. Of particular concern is the fact that the IMA demonstration, which entailed being asked to release the brakes and roll into the path of an oncoming vehicle, was conducted before drivers had the opportunity to familiarize themselves with the handling of the vehicle—especially its brakes—with a test drive. The slightly lower scores for the IMA relative to other alert types might therefore be partly due to a lack of comfort driving an unfamiliar vehicle.

Furthermore, many of the drivers expressed admiration for the brand-new trucks used in the DACs, mentioning that they themselves generally operated older vehicles with older technology and less responsive brakes. It is therefore possible that some of the enthusiasm for the warning technology for all of the safety applications may have been affected by enthusiasm for the truck in which it was being demonstrated.

There is also the concern that drivers strongly averse to new technology of this sort are probably less likely to volunteer for studies such as these in the first place.

Finally, since the DACs were designed to demonstrate the value of the safety applications under ideal circumstances without any of the variations, false alerts, and nuisance alerts that come into play in the real world, it is expected that acceptance would be high. Additional information on driver acceptance in the real world will come from the heavy trucks involved in the Model Deployment.

ACKNOWLEDGEMENTS

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REFERENCES

[1] http://www.its.dot.gov/safety_pilot/index.htm

[2] CAMP Vehicle Safety Communications 3. 2013. "Vehicle-to-Vehicle Safety System and Vehicle Build for Safety Pilot (V2V-SP) Final Report, Volume 1: Driver Acceptance Clinics," National Highway Traffic Safety Administration to be published.

[3] Pape, D.L. and R. Meyer. 2012. "Connected Commercial Vehicle Integrated Truck Project: Driver Clinics Test and Safety Plan: Final Technical Report," Federal Highway Administration, Washington, DC, to be published.

[4] Stevens, S. 2012. "Analysis of the Driver Acceptance Clinic Subjective Data," National Highway Traffic Safety Administration, Washington, DC, to be published.

STATUS OF THE SECONDARY SAFETY OF COACHES – UPDATED STATISTICS, CURRENT STANDARDS AND ADDITIONAL TECHNICAL MEASURES

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ABSTRACT

Although integrated safety has become more important, secondary (passive) safety is still relevant in ensuring that the consequences of the crashes which always happen on our roads are as low as possible. This is particularly true for coaches that may be occupied by many passengers. Attention has also to be paid to the safety of driver and tour guide sitting in foremost position of the compartment.

To give an overview of the accident situation, results of updated statistical analyses are displayed for Europe and (in a more detailed form) for Germany. Combined with the results of in-depth studies it can be seen that rollover and frontal impacts are still the most relevant scenarios encountered in severe bus/coach accidents.

Regarding rollover, the superstructure design of new coaches has to be improved to meet the requirements of the revised ECE-R 66-02. This is illustrated by an example.

On a voluntary basis, few OEMs have improved the structure of the front end in relation to frontal impacts by using pendulum tests and full-scale crash tests in combination with advanced numerical simulation techniques. As a result, a new safety system called Front Collision Guard was developed and implemented in the latest series of Setra and Mercedes-Benz coaches.

For best safety performance in all kinds of accidents occupants should buckle up in their seats. Seats and restraint systems used in coaches have to meet the requirements of ECE-R 14 and ECE-R 80. To address this, updated results of a literature review and examples of seats and restraint systems used in modern coaches show the state of the art.

The article gives a short but complete updated overview of the most relevant aspects of the secondary (passive) safety of coaches. The main part describes the design and evaluation of the performance of the Front Collision Guard which may bring the secondary (passive) safety of coaches to a new level.

1 INTRODUCTION

The evaluation of accident statistics reveals that the bus and, in particular, the long-distance coach is a very safe means of transport. Nevertheless, severe accidents involving buses always attract considerable public interest. It has long been known that – with the exception of catastrophic incidents – passengers involved in a bus collision accident are very well protected and are only injured on rare occasions. However, the risk of being injured in a bus accident rises if the bus tips or rolls over and, for example, guard rail posts penetrate the interior from outside. Since the seats for the driver and – if appropriate – the tour guide are located right at the front of the vehicle, a front-end collision presents a special problem for their occupants. In order to protect all the occupants of a bus and – in the event of a particularly severe accident – to reduce the number of dead and injured as far as possible – the preservation of the survival space in the bus and full use of the safety belts are regarded as essential.

The homologation and licensing of buses essentially requires compliance with the harmonised international regulations established by the European Union (EEC, EC, EU Regulations) or the Economic Commission for Europe at the United Nations (UN ECE Regulations). In addition, consideration must be given to the existing National German Road Regulation (StVZO). Today the latter corresponds overwhelmingly to the international regulations.

To improve the secondary (passive) safety of buses and coaches, special regulations and tests have been imposed in the past and some of these have been since revised. This has led to a minimum standard being established that guarantees a high level of safety for the passengers of buses/coaches. Beyond this, few OEMs have voluntarily carried out supplementary tests to still further improve the safety of their vehicles.

The following section gives a current overview of the statistical evolution of accident occurrence and the associated magnitudes of risk levels. This is followed by a description of the relevant regulations, technical measures and current technical developments concerning the secondary (passive) safety of buses/coaches. All the matters discussed relate to the safety of the occupants – no reference is made to primary (active) safety and the safety of third parties involved in bus accidents.

2 ACCIDENT STATISTICS

2.1 Bus/coach occupant fatalities in the European Union

In the European database CARE (Community database on road Accidents Resulting in death or injury) the current number of traffic fatalities for the year 2011 was recorded on November 29, 2012 as a total of 3,135 [1]. The data came from 26 member states of the EU (EU 27 without Latvia [Lietuva]) and they are being continuously updated by the latest available national statistics. On the stated day there was a total of 87 killed bus/coach occupants of which 23 were drivers (26%) and 64 were passengers (76%), Table 1. Relative to the total of 31,125 fatalities in the aforementioned member states, killed bus/coach passengers represent a proportion of 0.3%.

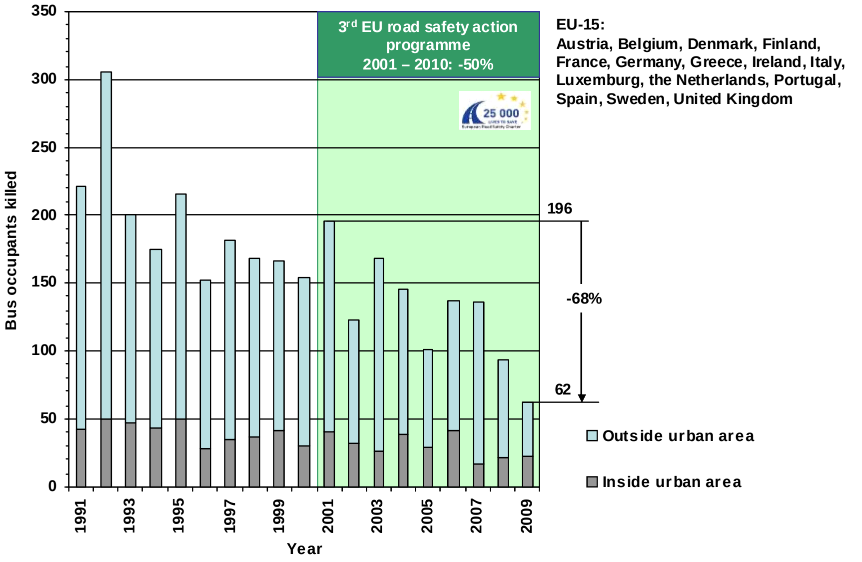
In the case of 15 EU member states it was possible for CARE to identify the number of bus/coach occupants killed annually from 1991 until 2011 and broken down according to the location of the accidents, Figure 1. The maximum was recorded in 1992 with a number of 305 killed bus/coach occupants. In 2009, the number fell to 62. Most bus/coach occupants died in accidents which occurred outside urban areas. The proportion in 2009 amounted to 65% (i.e. 40 out of a total of 62 fatalities).

The 3rd European Road Safety Action Programme set the objective of halving the number of killed traffic participants for the whole of the European Union (EU 27) over the period 2001 - 2010 [2]. This objective was almost attained by a reduction of 44% from 54,000 to 39,500. In the member states considered here (EU 15) the number of bus/coach occupants killed fell from 196 in 2001 to 62 in 2010, i.e. by 68%. This means that bus/coach occupants participated in the general development towards steadily increased safety levels on the roads of the EU.

Table 1: Current figures of bus/coach drives and passengers killed per year in road accidents in the member states of the EU (Source: CARE [1] as of November 29, 2012)

State	Belgique	Bulgaria	Ceská Republica	Danmark
Year	2011	2009	2011	2010
Driv.	2	0	2	0
Pass.	0	0	2	0
State	Deutschland	Eesti	Éire	Elláda
Year	2011	2009	2010	2011
Driv.	1	0	1	1
Pass.	9	2	0	3
State	Españia	France	Italia	Kýpros
Year	2010	2011	2010	2004
Driv.	0	0	2	0
Pass.	5	0	7	0
State	Latvija	Luxembourg	Magyarország	Malta
Year	2011	2011	2010	2010
Driv.	0	0	3	0
Pass.	1	0	9	0
State	Nederland	Österreich	Polska	Portugal
Year	2009	2011	2011	2011
Driv.	0	0	3	0
Pass.	0	0	9	0
State	România	Slovenijya	Slovensko	Suomi
Year	2011	2010	2010	2011
Driv.	3	0	0	1
Pass.	6	0	0	1
State	Sverige	Great Britain	**EU-26***	
Year	2009	2010	-	
Driv.	0	4	**23**	
Pass.	0	10	**64**	
***EU-26 = EU-27 without Lietuva (not reporting)**				

Figure 1. Evolution of the absolute figures of occupants of buses/coaches killed per year in road accidents inside and outside urban area in 15 member states of the European Union (EU-15) from 1991 until 2009 (data source: CARE [1] with last update on 29/Nov/2012)



2.2 Fatalities and casualties suffered by bus/coach occupants in Germany

In 2011 a total of 4,009 traffic participants died on German roads and 68,925 were seriously injured. Bus/coach occupants formed a very low proportion of these casualties with 10 fatalities and 427 severe injuries – namely 0.25% and 0.62% respectively, Figures 2 and 3. Occupants of buses/coaches are defined as those travelling in a vehicle with more than 9 seats, including the driver seat.

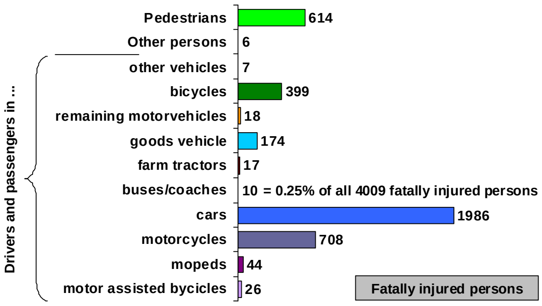


Figure 2. Road users fatally injured in accidents on German roads in the year 2011 (data source: Federal Statistical Office [3, 4, 5])

The number of persons killed and injured in road accidents since 1957 can be extracted from the publications of the Federal Statistical Office [3, 4, 5]. Figures 4 and 5 show the long-term evolution of the numbers of road users killed and severely injured up to 2011. The numbers given for 1991 and afterwards apply to the Republic of Germany after re-unification in 1990 – i.e. both old and 'new Laender'.

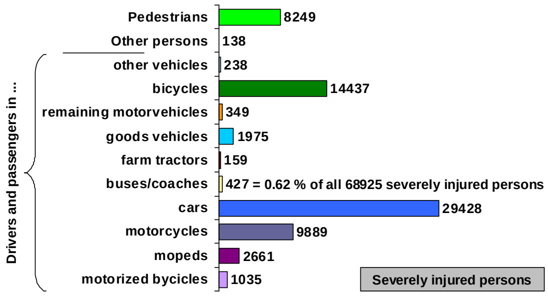


Figure 3. Road users severely injured in accidents on German roads in the year 2011 (data source: Federal Statistical Office [3, 4, 5])

The number of killed bus/coach occupants certainly remains at a very low level but the individual annual figures vary a great deal. The maximum number of fatalities during the stated period was 74 recorded in 1959. In that year there occurred the most serious bus accident since the 2nd World War. In Lauffen am Neckar a bus travelling over a level crossing was struck by the locomotive of an express train, killing 45 of the bus occupants [6, 7].

The previous minimum was 2 bus/coach occupants killed in 1998. The substantial variation over time of the numbers of fatalities is significantly influenced by individual serious accidents in which a relatively large number of occupants were killed. Table 2 contains four examples for 1959, 1992, 2007 and 2010.

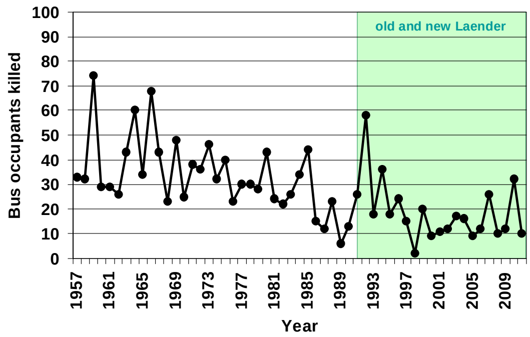


Figure 4. Bus/coach occupants killed in accidents on roads in the Federal Republic of Germany per year from 1957 until 2011 (data source: Federal Statistical Office [3, 4, 5])

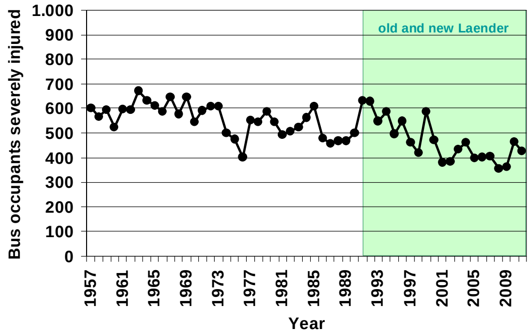


Figure 5. Bus/coach occupants severely injured in accidents on roads in the Federal Republic of Germany per year from 1957 until 2011 (data source: Federal Statistical Office [3, 4, 5])

When interpreting these numbers it needs to be noted that only those killed in traffic accidents are included in the statistics. For example, in Hanover 20 people died in a bus disaster on the A2 Autobahn in 2008. This was not the result of a traffic accident – the bus caught fire [8].

The long-term pattern of severely-injured bus occupants in Figure 5 is less apparent than the number of persons killed as influenced by annual variations. In the 'old Laender' of the Federal Republic of Germany (1957 -1990) brief periods of falling numbers were followed by some clear increases.

In the period shortly following reunification, sustained falls in the number of severely injured occupants could be observed over a lengthy period. This means that bus/coach occupants shared in the general trend offering greater vehicle and traffic safety on German roads.

Table 2. Examples of single catastrophic bus accidents which significantly influenced the figure of killed bus occupants in the corresponding year

Date	Accident description	Bus/coach occupants killed in the accident	Bus/coach occupants killed during the year	Percentage of bus/coach occupants killed during the year
June 1959	Bus struck on a railway level crossing by the locomotive of an express train	45	74	61%
Sept. 1992	Coach tilts after forcing a car and crashes into a guardrail	21	58	36%
June 2007	Truck crashes into the rear end of a coach	13	26	50%
Sept. 2010	Coach crashes into a car and a bridge post after evasion manoeuvre	13	32	41%

Further differentiation can be made between buses and coaches in terms of their particular function. The official German statistics differentiate between coaches, urban buses, school buses and trolley buses. There is also a category for "other buses" that covers buses/coaches which the police attending accidents were unable to assign to one of the above-mentioned categories.

According to the available statistics, the low numbers of fatalities differ, Figure 6. In the individual years of 1998, 2001 and 2006 not a single killed coach occupant was registered in the official statistics. In other years, such as 2002, 2003, 2007 and 2010 the number of coach occupants killed dominated compared with the total number of all bus/coach occupants killed.

In 1996 to 1998, 2000 to 2006, 2008 and 2010 no occupant of a school bus lost his/her life in a road accident. There are no records of trolley bus occupants being killed during the same period.

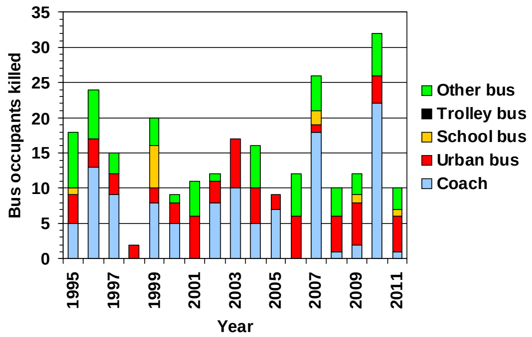


Figure 6. Fatalities in buses/coaches in Germany per year from 1995 until 2011 broken down into sub-groups corresponding to the categories of road users (data source: Federal Statistical Office [5])

The larger number of casualties (i.e. injured and killed) are dominated by the occupants of urban buses, Figure 7.

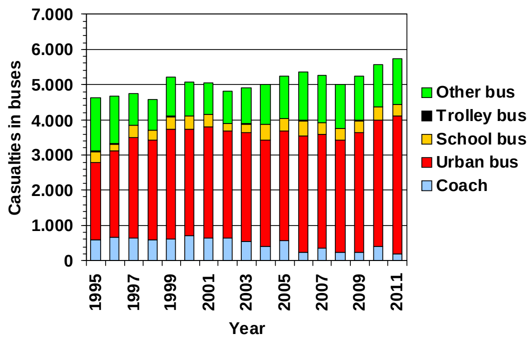


Figure 7. Casualties in buses/coaches in Germany per year from 1995 until 2011 broken down into sub-groups corresponding to the categories of road users (data source: Federal Statistical Office [5])

In individual years the number of fatalities or other casualties associated with "other buses" is always relatively high. For example, in 2010 six fatalities (19%) of the total of 32 killed bus/coach occupants were registered as occupants of "other buses". It can, therefore, be assumed that the number of occupants in urban buses, coaches and, where appropriate, school buses could have been greater than shown by the statistics.

The over-riding objective is to steadily reduce the absolute number of persons killed in traffic accidents. That is reflected by Vision Zero, a worldwide strategy promoted in Germany by the German Road Safety Council (DVR) [9]. The Accident Statistics already show that Vision Zero had already become a reality, not only for the occupants of trolley buses and school buses, but also for coach occupants on German roads during individual years.

At the same time, accident records for coaches demonstrate the importance of the constantly expressed statement that every traffic death is one death too many. The public memory retains severe individual coach accidents for a long time but takes no account of the individual years in which no coach occupants die. Consequently, severe coach accidents always provide occasion to refer to the fact that "according to the statistics, the long-distance coach is one of the safest forms of transport". However, in view of the current dramatic real consequences of accidents, the abstract statistics fade into insignificance and so there is only a limited opportunity to persuade the public to accept on a sustained basis the desired image that coach travel is "the safest way to make a land journey". In view of this it can be seen that there needs to be an over-riding strategic aim for all those involved – namely, to take appropriate measures to ensure that the number of bus accidents remains low, but also that the consequences of a serious accident, which can never be entirely eliminated, are kept to an absolute minimum.

2.3 Typical accident scenarios

In past years many examinations and studies of bus/coach accidents were undertaken as individual research projects and these were based upon individual case documentation [10, 11, 12, 13, 14, 15]. These amounted to a supplement to the official statistics. In order to contribute to a uniform and accessible presentation, DEKRA Accident Research teamed up with the OEM Evobus GmbH (Daimler Buses) to draw up a proposal in 2006 [16]. Use was made of a scheme originally developed by Volvo Accident Research to describe accident events involving heavy goods vehicles in Sweden. This scheme has also been used in a work-group project to analyse accident events involving heavy goods vehicles in the context of the European Research Initiative eSafety [17].

This allows the representation of bus/coach accidents within three groups: accidents resulting in death and injury to occupants of the buses/coaches concerned, accidents resulting in death or injury of occupants in cars involved and accidents resulting in death or injuries of unprotected road users involved (pedestrians, cyclists, riders of powered two-wheelers). To deal only with the safety of bus/coach occupants in the context of the present paper, 121 accident reports held in the DEKRA databases were reviewed and allocated within eight typical accident scenarios, Figure 8.

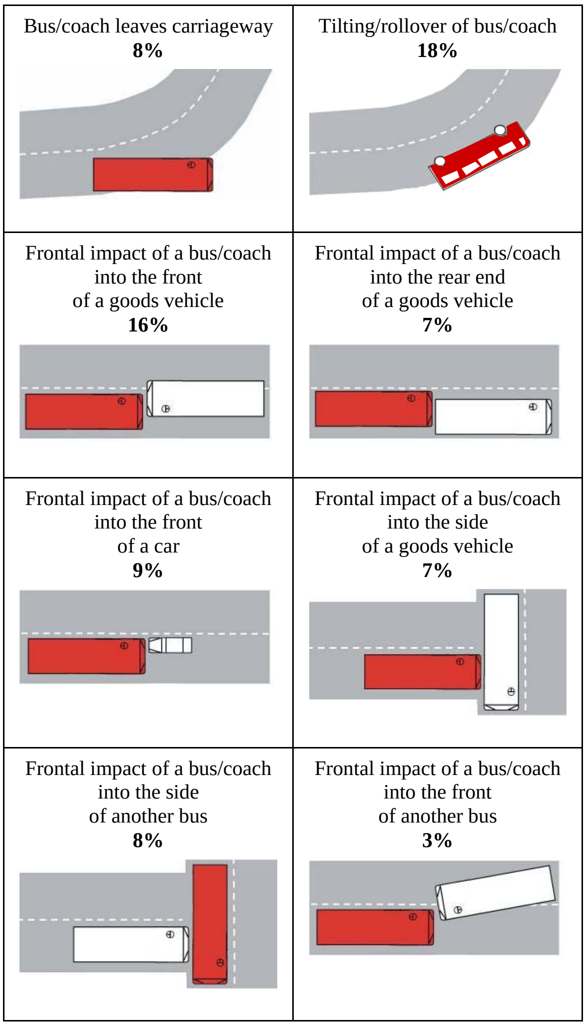


Figure 8. Proportions of typical bus/coach accidents scenarios resulting in fatal or severe injured bus/coach occupants (source: [16])

The highest proportion (18%) of the accidents which result in fatalities or severely injured bus/coach occupants are those in which the bus/coach tilts on its side or rolls over. The second highest proportion (16%) results from a frontal collision with an oncoming goods vehicle. Other scenarios include frontal collisions of the bus/coach with an oncoming car (9%), accidents in which the bus/coach leaves the carriageway and when the front of the bus/coach impacts with the side of a goods vehicle (both 8%), others when the bus/coach drives into the rear of a goods vehicle and when the side of the bus/coach impacts with the side of a goods vehicle (both 7%). In 3% of the cases a bus/coach crashed into the front of another bus/coach. Overall, frontal collisions by buses/coaches play a dominant role. Associated individual cases are described in [16].

3 RISK INDICES

To be able to compare the safety of drivers and passengers in vehicles it is customary to devise different risk indices. Illustrations of how three of the most significant indices have developed over time are given below.

Fatalities per 100,000 vehicles registered is an index which is relatively easy to calculate. It relates the number of fatal injuries of vehicle occupants on German roads to the number of registered vehicles. The index itself and the two numbers required to determine its value can be found in the published official accident statistics [3, 5].

Figure 9 compares the development of the risks related to the rolling stock of buses/coaches, cars and goods vehicles from 1962 to 2011. Since the collection of data for rolling stock numbers only applies to re-unified Germany from 1993 onwards, for the time up to and including 1992 only the numbers recorded in the 'old Laender' of the Federal Republic of Germany (FRG) have been taken into account.

Here, too, the influence of single severe bus/coach accidents causing a strongly varying pattern for bus/coach occupants killed per 100,000 vehicles can be seen. Conforming to the general pattern of evolution towards a higher level of safety for vehicles and occupants there was a significant reduction in the 1980s for all the three vehicle categories studied. After that curves flattened out.

It is noteworthy that the numbers of car occupants killed per 100,000 cars and the comparable index for the occupants of goods vehicles have converged to almost similar values. In 2011 both were close to 5 occupants killed per 100,000 vehicles. In 1998 when only 2 occupants were killed and the number of buses/coaches registered in the rolling stock was 83,000 the relevant index was 2.4 persons killed per 100,000 buses/coaches. No such favourable result was achieved in any other year when the index for buses/coaches was greater than for cars and goods vehicles. This was due to the significant unfavourable influence exerted by the relatively large number of occupants of buses/coaches who were killed in individual accidents.

The risk related to the total rolling stock of vehicles is indeed suitable as an abstract indicator for recognising and comparing different categories of vehicles. However, it does not permit the derivation of the actual level of risk to which individual vehicles and their occupants are exposed because that risk is related to both mileage covered and the number of occupants.

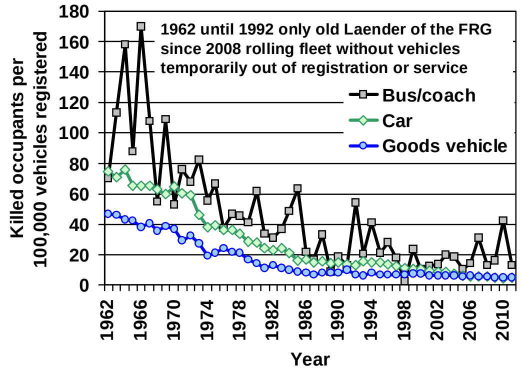


Figure 9. Risk indices for the occupants of buses/coaches, cars and goods vehicles calculated as killed occupants per 100,000 vehicles registered in the rolling stock (Federal Republic of Germany, 1962 until 2011)

Fatalities per billion kilometres travelled is a risk index determined by the relation between the number of vehicle occupants killed and the total mileage travelled per vehicle category per year (in 1 billion = 10^9 vehicle kilometres). This rate of occupants killed, also with respect to the vehicle kilometres travelled, can be clearly defined: the reciprocal index corresponds to the average risk that an individual occupant of a vehicle will be killed in a traffic accident after travelling a specific mileage. Data suitable for the calculation of this risk index associated with buses/coaches operating in public road traffic over the period 1991 - 2011 can also be found in the official accident statistics [5]. For cars and goods vehicles the travel data are available up to 2010 inclusive. The progression of the rate of fatal injuries relative to distance travelled can be seen in Figure 10.

The indices for all three vehicle categories display a downward trend which reflects the general evolution towards greater safety in road traffic. There is particularly strong evidence for this in relation to cars. As far as buses/coaches are concerned, there are further indications of the extent to which the situation can vary widely as a result of individual severe accidents. Without exception, the indices for goods vehicles are low. In 2010, based on a mileage of 1 billion km (10^9 km) of each vehicle, 9.7 occupants of buses/coaches, 3.2 car occupants and 2.1 occupants of goods vehicles were killed. In 2011, the corresponding fatality rate for buses/coaches was 3.1.

While the index considered here for car occupants – namely, 13.7 in 1991 – was far greater than for the occupants of goods vehicles (5.5) and the occupants of buses/coaches (6.6) in the 1990s and 2000s, the values approached so closely to one another that one can assume almost similar risk levels for the occupants of buses/coaches, goods vehicles and cars. Clearly this can be attributed to relatively substantial advances in improving the safety of car occupants.

A bus/coach is normally occupied by many more passengers than a car or goods vehicle. In that case, therefore, a level of risk based only on the mileage of a vehicle does not reflect the risk of an individual occupant being killed in an accident.

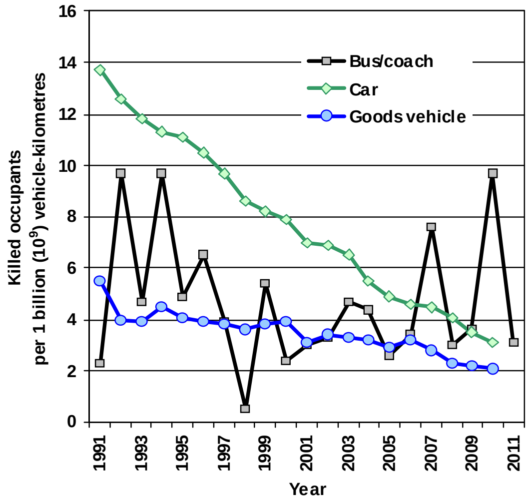


Figure 10. Risk indices for the occupants of buses/coaches, cars and goods vehicles calculated as killed occupants per 1 billion vehicle-kilometres (Germany, 1991 until 2010/2011)

Fatalities per billion person kilometres is a further index by which the overall transport performance (in billions = 10^9 person-kilometres) of the vehicles can be considered. This is the "classical" measure which shows the bus/coach with its large number of occupants to be the safest means of land travel. In a manner corresponding to the numbers published in the official statistics the evolution of this index for cars, goods vehicles, coaches in non-scheduled traffic (long-distance coach) and urban buses in line traffic between 1995 and 2010/2011 can be found in Figure 11. The relevant calculations assume a constant 1.5 occupants per vehicle-kilometre for cars and constant 1.0 occupant per vehicle-kilometre for goods vehicles.

Here it can be seen that for the occupants of urban buses very low risk factors are given, without any exception. In 2010 that risk factor was 0.1 occupants killed per billion person kilometres. Generally, the risk for occupants of long-distance coaches is low. In this instance, however, because of the relatively high number of persons killed in individual years (2007: 18 fatalities, 2010: 22 fatalities), the risk attached to these vehicles is in some years significantly greater than for urban buses. For 2010 there is a figure of 1.0 occupants in long-distance coaches killed per billion person-kilometres. For 2011 this figure is 0.05.

In earlier years risk indices related to transport performance for the occupants of cars and goods vehicles were still significantly higher than for the occupants of buses/coaches. As a consequence of the sustained evolution towards higher levels of safety for vehicles and traffic as a whole, the risk indices for the occupants of these vehicles has further approached that for the occupants of buses/coaches. The latest indices for cars and goods vehicles are around 2.0 – 2.1 occupants killed per billion person-kilometres and based on values of the year 2010.

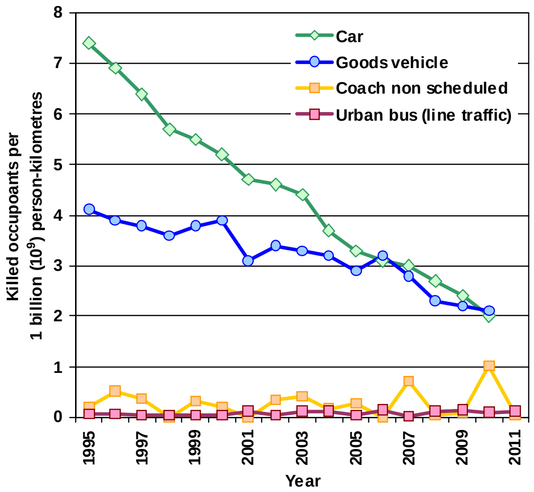


Figure 11. Risk indices for the occupants of urban buses, coaches, cars and goods vehicles calculated as killed occupants per 1 billion person-kilometres (Germany 1995 until 2010/2011)

4 STRENGTH OF THE SUPERSTRUCTURE

The basic prerequisite for effective protection of the occupants - even in a severe accident - is the preservation of the survival space in the vehicle. In that context, the ECE-R 66 requires evidence of the strength of the superstructure of large passenger vehicles [18, 19]. This regulation applies to single deck, rigid- or articulated vehicles belonging to categories M_2 or M_3, Class II or III or Class B able to carry more than 16 passengers. At the request of the manufacturer, this regulation may also apply to any other M_2 or M_3 vehicle that is not included in the scope described above, for example a double-decker coach.

The basic approval method in accordance with ECE-R 66 is defined as the rollover test on a specific vehicle. In order to prove that the necessary structural strength exists, the vehicle is slowly lifted sideways from an initial horizontal position until its centre of gravity passes beyond the tipping axis. It then tips into a ditch having a dry, smooth horizontal concrete surface and a nominal depth of 800mm, Figure 12. The superstructure of the vehicle has to be designed in such a way that the residual space as defined by ECE-R 66 is preserved at all times and along the entire length of the vehicle.

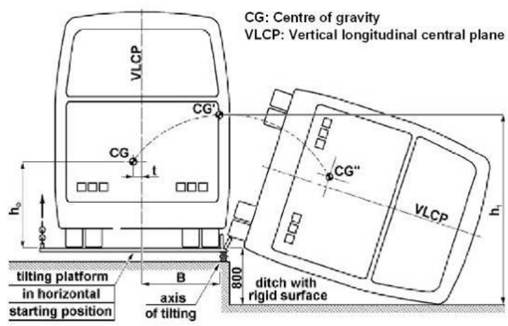


Figure 12. Rollover test on a complete vehicle in accordance with ECE-R 66 [18, 19]

ECE–R 66 first came into force on December 1st 1986. It was ratified in Germany on July 16th 1988. This was preceded by a number of examinations of real-world accidents in the course of which the bus/coach structure had deformed after it had tipped or rolled over. The behaviour of bus/coach structures in such accidents had been examined earlier in the 1970s and 1980s in countries such as Hungary under corresponding conditions and the results analysed comprehensively [20]. Similar activity had been carried out in Germany and in the UK. Rollover tests under various conditions had been performed at Daimler, for example. Figure 13 shows a test using a Mercedes-Benz coach O 303. The test conditions were as prescribed by ECE-R 66.

The amended Series 01 of ECE-R 66 came into force on the 15th October 2008. New vehicle types have had to satisfy this version of the regulation from November 19th 2010 [19].

The major difference compared with the original version is the fact that now 50% of the passenger mass has to be taken into account because the mass of belted passengers acts on the structure. This leads to a considerable increase of energy input into the structure compared with the situation described in the original version when only an empty vehicle had to be tested.

Figure 13. Rollover test on a Mercedes-Benz O 303 in accordance with ECE-R 66 conducted in 1987

In the most recent amendment (Series 02) the scope was extended to include minibuses (Category M_2) and double-decker coaches. For the latter the application of the regulation is optional. The ECE-R 66-02 came into force on August 19th 2010. From November 9th 2017 the registration application for a new vehicle may be refused if it does not comply with ECE-R 66-02.

The Setra Comfort Class 500 shown in Figure 14 is the first coach series from the manufacturer Daimler to comply with the new regulation. One major development target was the reduction of fuel consumption and the CO_2-emission rate. Since the vehicle weight has a considerable influence on those matters, considerable attention was paid to lightweight design. Figure 15 shows the superstructure of the new coach series. The most important elements are the U-shaped roll bars, which form the safety cage of the vehicle. In case of a rollover they will carry most of the load and will absorb a high proportion of the kinetic energy by means of plastic deformation. In order to maximise the potential of energy absorption, high-strength steel is used as indicated in Figure 15.

Beginning from the conceptual phase and throughout the complete design process, numerical simulations helped to optimize the superstructure. Results from tests on sections (see Figure 16) were taken to verify the finite element models used for the rollover simulation. Consequently, for type approval the method described in Annex 9 of ECE-R 66-02 was chosen (i.e. computer simulation of rollover test on a complete vehicle as an equivalent approval method).

Figure 14: Coach Setra ComfortClass 500

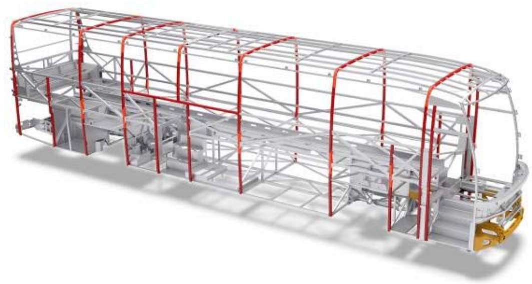


Figure 15: Superstructure of the new Coach Series Setra ComfortClass 500

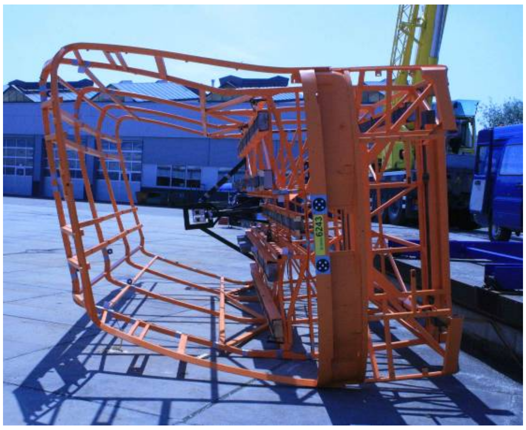


Figure 16: Test of a segment of the superstructure (prototype version)

Finally, it can be summarized that in comparison to the preceding series the strength of the superstructure has been greatly increased in order to comply with the most recent amendment of ECE-R 66. Although this has led to a weight increase of the side wall structure, the total weight of the body in white could be reduced by 5%. As mentioned above this has been achieved by intensive numerical simulations, which helped to identify regions with potential to weight reduction.

5 FRONTAL IMPACT PROTECTION

On its own initiative and without the compulsion of a legal requirement, the bus manufacturer EvoBus has developed a special protective system to improve passenger safety in the event of a frontal impact. It has been installed under the name "Front Collision Guard" in the series production of current vehicles of the Setra TopClass and Setra ComfortClass types and also in the Mercedes-Benz Travego. The system embraces the different elements front underrun protection, crash structure and rigid platform, Figure 17.

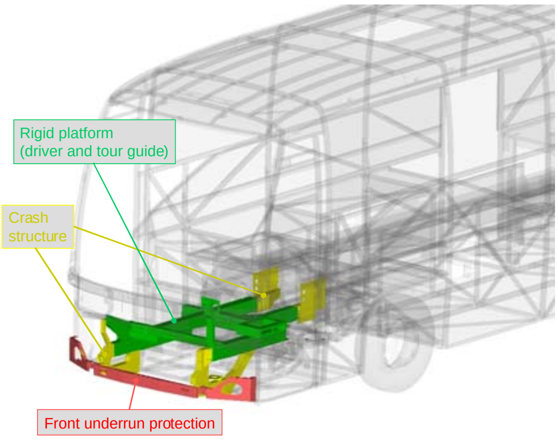


Figure 17: Elements of the Front Collision Guard installed in the Setra ComfortClass 500

The system was developed in view of the fact that buses/coaches have virtually no front-located deformation structure (crumple zone). In the event of a frontal impact the system ensures that no intrusions into the internal space at the front of the bus will reach the area where the seats for the driver and the tour guide are located. To this end the immediate front area has been designed to be extremely stiff and the crash structure behind it can absorb controlled deformation energy.

The rigid platform serves to provide further protection of the survival space of the driver and tour guide. Essentially, it consists of a stiff frame structure which carries the driver seat and the steering column. When an impact occurs, the whole platform can be forced passively backwards and thereby preserving the original volume of survival space.

The front underrun protection – which is not prescribed by law for buses – prevents cars from sliding under the front of the coach in a head-on collision. It consists of a beam-like structure that is located on the same level as a typical car bumper thus utilizing the energy absorbing mechanism of the car's front structure (crumple zone) in the best possible way.

The development of the Front Collision Guard has been based upon numerical simulations and physical crash tests for validation defined by reference to real-world accident scenarios. All the tests were carried out by DEKRA at the Neumünster Crash Test Center and commissioned by EvoBus. In those tests the weights of the individual trial buses were, as a rule, 70% of the total weight of the heaviest vehicles in the series. The weight of the occupants was simulated by sandbags which were firmly secured to the seats. In this way, the inertial effect of their mass begins immediately after the start point of the collision. When occupants in buses/coaches are restrained by an appropriate system there is a time delay before this has an effect on the loadings and this moderates the maximal strains imposed on the seats and the structure of the vehicle. The seats of the driver and the tour guide were occupied each with a buckled-up instrumented dummy (Hybrid III, 50th percentile male). The vehicle impacts at a speed of 25 km/h with its full width of the front a stationary rigid barrier. 80% of the corresponding real-world accident scenarios involving frontal impacts conform to these parameters (see Figure 8). Further details concerning the front collision guard and the related testing are reported in [21].

Compared to the previous series the Front Collision Guard of the Setra ComfortClass 500 series has undergone further optimisation. This has resulted in an extension of the rigid platform to the right side including the tour guide place. Two crash tests have been performed in accordance with the above-mentioned specification. The most recent test was conducted in June 2012. The deformed structure of the tested vehicle, a Setra 515 HD, is shown in Figure 18.

The effect of the impact forces shortened the vehicle length by 380 mm. The survival space for the driver and the tour guide was not affected. The peak value of the deceleration of the bus between its axles was about 18 g. The stresses suffered by the instrumented dummies were without exception less than the bio-mechanical limit values prescribed in relevant technical regulations. The values for driver and tour guide are shown as a bar diagram in Figure 19. Each value is related to its corresponding threshold of the Standard FMVSS 208

On a voluntary basis and without any legal requirement to do so the full-scale crash tests were supplemented by pendulum impact tests in accordance with ECE-R 29. The kinetic energy of the pendulum was 44 kJ. Figure 20 gives both an internal and an external view of a Mercedes-Benz Travego after the test. It can be seen that the impact led only to minor deformations. The survival space of the driver and tour guide was completely preserved.

Figure 18: Coach Setra 515 HD after a full-frontal impact with a stationary rigid barrier at 25 km/h

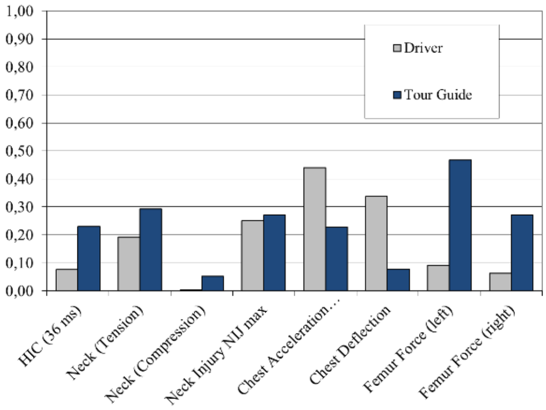


Figure 19: Occupant loadings relative to threshold values from the Standard FMVSS 208

For the Setra ComfortClass 500 the impact energy has been increased to 55 kJ. It could be shown by computer simulation that the requirements have been met. For this reason no physical pendulum test has been conducted.

Overall the Front Collision Guard system has set new standards in the area of the passive safety of coaches. The current configuration of the new Setra ComfortClass 500 series resulted in a further improvement of the secondary (passive) safety.

Complete preservation of the survival space is guaranteed for all front occupants in the context of the selected test conditions.

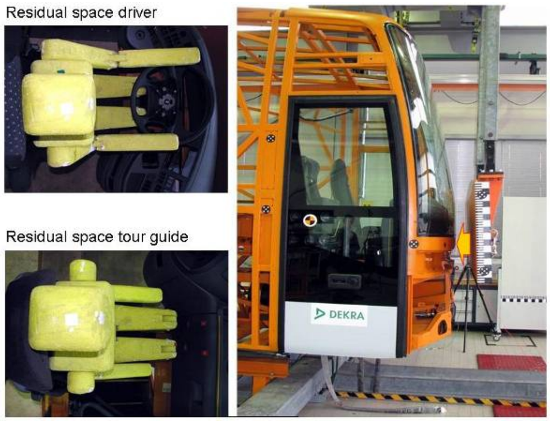


Figure 20: Mercedes-Benz Travego after frontal pendulum-impact test

6 RESTRAINT SYSTEMS

Assuming that the survival space is unaffected when an accident occurs, it is also necessary that the occupants are held in their seats to receive the highest possible level of protection. Consideration must be given not only to restraint during frontal collisions but also in the event of other types of accident in particular those involving a rollover. The analysis of real-world accidents has frequently shown that it is generally safer for the occupants to be retained in the vehicle in case of a rollover as distinct from being ejected out of the vehicle. In trials with buses being rolled over it has also been observed that belted dummies remain protected in their seats while unbelted ones are thrown out through a broken window [22].

In a coach when another seat is positioned in front of a particular seat, the back of the seat in front can act as part of the restraining system. In such seats it is sufficient to provide the equipment with 2-point lap belts. Figure 21 illustrates the combined effect of the lap belt and the back of the seat in front in restraining the movement of an occupant when a frontal collision occurs.

Buses that have been registered for the first time after October 1st 1999 need to comply with the EC-Directives 74/408/EEC "Seat Anchorages", 76/115/EEC "Seat Belt Anchorages" and 77/541/EEC "Seat Belts" in their relevant editions, according to the current requirements for registration in Germany. This results in a 3-point belt for driver and crew members (see Figure 22) and either 2-point or 3-point belts for the passengers (see Figures 23 and 24), depending on the bus operator's choice. In the case of 2-point belts parts which are positioned in a reference zone, i.e. a predefined area describing where the passenger might hit an obstacle because the lower half of his body is retained on the seat while the upper torso moves towards the front of the vehicle, need to be energy absorbing.

Under German legislation buses without specific luggage rooms or with an area for standing passengers larger than the gangway plus an area larger than the area for two double seats are exempted from mandatory compliance with the three EC-Directives mentioned above.

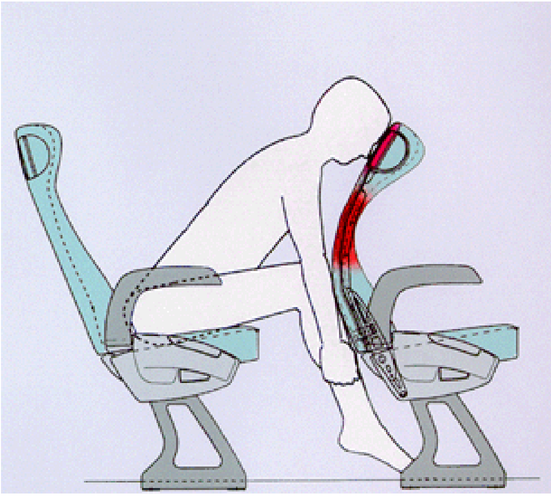


Figure 21: Function of a 2-point lap belt combined with the seat back in front as a restraint system for occupants in coaches

Figure 22: Coach driver seat fitted with 3-point-belt

In the case of frontal impacts the seat structure with the associated seat and belt anchorage must be able to hold the entire mass of the passenger occupying the seat. The loads on the anchorage points are then correspondingly greater.

Figure 23: Coach passenger seats fitted with 3-point belts

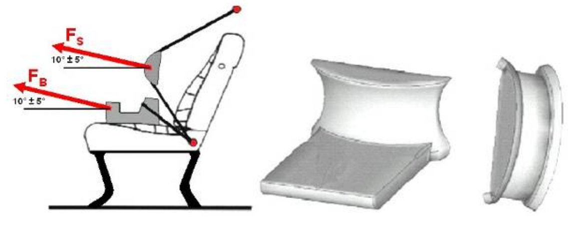
Figure 24: Coach passenger seats fitted with 2-point lap belts

The effectiveness of 3-point seat belts in rollover accidents still continues to be a controversial subject. On the one hand, the shoulder element of a 3-point system can fail to retain the upper body of an occupant when the vehicle has rolled over or is resting on its side. In such a situation the whole system becomes ineffective. In that context it needs to be noted that with the automatic seatbelts currently used the retractor not only blocks when it experiences large extraction speeds (when a frontal collision begins) but also when a vehicle tilts laterally. This means that the risk of the shoulder belt being displaced can be reduced.

Belt tensioners such as those used in cars are not necessary for belt systems in coaches because of much lower deceleration rates.

The mechanical strength of the seat and belt anchorages is prescribed by ECE-R 14 [23]. Static tests are carried out and these take account of the different strength levels required for different classes of vehicles, Table 2.

Table 2: Static forces to test the strength of the seat and seat-belt anchorages in motorized vehicles according to ECE-R 14



Vehicle category	M_1, N_1	M_3, N_3	Other vehicles
Test force F_S	1,350 daN*	450 daN*	675 daN*
Test force F_B	1,350 daN*	450 daN*	675 daN*
Additional forces in tests for belt anchorages located wholly within the seat structure or dispersed between the vehicle structure and the seat structure	Consideration of the inertia load of the mass of the seat by an additional test force: M_3, N_3: Force equal to 6.6 times the mass of the complete seat M_2, N_2: Force equal to 10 times the mass of the complete seat Other vehicles: Force equal to 20 times the mass of the complete seat		
* ± 20 daN			

For cars (M_1) and light goods vehicles up to 3.5 tonnes (N_1) the test forces applied to both shoulder and lap belts amounts to 1,350 kN. As a rule, the occupants of heavier vehicles involved in accidents – e.g. for vehicle-vehicle collisions – experience lower levels of deceleration. Accordingly, the test forces used to evaluate belt-anchorages in such vehicles are at a lower level. For coaches of 5 tonnes upwards, (Class M_3) the test force is 450 daN.

If the belt anchorages are completely integrated into the structure of the seat or distributed to the structures of vehicle and seat, higher test forces must be applied to take account of the greater loads imposed on the belt anchorages by the deceleration effect of the mass inertia experienced during an accident. In the case of coaches the value is 6.6 times mass of the complete seat unit.

The relevant properties of the seatbelts themselves can be found in ECE-R 16 [24]. These apply to all types of vehicle classes.

ECE-R 80 [25] contains special requirements relating to the seats of motorized buses/coaches (Categories M_2 and M_3 Classes II, III and B) and their anchorages. This directive was introduced in 1989 and ratified by Germany in 1990. At the present time the second version of the Modification Series 03 and dated July 26th 2012 is in force.

The regulation requires that every type of seat must undergo either a dynamic test (Appendix 1, ECE-R 80) or a static test (Appendices 5 and 6, ECE-R 80). This includes testing the performance of the seat anchorage. It should be noted that a static comparison test does not correspond to a real-world accident scenario.

The dynamic testing simulates a front impact test using a sled. This requires a testing platform on which the seat to be tested and its anchorage are mounted. A second seat is mounted behind the first seat (auxiliary seat). Two tests are carried out at an impact speed of the sled of between 30 and 32 km/h. During the test the deceleration must run along a defined corridor and have a maximum value of between 8 and 12 g.

For the first test an unbelted dummy sits in the auxiliary seat. In a simulated impact it is restrained only by the back of the seat under test (see test using 2 dummies in Figure 25). For the second test a belted dummy occupies the auxiliary seat (see test using 2 dummies in Figure 26). In this case both the belt and back of the seat under test restrain the dummy.

Figure 25. Dynamic test of a coach seat bench according to ECE-R 80 with 2 dummies unbelted impacting the back rest of the tested seats in front

ECE-R 80 does not require the additional occupation of the seats under test by a belted dummy when an unbelted dummy impacts the back of the seat from behind (see also [20]).

According to current enquiries made in individual vehicles the proportion of passengers in coaches who wear their seatbelts is only around 25% [26]. Higher belt-use rates may be reached by specific information and safety instructions resulting in better exploitation of the existing safety potential.

Figure 26: Dynamic test of a coach seat bench with 2 belted dummies according to ECE-R 80

SUMMARY

Although the safety-levels of cars and goods vehicles have improved considerably, the bus/coach remains the safest means of travelling on the road. The safety of buses/coaches has been at a very high level for decades now.

ECE-R 66 was legally prescribed for the superstructure to resist the consequences of a lateral rollover. This was supplemented by restraint systems which satisfy the requirements of ECE-R 14, ECE-R 80 and ECE-R 16.

Amendment series ECE-R 66-01 and -02 constituted further steps to improve the superstructure on a very high level taking into account the loading of belted occupants. Beyond that, additional measures were undertaken on a voluntary basis by certain OEMs without legal requirements. Confirmed by crash and pendulum tests, the safety in the event of a frontal impact has been improved significantly. As this paper shows, the introduction of the Front Collision Guard system has set a new standard in the area of secondary (passive) safety of coaches.

For all these measures to become fully effective it is necessary that all occupants wear their seatbelts throughout the journey. Therefore, it is important to increase the proportion of passengers using their belts.

Recently, essential improvements of the safety of coaches and buses have been achieved by primary (active) safety systems such as Active Brake Assist 2, Lane Departure Warning and Attention Assist (drowsiness warning). Supplemented by the secondary (passive) safety systems described above modern coaches are safer than at any time before and will keep their status as the safest means of road transport.

REFERENCES

[1] European Commission – Road safety – Accident Data. http://ec.europa.eu/transport/road_safety/specialist/statistics/index_en.htm

[2] European Commission - COM(2003) 311 final: European Road Safety Action Programme. Halving the number of road accident victims in the European Union by 2010: A shared responsibility. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2003:0311:FIN:EN:PDF

[3] Verkehrsunfälle. Jahresberichte des Statistischen Bundesamtes Fachserie 8, Reihe 7. https://www.destatis.de/DE/Publikationen/Thematisch/TransportVerkehr/Verkehrsunfaelle/VerkehrsunfaelleJ2080700117004.pdf?__blob=publicationFile

[4] Verkehrsunfälle. Zeitreihen des Statistischen Bundesamtes. https://www.destatis.de/DE/Publikationen/Thematisch/TransportVerkehr/Verkehrsunfaelle/VerkehrsunfaelleZeitreihenXLS_5462403.xls?__blob=publicationFile

[5] Verkehrsunfälle. Unfälle von Kraftomnibussen im Straßenverkehr. Jahrsbereichte des Statistisches Bundesamtes, Wiesbaden. https://www.destatis.de/DE/Publikationen/Thematisch/TransportVerkehr/Verkehrsunfaelle/UnfaelleKraftomnibusse.html

[6] Trauer und Bestürzung über das Lauffener Omnibusunglück. Heilbronner Stimme, 22. Juni 1959.

[7] Lauffen-Unglück – Was ist rechtzeitig? Der Spiegel, 26. Dezember 1959

[8] Tote und Verletzte bei Busunglück auf A2. Meldung in Spiegel online vom 04.11.2008. http://www.focus.de/panorama/welt/hannover-tote-und-verletzte-bei-busunglueck-auf-a2_aid_346150.html

[9] DVR Schriftenreihe Verkehrssicherheit Nr. 16. Vision Zero. Grundlagen und Strategien. Bonn, 2012 http://www.dvr.de/betriebe_bg/daten/studien3042.htm

[10] Danner M., Langwieder K.: Die Bedeutung von Bus-Unfällen im gesamten Unfallgeschehen der Bundesrepublik Deutschland. Vortrag auf der XII Konferenz für Autobus-Experten, 2. - 5. Juni 1981, Budapest

[11] Langwieder K., Danner M., Hummel T.: Collision Types and Characteristics of Bus Accidents - Their Consequences for the Bus Passenger and Accident Opponent. Proceedings 10th International Technical Conference on the Experimental Safety Vehicles (ESV), Oxford, England, July 1-4, 1985, pp. 585-594

[12] Grandel J., Müller C.-F.: Beitrag zur Sicherheit von Omnibussen. Fachpublikation der DEKRA-Unfallforschung, November 1994

[13] Berg F. A. Niewöhner W.: Pointers towards the improvement of safety in buses, derived from an analyses of 371 accidents involving buses in Germany and from crash test results. Proceedings 16th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Windsor, Ontario, Canada, May 31- June 4, 1998, Paper Number 98S4-O-03, http://www-nrd.nhtsa.dot.gov/pdf/esv/esv16/98s4o03.pdf

[14] ECBOS: Enhanced Coach and Bus Occupant Safety. Project funded by the European Commission under the 5th framework programme for the period from 01/01/2000 to 30/06/2003; Project N°: 1999-RD.11130, http://ec.europa.eu/transport/roadsafety_library/publications/ecbos_final_report.pdf

[15] Hummel T., Bende J., Kühn M., König T., Strzeletz R: Unfälle mit Kraftomnibussen - Aspekte der Insassensicherheit und Nutzenpotenziale von Fahrerassistenzsystemen. Berichte zur 11. Internationalen VDI Fachtagung Nutzfahrzeuge, Styr, Österreich, 19. und 20. Mai 2011, VDI-Berichte Nr. 2128, S. 155-175

[16] Niewöhner W., Berg F. A., Vorgerd D.: Überblick und ausgewählte Szenarien des Unfallgeschehens mit Bussen in Deutschland und Europa. Tagungsband zum DEKRA/VDI-Symposium Sicherheit von Nutzfahrzeugen. Neumünster, 12.-13. Oktober 2006

[17] Final Report of Heavy Duty Vehicles Working Group. Brussels, October 2005. http://ec.europa.eu/information_society/activities/esafety/doc/esafety_forum/aghdvfinalreport_eng1_2.pdf

[18] ECE-R 66: Uniform technical prescriptions concerning the approval of large passenger vehicles with regard to the strength of their suoerstructure. United Nations Economic Commission for Europe http://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/r066r1e.pdf

[19] Amtsblatt der Europäischen Union vom 30.3.2011, S. L84/1 - L84/45 http://www.bmvbs.de/cae/servlet/contentblob/44954/publicationFile/41757/r-66-festigkeit-des-aufbaus-von-autobussen-pdf.pdf

[20] Vincze-Pap, S.: European Test Methods for Superstructures of Buses and Coaches Related to ECE-R 66 (The applied Hungarian calculation method). Proceedings 16th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Windsor, Ontario, Canada, May 31- June 4, 1998, Paper Number 98S4-P-18 http://www-nrd.nhtsa.dot.gov/pdf/esv/esv16/98s4p18.pdf

[21] Steinmetz, G.: A New Front Structure for Coaches To Improve Their Crashworthiness. FISITA 2010, World Automotive Congress, May 30 – June 4, 2010, Budapest, Paper Number F2010-F-006

[22] Forslund B, Persson H.: Passive safety of Volvo´s buses and coaches. DEKRA/VDI-Symposium Safety of Commercial Vehicles, Neumünster, Germany, =ctober 12-13, 2006

[23] ECE-R 14: Uniform provisions concerning the approval of vehicles with regard to safety-belt anchorages, ISOFIX anchorages systems and ISOFIX top tether anchorages http://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/R014r4am6e.pdf

[24] ECE-R 16: Uniform provisions concerning the approval of: I. Safety-belts, restraint systems, child restraint systems and ISOFIX child restraint systems for occupants of power-driven vehicles; II. Vehicles equipped with safety-belts, safety-belt reminder, restraint systems, child restraint systems and ISOFIX child restraint systems http://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/R016r7.pdf

[25] ECE-R 80: Uniform provisions concerning the approval of seats of large passenger vehicles and of these vehicles with regard to the strength of the seats and their anchorages http://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/R080r2e.pdf

[26] Bach P., Bahlmann N.: Safety of coaches – integrity of the vehicle superstructure and the using of safety belts by the occupants. 6th DEKRA Symposium Safety of Comercial Vehicles, Neumünster, October 9-10, 2008

AN EXAMINATION AND COMPARISON OF PASSENGER TRANSPORT BUS OCCUPANT PROTECTION REGULATIONS ACROSS 5 CONTINENTS

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Paper Number 13-0469

ABSTRACT

A research project was undertaken to understand, compare and contrast the government regulations for mid to large size (mostly greater than 16 passengers) transport busses. The continent countries examined included Australia, Europe, Canada, United States, South Africa, Brazil, Chile and Peru. The occupant protection regulations examined included the requirements for superstructure capabilities, seat and seat attachments, seat belts and seat belt anchorages.

INTRODUCTION

Motor Coach/Bus (MCB) Regulations vary significantly around the world. After investigating a recent transport bus crash that included several fatalities, the team at Safety Engineering embarked on a research project to outline the differences in Governmental MCB Regulations for eight countries on 5 continents. Our main focus was on the occupant protection regulations that govern structural components and internal safety features. The investigated countries are shown with red stars on the global map in Figure 1.

Figure 1. Stars indicate country researched.

Types of Regulations Investigated

The main focus of our research comparison was the MCB superstructure regulations as adopted by various countries from the original United Nations joint resolution called the UN–ECE/R66 rule. [1] This regulation governs the superstructure strength minimum pass/fail testing requirements and has roof and side structure intrusion and deformation limits to protect occupants. The specific manufacturing and testing requirements for superstructures in the regulations are compared.

This research also investigated the associated regulations for internal occupant protection safety systems including seat belts, seats and the anchorage systems for both. It should be noted that there are both requirements for "having" seat belts on the MCB as well as requirements for "wearing" seat belts while riding in the MCB.

Application of Regulations

The research indicates that there are two main areas that classify the applicability of the regulations to any given MCB. First, some countries differentiate by MCB Service Type, i.e.: Public vs. Private Transport vehicles, and/or Paid vs. Free Transport vehicles, where some regulations apply to one and not the other. The second type of differentiation is the classification for the size of the MCB. There is some correlation of a global standard for MCB size classification, the "Category M" class which is almost universally used, but most countries had extensions, modifications and/or sub-classes for specialized vehicles such as the Double Decker MCBs found predominantly in Europe.

REGULATIONS RESEARCH

MCB Regulations vary significantly worldwide, from none at all to strict and seemingly affective standards. Some of the countries examined either didn't have regulations, didn't have regulations related to the superstructure or didn't have regulations for busses in the private sector. As a baseline understanding for these comparisons, the superstructure, seat belts and seat requirements are outlined in the next section.

Superstructure Regulations

Superstructure regulations for MCBs worldwide vary considerably. The Superstructure is defined as the *uppermost structural components* that form the outline of the imaginary envelope around the occupants, sometimes called the "Occupant Survival Space" or "Residual Space". These regulations are in place to govern MCB manufactures and the testing requirements that must be passed to limit intrusion and subsequent occupant injury from intrusion. A listing of these regulations by researched country is shown in Table 1. Three of the eight have adopted some form of United Nations Economic Commission for Europe (UNECE) Regulation No. 66 (R66), ECE/R66 the European Superstructure Standard.

Table 1.
MCB Superstructure Regulations by Country

Superstructure Regulations/Standards	
United States	N/A
Europe (ECE)	R-66
Australia (ADR)	59
South Africa (SANS)	1563
Canada	N/A
Peru	N/A
Brazil	N/A
Chile	N/A

History of ECE/R66 Superstructure Standard

The standard for MCB's Superstructure in Europe is ECE/R66. The regulation originated at the United Nations (UN) in Geneva in 1958 and entered into force in 1986 by the UN where 40 countries adopted the regulation shown in Table 2.

In 2002, at the UN 82nd Working Party on General Safety Provisions (GRSG) conference, the regulation was reviewed by informal expert groups who made recommendations to improve the regulation. ECE/R66 has been revised and amended several times over the last ten years with the most recent revision being in 2010, where they changed the language to define a "double-decker bus" and renumber the regulation.

Table 2.
Countries that Adopted ECE-R66 at
the Original United Nations Inception: 1986

Countries That Have Adopted ECE-R66*		
Europe		
Germany	Turkey	Finland
Ireland	Latvia	France
Spain	Denmark	Croatia
Bulgaria	Switzerland	Malta
Romania	Slovenia	Lithuania
Netherlands	Austria	Poland
Slovakia	Hungary	Sweden
Luxembourg	Portugal	Belarus
Norway	Belgium	Italy
Czech Republic	Estonia	Greece
United Kingdom	Russian Federation	
Serbia/Montenegro	Bosnia/Herzegovina	
Asia		
Azerbaijan	Cyprus	Ukraine
Japan	Korea	
The former Yugoslav Republic of Macedonia		
Australia		
Australia	New Zealand	
Africa		
South Africa		
*Not all requirements of ECE-R66 were adopted by all countries.		

Application of Superstructure Regulations by Country Researched

A comparison of this standard with the other requirements we found, and how they are applied, reveals that the most advanced standard in terms of crashworthiness is the ECE/R66. It requires MCBs to pass a superstructure strength test for compliance. This strength test includes the mass of the occupants in the MCB and to comply, the Superstructure must NOT intrude in to the "Residual Space" that surrounds the passenger seating locations. Both Australia and South Africa were among the countries that adopted ECE/R66 via the UN in 1986. However, both the Australian and South African standards have omitted the requirement to include the passenger mass as part of the test requirement. The United States and Canada do not have a MCB superstructure standard. In 2015, they will be instituting FMVSS 216 and CMVSS 216, a static roof strength test that requires a roof strength to vehicle weight ratio of one and a half for compliance and applies to vehicles with gross vehicle weight between 6000 and 10000 lbs, which may apply to some smaller MCBs.

The South American countries of Brazil, Chile and Peru also do not have a superstructure standard. Our study shows that these countries have the most risk of injuries due to rollovers for several reasons including poor road conditions, the lack of seat belt use, availability of black market driver's licenses, poor traffic regulations and a relatively older fleet of vehicles that most likely don't have ESC or other passive safety systems seen in newer vehicles.

Seat Belt "Wearing" Regulations

The general consensus from a global point of view is that seat belts should be worn on MCBs. Over the last ten years a number of countries have instituted regulations that make seat belt wearing on MCBs mandatory. The countries that have mandatory MCB seat belt wearing standards are Europe and Australia *if* there are belts in the bus. In 2015, Australia will have visual and auditory belt minders that will alert the driver. South Africa has a mandatory requirement for the driver of the bus and the driver/passenger relief person. Although the US currently has no standard, NHTSA recently proposed an amendment to FMVSS 208, the occupant protection standard, to include seat belts on MCBs of greater than 26000 lbs. A breakdown of mandatory belt use by country is in Table 3.

Table 3.
MCB Seat Belt "Wearing" Regulations

Countries **with** Mandatory **Wearing**	Countries **without** Mandatory **Wearing**
Europe (if equipped)	United States
Australia (if equipped)	Canada
South Africa (driver + relief driver only)	Brazil
Chile* (+ 2008 MY for public transport only)	Peru

Seat Belt and Anchorage Regulations

Most countries researched had some sort of seat belt and/or anchorage requirement for MCBs. Australia has the most stringent regulations including mandatory belts in MCBs as well as the mandatory wearing of belts. Table 4 shows the regulations.

Table 4.
MCB Seat Belts & Anchorages Regulations

Seat Belts & Anchorages	
United States	209, 210**
Europe	R14
Australia	4-05, 5-05
South Africa	1080, 1563, 1564, 20014
Canada	210, 209, 210.1-.2
Peru	Annex III
Brazil	N/A
Chile	Decree 122
** Driver's seat only (NPRM 208 – All Passengers, 2015)	

Seat Anchorage Regulations

It should be noted here that a significant finding from accidents investigated in Australia shows that in both rollover and frontal crashes, injuries in MCBs can occur from poor seat and seat belt anchorages allowing the seats and belts to come loose. Australia has increased the load requirements for both to prevent the seats and seat belt anchorages from dislodging under a 25g load. Table 5 shows the countries that have regulations for seat anchorages.

Table 5.
MCB Seat Anchorage Regulations by Country

	Seat Strength	Seat and Seat Anchorage
United States	207	207
Europe	R17	R80
Australia	66	3-03
South Africa	1429, 1430, 20017	1564
Canada	207	207
Peru	Annex III	
Brazil	N/A	N/A
Chile	N/A	N/A

Both seat and seat belt anchorages can have a significant effect on the injury potential for the passengers inside the MCB. The photo in Figure 2 shows how the seat anchorage comes loose and the seat rows pile up on each other.

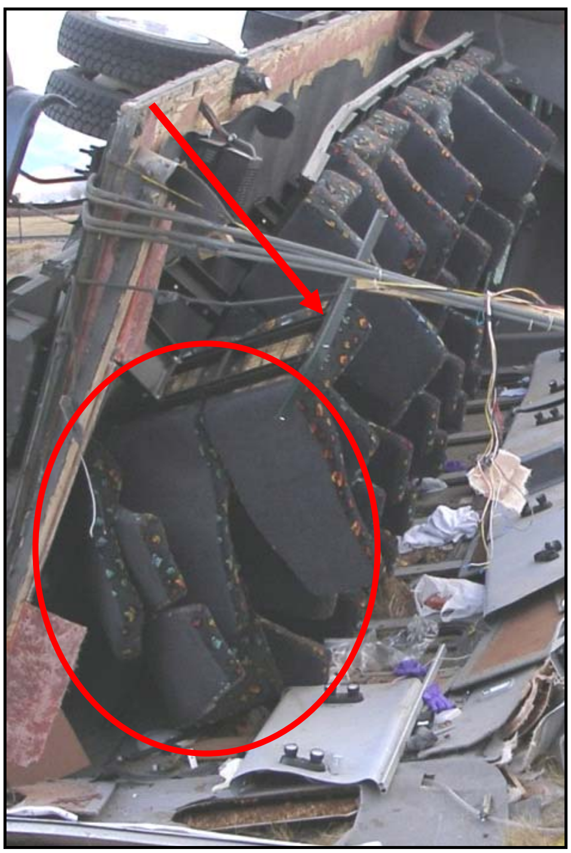

Figure 2. Seat Attachment Failure in MCB Rollover

REGULATION RESEARCH BY COUNTRY

The following sections contain the information gathered for the various counties in this study. Included in each section are the regulatory requirements for MCBs and specifically how they compare to the ECE-R66 requirement.

Regulations in Europe

The specific ECE/R66 regulation has been adopted by the European countries listed in Table 6. However, as each country adopted the regulation they may or may not have added or deleted from the specific section of the original regulation.

Table 6.
17 European Union Countries with ECE/R66

17 EU Countries with ECE/R66		
Austria	Greece	Netherlands
Belgium	Hungary	Portugal
Denmark	Ireland	Spain
Estonia	Italy	Sweden
Finland	Luxembourg	
France	Malta	United Kingdom

The scope of the R66 regulation as it is today applies to: single-deck rigid or articulated vehicles designed and constructed for the carriage of more than 22 passengers, whether seated or standing, in addition to the driver and crew.

It is clear that ECE/R66 is by far the most advanced regulation for MCBs with regard to the superstructure. The main reason is the additional mass added for the occupants which increases the amount of load the superstructure must withstand when being tested for certification.

After the mandatory seat belt regulations were enacted in 1997 and 2006, the UNECE recognized that the occupant mass becomes coupled to the structure increasing its overall mass and centre of gravity height. This results in an increased rollover energy absorption requirement before intrusion of the superstructure into the residual space. [2]

The United Nations website has Addendum 65 to Regulation No. 66, Revision 1 - Corrigendum 2, from December 2006 which added the "Restrained Occupant Mass" as part of the compliance calculation as follows:

"Paragraph 3.2.2.1., correct to read: " ….
$M_t = M_k + k \cdot M_m$, *where k = 0.5 and* M_m *is the total mass of the restrained occupants (see paragraph 2.15.).* [3]

Sections 2.14 to 2.18 define the parts of the calculation and in addition, define the specific weights to be used for the Driver and Individual Occupant Mass as follows:

- 2.14. "Unladen kerb mass" (Mk) means the mass of the vehicle in running order, unoccupied and unladen but with the addition of **75 kg** (165lbs) for the mass of the driver, the mass of fuel corresponding to 90 per cent of the capacity of the fuel tank specified by the manufacturer, and the masses of coolant, lubricant, tools and spare wheel, if any.
- 2.15. "Total occupant mass" (Mm) means the combined mass of any passengers, crew who occupy seats fitted with occupant restraints.
- 2.16. "Total effective vehicle mass" (Mt) means the unladen kerb mass of the vehicle (Mk) combined with the portion (k = 0.5), of the total occupant mass (Mm), considered to be rigidly attached to the vehicle.
- 2.17. "Individual occupant mass" (Mmi) means the mass of an individual occupant. The value of this mass is **68 kg**. (150lbs)
- 2.18. "Reference energy" (ER) means the potential energy of the vehicle type to be approved, measured in relation to the horizontal lower level of the ditch, at the starting, unstable position of the rollover process.

These definitions come into play when the calculation for the Reference Energy that the structure must withstand is performed. It is stated in section 3.2.2.1 and reads as follows:
The value of reference energy (ER) which is the product of the vehicle mass (M), the gravity constant (g) and the height (h1) of centre of gravity with the vehicle in its unstable equilibrium position when starting the rollover test (see figure 3)…

$$E_R = M.g.h_1 = M.g\left[0.8 + \sqrt{h_0^2 + (B \pm t)^2}\right]$$

where:
M = Mk*, the unladen kerb mass of the vehicle type if there are no occupant restraints, or, Mt, total effective vehicle mass when occupant restraints are fitted, and*
Mt = Mk + k • Mm*, where k = 0.5 and* ***Mm is the total mass of the restrained occupants***
t = perpendicular distance (in metres) of the vehicle centre of gravity from its longitudinal vertical central plane.
B = perpendicular distance (in metres) of the vehicle's longitudinal vertical central plane to the axis of rotation in the rollover test.
g = gravitational constant
h1 = the height (in metres) of the vehicle centre of gravity in its starting, unstable position related to the horizontal lower plane of the ditch.

Section 5 of R66 explains the performance requirements for the superstructure of each vehicle that falls under the regulation. The requirements specify that no part of the superstructure shall intrude into the "Residual Space" during and after the rollover test on complete vehicle as defined in the regulation in section 5.2 and shown by the shaded outline in Figures 3 and 4. The test configuration is shown in Figure 5.

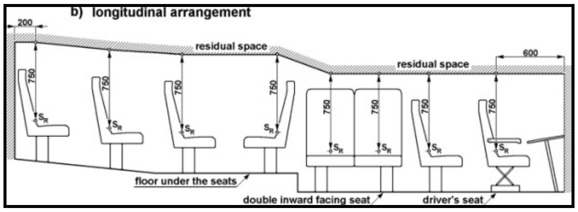

Figure 3. Side view showing step-up of Residual Space as the floor rises toward the rear.

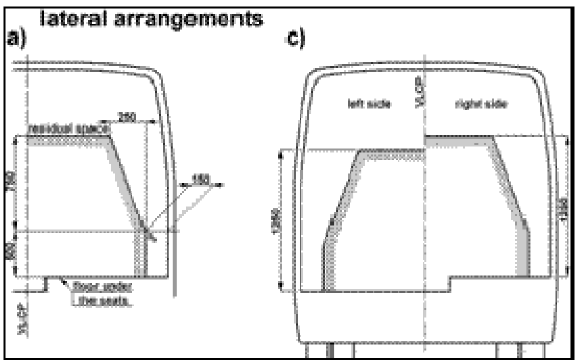

Figure 4. Lateral arrangements of the Residual Space for occupants. a) Cut out view from rear and c) Rear view showing both sides.

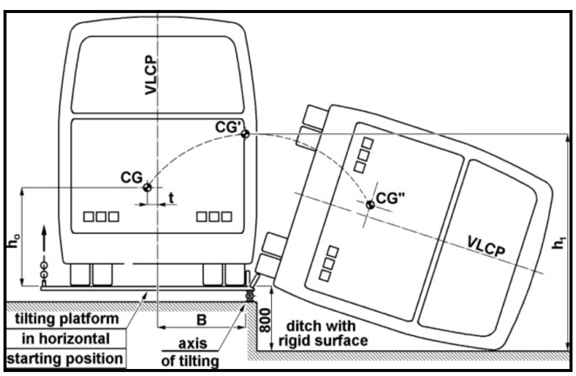

Figure 5. Image of 3.2.2.1, figure 3. Specification of the rollover test on a complete vehicle showing the path of the centre of gravity through the starting, unstable equilibrium, and at the end position.

The regulation specifies the following details further defining the requirements in sections 5.1.1, 5.1.2 and 5.3.2, which are given below:

5.1.1. No part of the vehicle which is outside the residual space at the start of the test (e.g. pillars, safety rings, luggage racks) shall intrude into the residual space during the test.

Any structural parts, which are originally in the residual space (e.g. vertical handholds, partitions, kitchenettes, toilets) shall be ignored when evaluating the intrusion into the residual space.

5.1.2. No part of the residual space shall project outside the contour of the deformed structure.

The contour of the deformed structure shall be determined sequentially, between every adjacent window and/or door pillar. Between two deformed pillars the contour shall be a theoretical surface, determined by straight lines, connecting the inside contour points of the pillars which were the same height above the floor level before the rollover test (see Figure 5).

5.3.2. The rollover test starts in this unstable vehicle position with zero angular velocity and the axis of rotation runs through the wheel-ground contact points. At this moment the vehicle is characterized by the reference energy ER.

These ECE-R66 superstructure requirements are the most robust of all the countries that were part of this research. Additionally, R66 has the requirement for a physical MCB test vehicle to perform the compliance test making it a costly endeavor for Manufacturers but at the same time keeping substandard MCBs off the market. The regulation drove down MCB fatality rates in the countries that adopted it. In the last few years, with new modeling tools, some companies have successfully presented their testing compliance via modeling. [3]

Regulations in Australia

The Department of Infrastructure and Transport governs the regulations for MCB's in Australia. R66 has been adopted in Australia throughout the 6 states that make up Australia including New South Wales, Victoria, Queensland, South Australia, Western Australia and Tasmania and 2 territories; the Australian Capital Territory and the Northern Territory as shown in Figure 6. However, the final adopted version of the R66 regulation, called Australian Design Rule (ADR) 59/00, does not require the occupant mass be included in the testing pass/fail requirement. [4]

Figure 6. Australia States and Territories

Australian Rule (ADR) 59/00

The Australian Design Rule for MCBs (Omnibuses) is ADR 59/00 which specifies requirements for bus superstructures to ensure that they withstand forces encountered in rollover crashes and maintain a survival space for each passenger. This regulation applies to vehicle in the MD and ME classes. MD is a Light omnibus with the subclasses of MD1-4 with GVM of between 3.5 and 5 tonnes and for MD2-4, more than 12 seats. ME is the class for a Heavy omnibus, over 5 tonnes.

ADR 59/00 technical content is based on ECE/R66 and includes design and construction of single-deck, rigid or articulated vehicles, constructed for the carriage of more than 16 passengers, whether seated or standing, in addition to the driver and crew.

The scope of the ADR.59 covers the following:
1. All the single deck buses having a passenger capacity more than 12.
2. Class B buses - (those **not** designed to carry standing passenger)*
3. Busses carrying 16 passengers *
4. Double Deck Busses are optional.*

**Amended in August 2010 which came from the R 66/02 as an alternative standard. The industry will continue to have the option of complying with UNECE R 66/00 and UNECE R 66/01 as well as the Australian requirements at Appendix B of the ADR. Appendix B is a modified extract of the technical provisions of UNECE R66/00 standard.*

Certain low floor height MCBs will continue to be exempted. Omnibuses are not required to comply with this rule if the following percentages of the area of the upper surface of the floor measured between its ‘Axles’, is not more than 550 mm (22 in.) above the ground. The floor height of 550 mm (22 in.) is measured at the ‘Suspension Height’ corresponding to the ‘Unladen Mass’ of the vehicle.
For a wheel base: 6.5 metres and over 75% , less than 6.5 metres 70%, less than 6.0 metres 65%, less than 5.5 metres 60%, less than 5.0 metres 55%, less than 4.5 metres 50%
What this means is that for a MCB that’s wheel base (between the axels) is 6.5 meters (21 ft), 75% of that distance must be 550 mm (22 in) from the ground. This ensures that the center of gravity is low and thus keeps the MCB safer from a high propensity to rollover.

The “CALCULATION OF TOTAL ENERGY (E*)” under the ADR 59/00 Appendix B [5] states the same equation for E* as the R66 but has stricken the word “kerb” again and left it as “unladen mass of the vehicle”.
For testing the calculation method of the fall of the centre of gravity (h) is determined by graphical method E may be taken to be given by the formula:*

Alternatively, E may be calculated by the formula:*
Where
M = the unladen ~~kerb~~ mass of the vehicle (kg)
g = 9.8 m/s2
W = the overall width of the vehicle (m)
Hs = the height of the centre of gravity of the unladen vehicle (m)
H = the height of the vehicle (m)

The wording in the 2007 version of the ADR 59/00 regulation at clause 8.1.3 is now “written” without the word “kerb” present.

There are additionally twenty regulations that are required by busses of this size. For example, Australia’s regulation requires “lap/shoulder belts” at “all” passenger positions, even though they don’t account for the occupant mass in the testing requirement. The more recent updates to the ADR Standards includes more robust requirement for both seat anchorages and seat belt anchorages. This was in response to two frontal MCB crash investigations where the seat anchorages failed and the occupants were crush or injured between the seats.

A comparison between ECE R-66 and ADR 59/00 shows that the Australian's have stricken several regulations including many that speak to the interpretation or examination of the testing results. Not included in the 2007 version, which repealed the 2006 version) were: No application of approval (3.0), No approval (4.0), Modifications of the vehicle type and extension (9), Conformity of production (10), Penalties for non-conformity of production(11), Names and Addresses of Technical Services Responsible for Conduction approval tests and of administrative departments (13). Annex 2 of the regulation ECE R-66 required the arrangement of the approval mark which was also "stricken" in the ADR. With the exception of the occupant weight being excluded, the Australian rules do seem to be working as the fatality rates for injuries occurring inside the MCBs are dropping.

Regulations in the United States of America

The regulatory body for vehicle crashworthiness in the United States is the National Highway Traffic Safety Administration (NHTSA). This agency oversees the governing of safety regulations in the US. The regulations fall under two departments, the Federal Motor Vehicle Safety Standards (FMVSS) and the Federal Motor Carrier Safety Administration (FMCSA).

FMVSS regulations generally apply to consumer and some commercial vehicles at less than 10000 lbs. FMCSA regulations generally apply to Public and Private Transport in vehicles over 10,000 lbs. Both sets of requirements are enforced across all 50 states.

Some regulations, or "Standards" as they are called in the US, have different requirements based on vehicle weight. Federal Motor Vehicle Safety Standards (FMVSS) 216, the statically tested roof strength requirement calls for a 3-times strength to weight ratio for vehicles under 6000lbs, but only 1.5-times ratio for vehicles from 6000 to 10000 lbs. Most 8 to 12 passenger transport vehicles fall under the jurisdiction of FMVSS Standards. [5]

The standards for a vehicle of less than 10,000 lbs but greater that 8,550lbs (empty at 5,000) are limited and those in place mainly apply to vehicles that fall under the regulations for "vehicles for hire" such as mass transportation and school buses. Both the FMVSS and FMCSA versions of regulation # 217 contain some regulations pertaining to Transport MCBs such as windows, windshield and markings and emergency exits. [6] The purpose of FMCSA No. 217 is to minimize the likelihood of occupants being thrown from an MCB in a crash and to provide a means of readily accessible emergency egress. In addition to FMCSA/FMVSS No. 217, MCBs must comply with the following crashworthiness standards:
FMCSA/FMVSS No. 208, "Occupant crash protection"
FMCSA/FMVSS No. 209, "Seat belt assemblies"
FMCSA/FMVSS No. 210, "Seat belt assembly anchorages"
FMCSA/FMVSS No. 302, "Flammability of interior materials"
* FMCSA/FMVSS *Nos. 208, 209, and 210 presently apply to the Driver's seat only.* [7]

The Federal Motor Vehicle Safety Standards (FMVSS) define a MCB as a motor vehicle with motive power, except a trailer, designed for carrying more than 10 passengers. Per FMVSS, a bus can be either a school bus or "other type of bus".
Because of the lack of specific crashworthiness standards, Para transit MCBs of Gross Vehicle Weight Rating (GVWR) often exceeding 10,000 lb are not subjected to any design restrictions unless a specific bidding process requires so.

The regulatory body for Heavy Vehicle crashworthiness is the Federal Motor Carrier Safety Administration (FMCSA). This agency is concerned with vehicles over 10000 lbs and regulate the trucking and heavy transport industry. FMCSA does not have a regulation for superstructure or design construction of an MCB and MCBs are not regulated by any national crashworthiness standard under the FMCSA.

The United States regulations, as compared to Europe and Australia, historically have been followers rather than leaders on the subject of MCB safety. However, in 2012, under the newly enacted Motorcoach Safety Provisions, NHTSA (DOT) is directed to require seatbelts on motocoaches within one year as well as regulations for roof strength and anti-ejection safety countermeasures and rollover crash avoidance regulations within two years. [8]

Regulations in South Africa

The regulatory body for vehicle crashworthiness in South Africa is the South African Bureau of Standards (SABS). [8] This statutory body was established as the national institution for the promotion and maintenance of standardization and quality. SABS is responsible for maintaining South Africa's database of more than 6,500 national standards, as well as developing new standards and revising, amending or withdrawing existing standards as required. SABS issues the South African National Standards called “SANS” which apply across all 9 Provinces shown in Table 7.

Table 7.
South African Provinces

South African Provinces	
EC = Eastern Cape	MP = Mpumalanga
FS = Free State	NC = Northern Cape
GA = Gauteng	NW = North West
KZ = KwaZulu-Natal	WC = Western Cape
LI = Limpopo	

The SANS 1563 standard applies to single-decked vehicles (M2<11,000 lbs, M3>11,000 lbs) constructed for the carriage of more than 16 passengers (not M1), whether seated or standing (Class I-III).

It is accepted as the text of E/ECE/324 Addendum 66, Regulation 66 (Uniform provisions concerning the approval of large passenger vehicles with regard to the strength of their superstructure) as suitable as the South African standard.

In SANS 1563, “Unladen kerb mass” is defined as the mass of the vehicle in running order, unoccupied and unladen, but complete with fuel, coolant, lubricant, tools and spare wheel, if any. The mass of the occupants has not been included in any calculations for testing, energy or mass.

M2 and M3 vehicles are subjected to one of the following below to ensure sufficient superstructure strength:

- Rollover Test on a complete vehicle
- Rollover Test on a body section or sections representative of a complete vehicle
- Pendulum test on a body section or sections
- Verification of strength of superstructure by calculation

After completing one of the testing methods or calculations, the superstructure shall be strong enough to ensure that during and after test methods or calculations that:

- No displaced part of the vehicle intrudes into the residual space
- No part of the residual space projects outside the deformed space

If the test methods prescribed in 2-4 cannot take account of a significant variation between one section of the vehicle and another, the vehicle must undergo the Rollover Test on a complete vehicle.

Additionally, South Africa has M2 & M3 Compulsory Specifications for Seat Belts and Anchorages which are:

3.6.3 Restraining devices (safety belts)
Subject to the proviso that no restraining devices (safety belts), excluding those given in (c) below, are required to be fitted to any vehicle of GVM exceeding 3.5 t , the following requirements shall apply:

a) the restraining devices (safety belts) that are fitted to a vehicle shall comply with the relevant requirements given in SABS 1080: 1983, (Seat belts and anchorages) Restraining devices (safety belts) for occupants of adult build in motor vehicles.

b) the type and location of the restraining devices (safety belts) required to be fitted to a vehicle and the method of installation thereof shall comply with the relevant requirements given in SABS 01 683 983.

*c) **in the case of class III vehicles**, non-protected seats (see 4.3.3 of the said SABS 1430), the details of which are specified in 3.6.2 (Excluding seating positions that have seats of the folding tip-up (jockey), rearward-facing or sideways-facing type, and seating positions in the rear rows of seats on simple single-box type construction), shall be fitted with at least a restraining device of the lap belt type.*

The South African Bureau of Standards "deleted" several of the ECE sections from which the regulations were originally adopted. The comparison is similar to the Australian changes of ADR 59/00 between the ECE R-66 and SAN 1563 from South Africa, which shows they have stricken several regulations including many that speak to the interpretation of the testing results.

Regulations in Canada

The Canadian Motor Vehicle Safety Regulations (MVSR) C.R.C., c. 1038 comes primarily from the safety standards in the United States (FMVSS). [10] A Canadian Technical Standard Documents (TSD) is a document that reproduces an enactment of a foreign government (e.g. a Federal Motor Vehicle Safety Standard issued by the United States National Highway Traffic Safety Administration). Canada has adopted many of the US standards and they are enforced across all of Canada including the Prairie and Northern Region, Yukon Territory, Northwest Territory, Pacific Region, Ontario Region, Quebec Region, and the Atlantic Region.

The most important rule for MCBs in Canada is that it has "admissible" vendors and approved MCBs that are allowed to be imported without modifications. [11] If the manufacturer and/or MCB type are not on the list, they cannot be imported for service.

The document or MVSR is known as the 1038 and is currently the accumulation of all the TSDs that the Canadian Government follows. The TSD for No. 216, Revision 1[12] is the document that speaks to the Roof Crush Resistance that pertains to MCBs; with a GVWR of 4 536 kg or less; that is built in two or more stages not using a chassis-cab and with a GVWR of 4 536 kg or less; bus with a GVWR greater than 2 722 kg but not greater than 4 536 kg and with an altered roof shall conform to the requirements of TSD 216 or TSD 220 (Rollover Protection) [13], which is referred to in section 220 of that schedule. The requirements of both TSD 216 and TSD 220 expire pertaining on January 1, 2014.

Schedule III of the MVSR shows a listing of all regulations that are associated with MCBs. All admissible vehicles must be labeled with the sticker shown in Figure 6, validating that it's authorized by the MVSR for use.

Figure 6. MVSR Official Compliance Stamp

Transport Canada defect investigators identify safety defects and take steps with manufacturers to correct defects through the Motor Vehicle Safety Act Notice of Defect provisions. MCB operator associations participate in regular National Public Safety Organizations consultation meetings with Transport Canada. Officials represent Canada on the ECE committee on occupant restraints, which developed the referenced European MCB passenger safety regulations. International standards are adopted where possible, when they meet safety needs and are consistent with Canadian regulatory policy.

Explanation of Mandatory Compliance Canada has a list of importation into the country of manufacturers of vehicles, specifically MCBs and passenger transport vehicles that are admissible. If the vehicle is not on the list you will not be able use them in Canada.

Canada has taken a different approach in that vehicles must meet standards in order to be allowed to operate or to be imported into the country. That leaves the responsibility of the safety compliance with the manufacturer or buyer of the MCB to be used in country. The 100 series crash avoidance standards and most of the Motor Vehicle Safety Regulations 200 and 300 series crashworthiness standards are now applicable to MCBs and all vehicles of a given weight category. Their revised standards, similar to the United States FMVSS 220 that now encompasses MCBs (not just school buses) require additional standards and testing for the manufacturers' compliance and this should continue to keep their fatal crashes to a minimum.

Regulations in Brazil

Brazil does not have a superstructure standard. In fact, there was no information as to Governmental Regulations for MCBs at all. Brazil has the 3rd largest overall fatality rate in Latin and South America at 25.6 deaths per 100,000 population. Recently, the Bloomberg Foundation donated several million dollars to create a better infrastructure for 10 emerging countries and Brazil is one of the countries that will receive funding from the foundation. [14]

Brazil is broken into five regions: North, Northeast, Southeast, South and Centerwest. The largest numbers of fatalities are in the Southeast, Northeast and South regions where concentrations of vehicles, urban population, and roads are the highest.

Regulations in Peru

Approved National Vehicle Regulation Supreme Decree No. 058-2003-MTC is the standard that is regulated by the Ministry of Peru for MCBs. The 2003 adopted National Vehicle Regulation consists of one hundred forty-three articles, and twenty additional provisions. The regulations are made up of Articles that describe the standards and Annex's that further explain information relating to specific requirements. Article 17 includes the "Additional Technical Requirements for vehicles of categories M2, M3, N2, N3 OR 2O3ad O4". The vehicles of category M2 & M3 are defined below and are obligated to follow a set of regulations and must have the approval documentation of the General Directorate for Land Traffic for both imports and vehicle manufactured in Peru. [15]

Category M: Motor vehicles of four or more wheels designed and constructed for the passenger transport.

M1: Vehicles of eight seats or less, excluding the driver's seat.

M2: Vehicles of more than eight seats excluding the driver's seat and gross vehicle weight of 5 tons or less.

M3: Vehicles of more than eight seats excluding the driver's seat and gross vehicle weight of over 5 tons.

Vehicles of category M2 and M3 transport of passengers are classified as:

Class I: Vehicles constructed with areas for standing allowing passengers frequent displacement

Class II : Vehicles constructed primarily for the transportation of passengers, sitting designed to allow the transport of passengers standing in the passage and / or an area which does not exceed space provided for two double seats.

Class III: Vehicles constructed exclusively for the carriage of passengers seated.

For M3:

1**. Bus standard** . - Vehicle body attached directly to the chassis frame, frame that does not undergo any alteration or modification structural or dimensional change in the distance between axes during the process of bodywork. Vehicles of this type can have the engine located on the front or rear of the chassis.

2. **Bus integral. -** Vehicle with the self-supporting single body to which sets the directional set at the front and the entire power train in back. The distance between axes is determined by the manufacturer bodywork. Vehicles of this type must locate the engine rear of the vehicle.

3. **Bus articulated** . - Vehicle composed of two rigid sections connected together by an articulated joint allowing free passage between one section to another.

4. **Omnibus bi-articulated** . - Vehicle composed of three rigid sections joined other by two articulated joints allowing free passage between the sections.

There are no "super structure" testing requirements but in the definitions of Annex II as stated above shows the way that the framework must be attached to the structure. Figure 7 describes the MCB framework and chassis connection for type M3.

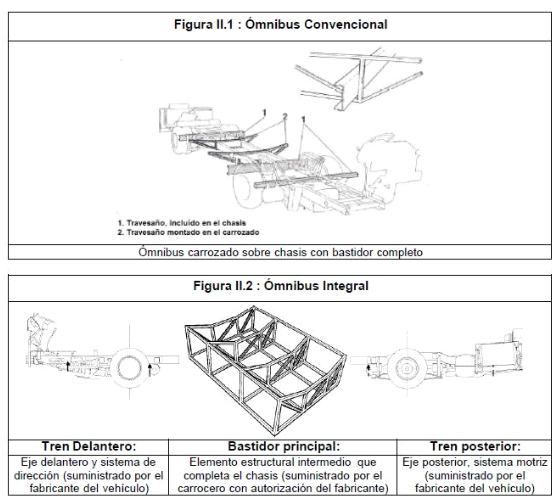

Figure 7. Framework and chassis description for M_3 vehicle category

There is an approval/checklist of about 100 characteristic for safety features, weights, lengths, and axels types and locations, in order for a MCB to be approved and operating on the road systems.

Regulations in Chile

The body that regulates MCBs in Chile is the Ministry of Transport and Telecommunications. The division responsible for vehicle regulations is the Undersecretary of Transportation. A search of their website for MCB superstructure regulations and/or rollover regulations in general returned "no results".

However, Chile does have other requirements for MCBs that "perform services of paid transport of passengers" and defines the vehicle as "minibuses, with 12 or more seats, including the driver." There are a number of regulations that govern MCBs and some come from the Traffic Act. Decree-Law No. 1 dated October 29, 2009. [16] The regulations listed below come from Decree No. 122 out of Santiago on June 18, 1991 for fixed dimensional and functional requirements for vehicles of public transport serving urban and rural areas. There is also Decree No. 212 on November 21, 1992 for the regulation of national public passenger transport and Decree No. 80 dated September 13, 2004 that regulates private transport of passengers for reward. [17]

We found no information that shows that MCBs being manufactured or sold in Chile for any purpose other than public transportation are under any performance regulations.

The public transportation regulations apply to vehicles not older than 18 years and the regulation does include the passenger's weight at 65kg as a calculation of the vehicle passenger capacity. Additionally, in 2008 it became mandatory that MCBs of the model year 2008 and newer be equipped with seat belts and gave power to the MCB Driver/Company to enforce the rule.

In Article 2 and 3 of these documents are a few of the more important findings during our translation.

Article 2 °. - Buses that are made urban public transportation services, serving transportation capacity, fall within the following types:

a) Bus light (or **L** type): bus with no more than 26 seats including the driver, and with a gross weight less than 10 ton vehicle.

b) Medium Bus (Type **M)** bus with 26 seats, including the driver, and gross vehicle weight equal 10 tons or more but less than 14 tons.

c) Heavy Bus (Type **P**): bus with 26 seats, including the driver, and gross vehicle weight equal or greater than 14 tons.

Article 3. - Buses M and P type referred article 2 above, shall comply with the following requirements:

1. Overall dimensions: The outside width of the vehicle shall not exceed 2.60 m., In any case, the ratio between the width the vehicle and the distance between the outer faces of the rear axle wheels shall not exceed 115%. The length must be greater than 9.00 m for buses Type M and greater than 11.00 m.

for buses type P. The long rear overhang may not exceed 65% of the wheelbase.

2. Technical requirements relating to capacity passengers: Total number of passengers: The total number of passengers (N), both sitting and standing, should not exceed the numbers Nc and Ns, which are calculated as as follows:

Nc = (PBV - POM) / q, and Ns = A + IF / s in which:

GVW: Gross weight of the vehicle indicated by the manufacturer.

POM: Weight in running order, including the tare vehicle fuelling, spare wheel and normal tools, plus 75 kg to the weight of the driver.

q: a passenger's weight equal to 65 kg.

s: area required for a standing passenger equal to 0.167 m2.

Due to the length of this requirement and all the subsections that go along with it, we have abbreviated the listing in Table 8 with just the section headings.

Table 8.
MCB Regulation Section Headings for Chile

Types of Regulations in Chile	
Bumper	Handholds/handrails
Corridor	Internal lighting
Dividing panels	Levels of Noise
Driver's seat	Passenger seats
Emergency Exits	Service Doors
Exterior lights	Travel indicator
Floor of vehicle	Vehicle Systems
Glass windows/rear windshield	Warning system shutdown

The Chilean Regulations for the paid transport of passengers has some good rules in it that should be used as a baseline for more regulations. There are no regulations for the MCBs manufacturer to pass if the MCB will not be used for paid public transport.

METHODS AND DATA SOURCES

Research was conducted on the main governmental transportation websites governing MCB transport for each country. The United Nations website was used for the original UN resolution language and the adoption by nations. Many published papers were reviewed as well as articles and websites with verifiable information are referenced.

LIMITATIONS

This research was potentially limited by the language barrier in being able to identify and clearly understand the regulations in other than English speaking countries. It should be noted that the application of these regulations in some countries is limited by the generation of vehicles they have in service. Countries with little funding for new vehicles may have fleet vehicles that are older than the regulations and would not pass today or need to be retrofitted to pass.

CONCLUSIONS

MCB regulations vary significantly across these continents and countries. The more underdeveloped countries have a few occupant protection regulations for MCB passenger transport. The more developed countries have specific occupant protection regulations for both the public and private sectors which are strictly enforced.

Europe’s ECE/R66 is the most comprehensive for superstructure testing and Australia’s ADR 59/00 for seats, belts and anchorages. Australia and South Africa’s SANS 1038 are good, but could use an upgrade to include occupant mass in the superstructure compliance calculation. The US and Canada seem to be starting to recognize the value of seat belts and rollover structural regulations and we are hopeful that the new Motor Coach Safety Provisions will help rectify the shortcomings in the regulations. Peru and Chile have some basic regulations for occupant protection, but would do well to adopt more. Brazil will hopefully benefit from the Foundational support they should be recieving.

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REFERENCES

[1] UNECE Regulation No. 66 - Rev.1 - Strength of the superstructure of large passenger vehicles, 22 February 2006
[2] A.C. Walton, S.M.R. Hashemi, and J.C. Anderson. 2006. Preventing Passenger Ejection from Buses, Coaches and Minibuses, Final Report, TTS Project S0320/VE, DfT Contract PPAD 9/33/127, Cranfield University, UK.
[3] C.Chirwa, 2012-009 Modelling a 32 Seat Bus and Virtual Testing for R66 Compliance, ICrash 2012 Milan, Italy.
[4] www.comlaw.gov.au/details/F2012C00535, Vehicle Design Rule ADR 59/00, Dated April 26, 2006
[5] http://www.fmcsa.dot.gov/rules-regulations/administration/fmcsr/fmcsrruletext.aspx?reg=571.216
[6] http://www.fmcsa.dot.gov/rules-regulations/administration/fmcsr/fmcsrruletext.aspx?reg=571.217
[7] http://www.fmcsa.dot.gov/rules-regulations/administration/fmcsr/fmcsrruletext.aspx?reg=571.208
[8] Advocates for Highway and Auto Safety http://www.saferoads.org/ and www.fmcsa.dot.gov/documents/safety-security/Motorcoach-Safety-Action-Plan-2012.pdf
[9] Https://www.sabs.co.za/webstore/standards/product.php?id=14015595
[10] www.tc.gc.ca/eng/acts-regulations/regulations-crc-c1038.htm
[11] www.tc.gc.ca/roadsafety/safevehicles/importation/usa/vafus/list2/Explanations.htm
[12] www.tc.gc.ca/eng/roadsafety/safevehicles-mvstm_tsd-tsd-2160rev1_e-1072.htm
[13] www.tc.gc.ca_roadsafety_safevehicles_mvstm_tsd_tsd_pdf_2200rev0_e
[14] http://www.mikebloomberg.com/index.cfm?objectid=4DCD9F53-C29C-7CA2-F5345D6A84C908A4
[15] http://transparencia.mtc.gob.pe/idm/NormasSA.aspx?id=11
[16] www.moptt.cl - No. 122. - Santiago, June 18, 1991. - Views: The provisions of Article 56 of Law No. 18290, Traffic, Article 3 of Law No. 18,696, in connection with Law ° 18,059, and Exempt Resolution No. 366 of 1991, the Ministry of Transport and telecommunications at
[17] http://www.bcn.cl/lc/leyes_por_tema Biblioteca del Congreso Nacional de Chile – Legislacion Chilena

FIRE SAFETY OF BUSES - RESEARCH ACTION FOR IMPROVING VEHICLE REGULATIONS

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ABSTRACT

Although the bus belongs to the safest traffic means, single accidents can be particularly severe and concern many passengers. Especially in case of fires a high number of injured and killed persons can be the outcome. Fire safety of buses therefore is of high importance. With the increase of synthetic and plastic materials as a material for the interior equipment of buses and coaches because of their good mechanical properties combined with low weight, the question arises whether the safety level has decreased in case of a fire during the last years - also compared to other means of transport. Because of the combustible plastics and their ability to release a high amount of heat the main fire load in buses is no longer the fuel but the plastic materials which are also often easy to ignite. Besides the flammability of the equipments, the production of smoke, the smoke development and propagation and its toxicity for the people as well as the testing methods and limit values are of interest.
For those reasons research projects were initiated on behalf of the German Federal Highway Research Institute. At the one hand the fire behavior of coach interiors was examined in general focusing on fire propagation as well as fire detection and signalling. As result, recommendations with regard to early fire detection systems for the engine compartments and on-board extinguishing equipment were elaborated. At the other hand research is carried out to examine heat release, smoke, smoke propagation and its toxicity due to burning bus interior materials.
The paper describes which effective and economically reasonable fire safety requirements for interiors of buses would improve the current situation. Proposals for amendments of current requirements are recommended including the specification of appropriate limit values. In particular, it is taken into consideration which reasonable fire safety standards from other transport sectors, especially the rail sector, should be transferred to buses.

INTRODUCTION

Already in the year 2000 BASt (Bundesanstalt für Straßenwesen, Federal Highway Research Institute, Germany) initiated two research studies in order to investigate how road traffic safety of buses could be improved [1]. On the one hand fire safety performance was an issue to be dealt with. On the other hand emergency exits should be examined.
The first study with regard to burning behaviour of coach interior equipment was carried out by DEKRA, a German testing organisation [2]. Based on theoretical considerations and several real scale fire tests, a variety of recommendations was given. Especially the installation of fire detectors in the engine compartment was claimed. In addition emphasis was laid on the equipment with appropriate fire extinguishers since it turned out that already an essential safety gain would be achieved if small fires were extinguished early before they could spread.
There should be at least two extinguishers, one next to the driver's seat, filled with foam and powder for extinction of fires in the passenger cabin and the engine compartment. However, if one considers the package of parts in the engine compartment, the capability of a conventional extinguisher is limited. Also opening the engine compartment could deliver fresh air which supports the fire.
The second study was carried out by Trier University of Applied Sciences [3]. To optimise the emergency exit systems for coaches weak points in existing solutions and in regulations were analysed. On the one hand experts were consulted, on the other hand evacuation tests were carried out with test persons using coaches tilted by an angle of 90 degrees to the side. The results were summarised in a performance specification list for an optimised emergency exit system for coaches specifying e. g. the forces and maximum time for emergency exit opening, misuse countermeasures, width and number of roof escape hedges or usability of escape routes. Many of the recommendations are meanwhile part of the international vehicle regulations of the United Nations Economic Commission for Europe (UNECE). To complete the work BAM (Bundesanstalt für Materialforschung und -prüfung, Federal Institute for Materials

Research and Testing, Germany) was assigned in the year 2009 to carry out fire tests with the focus on smoke and toxicity of smoke gases. Mainly the findings of this third project are presented in the following chapters [4].

DEFINITIONS

According to the UNECE Regulations [5] buses are defined as being vehicles belonging to one of the following categories:
Category M2: Vehicles used for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass not exceeding 5 tonnes.
Category M3: Vehicles used for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5 tonnes.
For vehicles of category M2 and M3 having a capacity exceeding 22 passengers in addition to the driver, there are three classes of vehicles to which they belong:
Class I: Vehicles constructed with areas for standing passengers, to allow frequent passenger movement.
Class II: Vehicles constructed principally for the carriage of seated passengers, and designed to allow the carriage of standing passengers in the gangway and / or in an area which does not exceed the space provided for two double seats.
For vehicles of category M2 and M3 having a capacity not exceeding 22 passengers in addition to the driver, there are two classes of vehicles:
Class A: Vehicles designed to carry standing passengers; a vehicle of this class has seats and shall have provisions for standing passengers.
Class B: Vehicles not designed to carry standing passengers; a vehicle of this class has no provision for standing passengers.

MOTIVATION FOR THE EXAMINATION OF THE FIRE SAFETY PERFORMANCE OF BUSES

Incidents

Buses are one of the safest passenger transport means. However, if severe bus accidents or bus fires occur the number of casualties can be high and cause significant public awareness. An analysis of past bus fires [2, 6, 7] in Germany revealed the following facts: There are approximately 350 bus fires per year, of which about 75 % start in the engine compartment. Most of the accidents are less severe with no or only few casualities. However single accidents in which a majority of passengers is killed are outstanding. The main cause for injuries in bus fire cases turned out to be intoxication by smoke gas inhalation. Even small doses of certain gases can lead to permanent damage. So smoke gas development and its toxicity in bus fires are issues worth to be examined in detail.

Material properties

The amount of plastic materials used as interior parts of buses increased in the last decades since plastic components have excellent mechanical properties combined with light weight. However burning plastic materials can be able to generate toxic smoke gases. Already DEKRA [2] considered smoke and its toxicity as an issue however no recommendations with regard to limits were given at that time.
For buses the requirements for burning behaviour of interior materials and for general fire protection means are stipulated in the UNECE Regulations No. 107 and 118 [8, 9]. In the past the fundamental reaction to fire test for bus interior materials focused primarily on the horizontal burning rate. Taking new findings into account, partly elaborated within the studies at hand, in the last years extensive revisions of the UNECE Regulations were discussed with the following results which constitute a great progress for bus fire safety: A vertical test for vertical mounted materials was foreseen, reaction to fire tests were tightened, fire detectors in the engine compartments became mandatory and fire or smoke detectors in closed bus compartments will have to be installed. Details of these efforts are described further below (see section with regard to status quo of regulations). However there are no requirements with regard to heat release, smoke gas production and toxicity up to now.

Comparison with requirements for passenger trains

Generally bus and rail vehicles operate in a similar way and the evacuation conditions for the passengers in case of fire are widely comparable. However there are more reaction to fire tests for interior of passenger trains than of buses. Also the parameters for which limits have to be fulfilled are more diverse. Especially heat release of burning specimen, smoke production and toxicity of smoke gases are limited. In addition tests with complete seats have to be carried out for trains. The requirements for the rail sector are given by the standard EN 45545-2 [10].
Since the risk arising from burning rail vehicles depends mainly on how the train is operated (on tracks with or without long tunnels) three hazard levels (HL) are defined in the standard. Hazard Level 3 (mainly for subways and couchette coaches) requires most stringent fire protection properties and Hazard Level 2 is stricter than

Hazard Level 1. Correspondingly bus types could be classified in the same way in order to be allocated in different Hazard Levels. Vehicles of categories M2 / M3 of Class I, II or Class A ("city buses", with standing passengers) could be classified as to fulfill Hazard Level 1 and vehicles of category M2 / M3 of Class III or Class B ("coaches", not designed for standing passengers) could be classified as to fulfill Hazard Level 2.

All these facts mentioned above generated the idea to examine how far it is possible to transfer and adapt the requirements for train interior to buses. For that purpose a lot of burning behaviour tests with small specimens of bus interior materials, with complete seats and using whole buses were carried out which are described below.

TEST OF BUS INTERIOR MATERIAL

For rail vehicles detailed standards for the test of the fire safety performance exist. There are a variety of tests that are not required for bus interior materials. In order to investigate how far fire safety of buses can be improved by transferring requirements from rail vehicles to buses, bus equipment was taken and tested against the existing requirements for passenger trains by applying the test methods for the interior of rail vehicles (EN 45545-2). For example parts of the body insulation, the floor covering or the side panel were examined.

Heat release

Small scale tests with specimens of bus interior materials were carried out with a Cone Calorimeter (EN ISO 5660) in which the specimen is exposed to a conical heat irradiation source. With a Cone Calorimeter it is possible to determine the time to ignition and the heat release rates under predefined conditions. Only four of the fourteen tested samples passed the requirements for the maximum average heat release rate (MARHE) regarding Hazard Level 2. So most of the bus interior materials failed the heat release requirements for rail vehicles according to EN 45545-2.
With regard to the heat release not only small material specimens of interior parts were tested but also complete interior components. Because a bus is equipped with numerous passenger seats of which each is able to contain a high fire load the passenger seats were tested in whole. Paper cushions were used as ignition sources. DEKRA tested a seat within a real bus. At BAM tests were carried out according to the passenger train standard in a calorimeter. The burning behaviour of three different bus seats and one seat for train vehicles was compared. The measured differences between the tested seats were significant with regard to heat release. Here only a modern train seat and a 1995 city bus seat performed well.

Ignition and vertical flame spread

In the requirements of rail vehicles according to EN 45545-2 the Single-Flame Source Test (ISO 11925-2) is used as a test method for the ignitability and the dripping behaviour. In essence this test method is used to restrict a rapid and easy ignition of materials as well as a fast vertical flame spread. The test method of the Single-Flame Source Test contains a 20 mm high propane gas flame which flames a test specimen. Filter paper is placed below the specimen holder to observe the falling of flaming debris. Again small scale tests with specimens of bus interior material were carried out. The requirements according to EN 45545-2 were failed e. g. by the body insulation or the ceiling over seats. So it was shown that some bus interior materials ignite quickly and have a rapid vertical flame spread.

Smoke development and toxicity

Small scale tests with specimens of bus interior material were carried out with a Smoke Density Chamber (EN ISO 5659-2). The Smoke Density Chamber is a testing instrument for the determination of smoke gas production of flammable specimens which are exposed to a horizontal thermal irradiation. Photometrically the smoke density can be measured in terms of light transmission and specific optical density respectively. In addition a FTIR-spectrometer (Fourier Transform Infrared) enables the qualitative and quantitative analysis of the smoke gas composition. Of interest for toxicity are the smoke gases carbon dioxide (CO_2), carbon monoxide (CO), hydrofluoric acid (HF), hydrochloric acid (HCl), hydrobromic acid (HBr), hydrocyanic acid (HCN), sulphur dioxide (SO_2), and nitrous oxides (NOx).
The main parameter for assessing the smoke gas toxicity of railway materials is the Conventional Index of Toxicity (CIT). With applying the CIT all smoke components are limited together by a weighted sum. However manufacturers of rail vehicles use own standards in which concentrations of each single component of toxic smoke gases are limited separately since single gases might be lethal although the common limit is not exceeded.
Concerning the evaluation of toxic gas concentrations by the CIT-value e. g. the body insulation, the side panel or the foam of seats passed the requirements of Hazard Level 1 and 2 which are essential for corresponding rail vehicles. According the CIT-values of e. g. the investigated ceiling and floor covering, these materials did not

pass the tests. Results for some of the specimens are presented in Table 1.
Regarding the concentrations of single smoke gas components, especially the measured values of the side panel specimen which had a valid CIT-value according to EN 45545-2 contained extremely toxic concentrations of single smoke gas components (see HCN concentrations in Table 1 as example). Also for other parts the concentration of toxic gases in the smoke exceeded lethal concentrations by far. In conclusion all tested bus interior materials generated hazard till lethal concentrations of toxic smoke gas components. Thus it can be highly recommended to limit toxicity. When doing this, limiting toxic concentrations of single smoke gas components is more reasonable than limiting the CIT value.

Table 1.
Comparison between measured toxic smoke gas components and existing limits according to passenger train standards

	CIT (Conventional Index of Toxicity) according to EN 45545-2			HCN concentration [ppm]	
Material	meas-ured	limit HL1	limit HL2	meas-ured	limit of rvm
Body insulation	0,3	1,2	0,9	52	100
Floor covering	6,6	1,2	0,9	5	100
Side panel	0,6	1,2	0,9	245	100
Ceiling over seats	1,9	1,2	0,9	40	100
Ceiling over gangways	2,9	1,2	0,9	40	100
Foam of seats	0,3	1,2	0,9	7	100

HL: Hazard Level; rvm: rail vehicle manufacturer

Concerning the investigation of the light transmission in smoke gases the specific optical density (D_S) and the cumulative value of specific optical densities in the first 4 test minutes (VOF4) were measured. Regarding the optical density (D_S) only the body insulation and the foam of seats passed the requirements of Hazard Level 1 and 2. The side panel fulfilled Hazard Level 1 only. All other parts failed completely.
Regarding VOF4 the body insulation and the floor covering principally fulfill Hazard Level 1 and 2. However, VOF4-thresholds do not exist for the floor covering and the foam of seats though the D_S-thresholds are partially exceeded. So in summary for light transmission aspects most of tested bus interior materials fail the smoke production requirements of rail vehicles according to EN 45545-2. Results for some of the specimens are presented in Table 2.

Table 2.
Comparison between measured optical density of smoke and existing limits according to passenger train standards

	Optical Density according to EN 45545-2					
	$D_S(4)/D_{S,max}$			VOF4 [min]		
Material	meas-ured	limit HL1	limit HL2	meas-ured	limit HL1	limit HL2
Body insulation	128	600	300	261	1200	600
Floor covering	695	600	300	not req.	-	-
Side panel	560	600	300	1103	1200	600
Ceiling over seats	840	600	300	2390	1200	600
Ceiling over gangways	623	600	300	2225	1200	600
Foam of seats	101	300	300	not req.	-	-

D_S: specific optical density; $D_{S,max}$: maximum specific optical density within the 20 minutes of the test; VOF4: cumulative value of specific optical densities in the first 4 minutes of the test (time integral of D_S); not req.: not required

FIRE TESTS WITH A COMPLETE BUS

In addition to small scale and intermediate scale tests also several real scale fire tests were performed in a city bus. The test bus was a 12 m city bus from 1995. The fire scenarios represented different fire sources in the engine compartment and in the passenger cabin. The fire and smoke development were monitored and single concentrations of toxic smoke gas components were analysed during the tests. The main aim of these tests was to determine the time for a safe passenger escape regarding the smoke toxicity in different fire scenarios. Also tests to determine the benefits of fire detection systems (in passenger cabin and in engine compartment) and of extinguishing systems (in engine compartment) were performed.

Smoke development and toxicity in the passenger compartment

The smoke development in the passenger compartment was investigated under different ventilation conditions. In the city bus seven smoke detectors of two manufacturers, which were developed for the operation in trains, were installed to find out where the best positions for their installation are. Fire smoke cartridges and burning foam cubes served as smoke sources. In all tests the smoke generators were positioned at the end of the gangway (close to the engine compartment) because the majority of bus fires starts in the engine compartment.
The smoke spread tests showed that the smoke generated by a real fire streamed primarily fast to the top, spread rapidly along the whole ceiling and only then filled the cabin from the ceiling to the floor (if all openings were closed and the ventilation was off). Polyurethane foam blocks of only 100 g were already able to fill the whole bus with opaque smoke. Openings whether by raised aeration skylights, tilted windows or opened doors reduced obviously the smoke filling in the bus. The warm smoke then only filled the cabin from the ceiling down to the highest opening through which the smoke streamed out of the vehicle. So passengers might have a bigger smoke-free range in the bus to escape. Therefore fixed aeration skylights combined with smoke detectors that automatically activate the aeration skylights in case of fire could be very beneficial for a safer passenger escape. However ventilation conditions during a fire event have to be treated carefully in order to avoid promotion of the fire.
The experiments with regard to the smoke development were complemented by numerical fire simulations. For that purpose a bus with its material properties was modelled in the tool "Fire Dynamics Simulator" (Version 5) developed by the National Institute of Standards and Technology (NIST) in the United States. The fire source in the simulations was placed either in the lavatory or at the last passenger seat row. The main parameters that were varied were the interior material properties. On the one hand conventional bus equipment was chosen. On the other hand interior according to requirements for rail vehicles was modelled. As result a bus fire releases large amounts of heat and smoke, the fire propagates along the ceiling through the whole bus, even if it starts in the toilet cabin. Especially in the scenarios with equipment fulfilling passenger train standards it turned out that the fire development was retarded significantly. In the scenarios, in which arson was simulated, with train equipment the fire extinguished, with conventional bus equipment the ceiling burned.
Smoke development and toxicity were also tested in a real fire scenario. In a test at BAM with the complete bus a paper cushion served as ignition source to simulate arson. Although the fire was weak (only some adjacent seats were affected, ceiling parts above the fire begun to melt) the smoke contained concentrations of gases that cause first symptoms of intoxication.
For comparison a test reported by and carried out at SP (Sveriges Tekniska Forskningsinstitut, SP Technical Research Institute of Sweden), in which a fire in the lower rear part of a bus was generated, lethal concentrations of toxic smoke gases were reached in a few minutes [11].
Thus it can be recommended to limit the concentration of toxic smoke gases and to implement smoke detectors in all bus compartments which are not accessible to the driver's view, i. e. toilet cabin, luggage compartment and sleeping-cab.

Fire detection tests in the engine compartment

In the fire suppression tests described below fire detectors of three manufacturers were tested in order to find out reliable methods. Thirteen sensors were all placed in the engine compartment in which also the fire sources (e. g. sawdust and cotton drenched with fire load liquids) were placed. The detection principle was either thermal or optical (infrared sensor). The thermal detectors can be classified as:

- spot detectors (designed to detect a hot spot at a fixed location)
- discrete linear detectors (to detect a heating event at any point along the sensor (cable) lenght)
- averaging linear detectors (to respond when the average temperature along the whole length of the sensor exceeds a certain value)

As result, the spot thermal detectors did not provide an alarm during the tests. One reason for this result might be their sensitivity against their mounting position. In sum all linear thermal detectors and the optical detector provided an alarm within one minute, which would allow the passengers to leave the bus in time before smoke gas concentrations reach toxic values.

Fire suppression tests in the engine compartment

Seven fire suppression systems of four manufacturers were tested in the engine compartment of the bus. The agents used by the systems to suppress the fire were water spray with foam, water mist with additives, water mist with foam and additives, dry chemicals and powder. The test scenarios were based on current Swedish fire suppression standards [12], however they were slightly adapted for the tests at hand. On the one

hand a real engine compartment was used, on the other hand the engine was running during the tests. In the first test series with high additional fire load together with engine preheating and higher engine speed while testing, the fire suppression systems, which were activated manually after a determined preburn time, did not extinguish the fire completely but the systems could at least suppress the fire in its size for a certain time and could also interrupt the smoke entering into the passenger compartment. The running fan of the engine and the insulation material towards the passenger cabin were the main causes for the redevelopment of the fire after the suppression attempts. In the second series with shorter preburn times and engine at idle, all systems could suppress the fire and stopped the entrance of smoke into the passenger compartment.
During the fire tests for the suppression systems also the toxicity of the smoke in the passenger compartment generated by the fire in the engine compartment was measured. The concentrations of single smoke gas components did not reach toxic levels after the engine compartment had burnt for one minute (preburn time). With the activation of a suppression system the smoke production and thus the smoke concentration in the passenger cabin did not increase further.
Although automatic fire suppression systems cannot absolutely ensure total extinction of the fire they generate essential time for a safe escape of passengers in case of a fire in the engine compartment.

RECOMMENDATIONS

The study has shown that there is room for improvement with regard to the fire safety performance of buses and especially the burning behaviour of the bus interior equipment.
Revised requirements would help to increase the time of escape for passengers in case of a bus fire so that they are not exposed to the toxic smoke gas components that are produced when bus parts are burning.
Generally bus and rail vehicles are operated in a similar way and the dangers for the passengers in case of fire are comparable. Since for the rail sector reasonable requirements exist, it is considered to be appropriate to transfer and adapt the passenger train requirements to buses. That primarily concerns the railway standard EN 45545-2. For that purpose buses should be allocated to two different Hazard Levels. Hazard Level 2 would require more stringent fire protection properties than Hazard Level 1. City buses (ECE classes I, II or A) should be classified as to fulfill Hazard Level 1 and coaches (ECE classes III or B) should be classified as to fulfill Hazard Level 2.
In detail the following recommendations can be given as result of the various experiments described above. Attention was already payed to different findings by international legislation. So some of the recommendations are meanwhile mirrored by amendments of the relevant international vehicle regulations for bus fire safety, however some can serve as basis for necessary further revision work.

- Ignition test
  Since ignition is crucial for the further development of a fire, the ignitability of the bus interior should be limited and be included in the fire safety requirements for buses in order to ensure protection against a quick ignition of interior parts. Ignitability can be tested using the Single-Flame Source Test (EN ISO 11925-2).
- Vertical fire test
  The experiments and numerical simulations showed that for instance wall materials or backrests of seats have a significant influence on the fire development in the passenger compartment. A vertical fire test which limits the vertical spread of the flames is therefore recommended for all bus interior materials. Again the Single-Flame Source Test can be utilised for that purpose.
- Test of smoke production
  As demonstrated in the experiments, in case of a fire the air in a passenger compartment of a bus is quickly filled with large amounts of opaque smoke that impair visibility and hinder a safe escape. Therefore the smoke production should be restricted. Tests using the Smoke Density Chamber (EN ISO 5659-2) would be reasonable at a first stage. At a second stage, when ongoing standardisation work is completed, using a vitiated Cone Calorimeter might even be more suitable for limiting smoke production, since the test conditions would be more realistic, especially with regard to the oxygen being available during the test.
  In addition, in order to reduce the amount of smoke in the passenger compartment of a bus, automatic skylight openers which are coupled with smoke detectors can be regarded as reasonable equipment.
- Test of smoke toxicity
  During a bus fire the toxicity of the generated smoke is the most imminent danger for the passengers. It is therefore highly needed to limit the concentrations of toxic smoke gas components. It is not enough to limit all components together by a weighted sum as in the current railway standard (EN 45545-2) since single gases might be lethal although the common limit is not exceeded. It is rather recommended to limit concentrations for each single

component of toxic smoke gases, namely CO_2, CO, SO_2, NO_X, HCl, HF and HCN. The measurements can be carried out in the Smoke Density Chamber. In the future it might be possible to use the vitiated Cone Calorimeter as mentioned above instead and to apply the "Fractional Effective Dose" concept which takes the time of exposure and the accumulation of the different toxic components into account.

- Test of reaction on heat radiation
  Heat radiation impacting a material can be responsible for the release of flammable gases (pyrolyse) that in turn can be ignited by themselves or by a spark. In order to avoid this situation a fire test for the reaction on heat radiation should be foreseen. The test can be carried out according to the railway standard with the Cone Calorimeter (EN ISO 5660).
- Heat release test
  Some of the tested interior materials showed extreme rates of heat release. To limit the heat release rates is of great importance since a fire with high heat emissions spreads faster and ignites other parts easier. With the Cone Calorimeter also the heat release rates can be determined.
  With regard to the heat release it is not only recommended to test specimens of material but also complete interior components: Because a bus is equipped with numerous passenger seats of which each is able to contain a high fire load the passenger seat should be tested in whole in a calorimeter test according to the passenger train standard.
- Implementation of smoke detectors in secluded bus compartments
  Simulations and fire tests with smoke detectors yielded that an early detection of smoke generated by a fire is possible which then delivers more time for evacuation. Therefore smoke detectors should be installed in all bus compartments which are not accessible to the driver's view, i. e. toilet cabin, luggage compartment and sleeping-cab.
- Implementation of fire detectors and fire suppression systems in the engine compartment
  In the evaluation of a multitude of bus fires it turned out that most of them (about 75 %) start in the engine compartment. So a fire detection system in the engine compartment would be very effective. Further improvement could be reached by installing a fire suppression system additionally.
  With regard to fires in engine compartments also the choice of the noise insulation material should be scrutinised because soaked with fuel or lubricants it supports the propagation and lasting of a fire.

STATUS QUO OF EXISTING REGULATIONS FOR BUS FIRE SAFETY

The basic international documents stipulating bus fire safety performance measures are the ECE Regulations No. 107 and No. 118. [8, 9]. In the last years several studies showed that the fire safety of buses and coaches could be further improved by amendments to Regulation No. 107 and Regulation No. 118. For example the Swedish Transport Agency and the Norwegian Public Roads Administration initiated a research project together with SP Swedish National Testing and Research Institute, lasting from 2005 to 2008, with the aim to decrease the number and consequences of bus fires, to prevent and delay start of fires, to inhibit fire spread and smoke development in fire incidents and to provide more time for escape in case of fire. In France and Germany studies were carried out as well. Partially based on the findings of the studies discussed within the paper at hand, great efforts were undertaken by bus manufacturers and other stakeholders to improve bus fire safety and the corresponding requirements. Especially experts from France, Germany, Norway, and Sweden [13, 14, 15] commonly proposed several amendments of both ECE Regulations.

First Regulation No. 107 was amended to require fire detection systems in the engine compartment and the compartment where the combustion heater is located, then new requirements for smoke / fire detection systems in separate compartments, e. g. toilets, driver’s sleeping compartment were incorporated. Regulation No. 118 was amended to cover electrical cables and insulation materials. Since the existing Regulation No. 118 required testing of materials in a horizontal position independently from their real installation in the vehicle and only curtains had to be tested in vertical position, it was introduced that materials and components have to be tested taking into account their real installation situation in order to represent a realistic scenario. As an alternative to the horizontal and vertical burning behaviour test, using the test of the rail sector was allowed. In addition, the application of the tests for the passenger compartment was extended to the overall interior compartment of the vehicle.

Need for additional work was seen on two further issues:

Especially Sweden offered to support the development of new requirements dealing with

automatic fire suppression systems in the engine compartment [16, 12]. Since a significant number of fires start in the engine compartment, installation of such systems could be an important measure to improve fire safety. Suppression systems are already available on the market and are fitted on a voluntary basis by manufacturers or operators. A method for testing the performance of fire suppression systems has been developed by SP Technical Research Institute of Sweden (SP Method 4912). However, the international discussion on this issue is ongoing.
In addition, requirements for smoke development and smoke toxicity are still not included in the regulations. Here work is expected to be taken up when the German research project dealing with smoke and toxicity will be finished.
In the following the status quo of requirements for fire safety performace of M2 and M3 vehicles, resulting from the activities mentioned above, is summarised for both regulations separately:

ECE Regulation No. 107

Regulation No. 107 is titled "Uniform provisions concerning the approval of category M2 or M3 vehicles with regard to their general construction". The actual document (end of the year 2012) is the 05 series of amendments of revision 3 of ECE-R 107 which entered into force on 26 July 2012. Within ECE-R 107 the following main requirements with regard to the protection against fire risks have to be met by all vehicles (extracts from the text of the regulation are marked with quote signs):
For the engine compartment special properties of used materials and a detector system for high temperatures are required:

- "No flammable sound-proofing material or material liable to become impregnated with fuel, lubricant or other combustible material shall be used in the engine compartment unless the material is covered by an impermeable sheet."
- "In the case of vehicles having the engine located to the rear of the driver's compartment, the compartment shall be equipped with an alarm system providing the driver with both an acoustic and a visual signal in the event of excess temperature in the engine compartment and in each compartment where a combustion heater is located. The alarm system shall be designed so as to detect a temperature in the engine compartment and in each compartment where a combustion heater is located in excess of the temperature occurring during normal operation."

Also for other separate compartments than the engine compartment fire detection systems are required:

- "Vehicles shall be equipped with an alarm system detecting either an excess temperature or smoke in toilet compartments, driver's sleeping compartments and other separate compartments. Upon detection, the system shall provide the driver with both an acoustic and a visual signal in the driver's compartment. The alarm system shall be at least operational whenever the engine start device is operated, until such time as the engine stop device is operated, regardless of the vehicle's attitude."

However, transitional provisions are given within the regulation which schedule when certain measures will become mandatory so that some requirements do not have to be fulfilled at present but in the future. Fire detectors in the engine compartment will have to be installed from 31 December 2012 for new bus types and from 31 December 2013 for first registrations. Fire detectors (temperature or smoke) in other separate compartments become mandatory 26 July 2014 / 2015 (new types / first entry into service).

ECE Regulation No. 118

Regulation No. 118 is titled "Uniform technical prescriptions concerning the burning behaviour and / or the capability to repel fuel or lubricant of materials used in the construction of certain categories of motor vehicles". The actual document (end of the year 2012) is the revision 1 incorporating the 02 series of amendments (date of entry into force 26 July 2012). Within ECE-R 118 in essence specifications are given with regard to the burning behaviour of the components used in the interior compartment, in the engine compartment and in any separate heating compartment as well as the capability to repel fuel or lubricant of insulation materials used in the engine compartment and in any separate heating compartment (extracts from the text of the regulation are given in the bullet points).:

- The materials and / or equipment used in the interior compartment, in the engine compartment and in any separate heating compartment and / or in devices approved as components shall be so installed as to minimise the risk of flame development and flame propagation.
- Such materials and / or equipment shall only be installed in accordance with their intended purposes and the tests which they have undergone, especially in relation to their burning and melting behaviour

(horizontal / vertical direction) and / or their capability to repel fuel or lubricant.

- Any adhesive agent used to affix the interior material to its supporting structure shall not, as far as possible, exacerbate the burning behaviour of the material.

There are five main tests (each described in a separate annex of ECE-R 118) which have to be passed by the materials depending on where they are fitted in the bus (parts made of metal or glass do not have to be tested):

- Materials and composite materials installed in a horizontal position have to undergo a test to determine the horizontal burning rate. The test is passed if the horizontal burning rate is not more than 100 mm / minute or if the flame extinguishes before reaching the last measuring point.
- Materials and composite materials installed more than 500 mm above the seat cushion and in the roof of the vehicle as well as insulation materials installed in the engine compartment and any separate heating compartment have to fulfill a "drop test" in which the melting behaviour of materials is determined. The result of the test is considered satisfactory if no drop is formed which ignites the cotton wool beneath the specimen.
- Materials and composite materials installed in a vertical position have to undergo a test to determine the vertical burning rate of materials. The test is passed if the vertical burning rate is not more than 100 mm / minute or if the flame extinguishes before the destruction of one of the first marker threads occurred.
- All insulation materials installed in the engine compartment and any separate heating compartment have to be tested to determine the capability of materials to repel fuel or lubricant. The increase of the weight of the test sample must not exceed 1 g.
- Electric cables have to undergo the resistance to flame propagation test described in ISO standard 6722:2006, paragraph 12. Any combustion flame of insulating material must extinguish within 70 seconds and a minimum of 50 mm insulation at the top of the test sample must remain unburned.

Instead of the drop test and the vertical burning test described in the annexes of ECE-R 118 also testing according to ISO 5658-2 [17] which is required in the rail sector is allowed:

- Materials achieving an average CFE (critical heat flux at extinguishment) value greater or equal to 20 kW / m^2, when tested according to ISO 5658-23, are deemed to comply with the requirements, provided no burning drops are observed when taking the worst test results into account.

Again transitional provisions are given within the regulation which schedule when certain measures become mandatory. With the 01 series of amendments (date of entry into force 9 December 2010) the test to determine the capability of materials to repel fuel or lubricant and tests for electric cables were added. It becomes mandatory 9 December 2012 for new bus types and component types and 9 December 2015 for first registrations. With the 02 series of amendments (date of entry into force 26 July 2012) the requirements for material installed in a vertical position with regard to the vertical burning rate were extended and the possibility to use the tests of the railway standard was introduced. These requirements become mandatory 26 July 2016 for new component types, 26 July 2017 for new vehicle types and 26 July 2020 for first registrations.

SUMMARY

Bus fires occur frequently but are usually not accompanied with severely injured persons. In most of the cases the fire starts in the engine compartment and does not affect any passengers because they can leave the bus in time. However single accidents, in which the fire enters the passenger compartment, resulted in a high number of fatalities. More dangerous than the fire itself is the toxicity of smoke gases due to burning interior parts made of plastic materials.
Although buses and passenger trains are operated in a similar way, railway standards for fire safety performance comprise more relevant parameters and are more stringent than bus requirements. Therefore a lot of burning behaviour tests with small specimen of bus interior material, with complete seats and using whole buses were carried out in order to examine possibilities to further increase bus fire safety and to determine how far it is possible to transfer and adapt the requirements for passenger trains to buses.
Some of the outcome of the experiments is already incorporated into international legislation. Especially ECE Regulations No. 107 and 118 cover bus fire safety perfomance. E. g. fire detection systems in the engine compartment and smoke detection systems in separate interior compartments which turned out to be very useful are already required. Also the recommendations to test certain properties of insulation materials to repel fuel or lubricant as well as tests to perform a vertical burning test for vertically mounted parts are specified in the ECE Regulations. However some of the fixed measures will become mandatory only in

the coming years due to transitional provisions. The most important results of the work concern smoke development and toxicity of smoke gas components which are still not covered by legislation. Revised requirements would help to increase the time of escape for passengers in case of a bus fire so that they are not exposed to the toxic smoke gas components that are produced when bus parts are burning. Smoke density and toxic smoke gas concentrations should be limited. It is not sufficient to limit all components together by a weighted sum as in the current railway standard since single gases might be lethal although the sum limit is not exceeded. It is rather recommended to limit concentrations for each single component. Besides smoke also the heat release of burning parts and the ignitability should be limited in order to avoid ignition of adjacent parts and thus minimise fire propagation. The concept to use fire suppression systems in the engine compartment also should be pursued further.

REFERENCES

[1] Nicklisch, F., Ellmers, U.: "Sicherheitsmaßnahmen bei Reisebussen", 4. DEKRA/VDI Symposium Sicherheit von Nutzfahrzeugen, Neumünster, 20 October 2004

[2] Egelhaaf, M., Berg, A., Staubach, H., Lange, T.: "Brandverhalten der Innenausstattung von Reisebussen", Berichte der Bundesanstalt für Straßenwesen, Fahrzeugtechnik, Heft F 51, Bergisch Gladbach, September 2004

[3] Krieg, M., Rüter, G., Weißgerber, A.: "Schwachstellenanalyse zur Optimierung des Notausstiegssystems bei Reisebussen", Berichte der Bundesanstalt für Straßenwesen, Fahrzeugtechnik, Heft F 42, Bergisch Gladbach, August 2003

[4] Hofmann, A., Dülsen, S.: "Fire safety performance of buses", 2nd conference on FIVE - Fires in Vehicles, Chicaco, 27-28 September 2012

[5] United Nations Economic Commission for Europe, Inland Transport Committee, World Forum for Harmonization of Vehicle Regulations: "Consolidated Resolution on the Construction of Vehicles (R.E.3)", ECE/TRANS/WP.29/78/Rev.2, 30 June 2011

[6] Herrmann, L.: "Projektarbeit Busbrände", Präsentation der Universität Magdeburg bei der Bundesanstalt für Materialforschung und -prüfung, Berlin, 3 October 2010

[7] Pupa Versicherungsmakler GmbH: "Jährlich rund 400 Busbrände - Versicherungen zahlen meist nur durchschnittlichen Fahrzeugwert" http://www.pupa.at/news-details/items/jaehrlich-rund-400-busbraende---versicherungen-zahlen-meist-nur-durchschnittlichen-fahrzeugwert.html, 20 September 2010

[8] ECE Regulation No. 107: "Uniform provisions concerning the approval of category M2 or M3 vehicles with regard to their general construction", E/ECE/324/Rev.2/Add.106/Rev.3 − E/ECE/TRANS/505/Rev.2/Add.106/Rev.3, 18 October 2011

[9] ECE Regulation No. 118: "Uniform technical prescriptions concerning the burning behaviour and/or the capability to repel fuel or lubricant of materials used in the construction of certain categories of motor vehicles", E/ECE/324/Rev.2/Add.117/Rev.1 − E/ECE/TRANS/505/Rev.2/Add.117/Rev.1, 4 December 2012

[10] EN 45545-2: Railway applications - Fire protection on railway vehicles - Part 2: Requirements for fire behaviour of materials and components, Comité Européen de Normalisation, 2012

[11] Hammarström, R., Axelsson J., Försth, M., Johansson, P., Sundström, B.: "Bus Fire Safety", SP Report 2008:41, Fire Technology, SP Technical Research Institute of Sweden, Boras, 2008

[12] Brandt, J., Försth, M., Rosen, F., Bialas, O.: "Test method for fire suppression systems in buses and coaches", Informal document GRSG-103-22, 103rd GRSG, 2-5 October 2012

[13] Proposal for a Supplement to Regulation No. 107 (M2 and M3 vehicles), ECE/TRANS/WP.29/GRSG/2011/18, 31 January 2011

[14] Proposal for amendments to Regulation No. 118 (Burning behaviour of materials), ECE/TRANS/WP.29/GRSG/2011/11, 31 January 2011

[15] Proposal for Supplement 1 to the 02 series of amendments to Regulation No. 118 (Burning behaviour material), ECE/TRANS/WP.29/GRSG/2012/22, 19 July 2012

[16] Improve the fire safety of buses and coaches - Automatic fire suppression system in the engine compartment, Informal document GRSG-103-12, 103rd GRSG, 2 – 5 October 2012

[17] ISO 5658-2:2006 Reaction to fire tests – spread of flame – Part 2: Lateral spread on building and transport products in vertical configuration.