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Current Trends in Bumper Design for Pedestrian Impact

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ABSTRACT

Worldwide, the pace of development in pedestrian countermeasures is increasing rapidly. To better understand the state of the art in bumper design for pedestrian impact, a survey of literature and patents has been performed. Two general approaches to reducing the severity of pedestrian lower limb impacts were identified: (a) Provide cushioning and support of the lower limb with a bumper and a new lower stiffener, or (b) Use the bumper as a platform for impact sensors and exterior airbags. This study focused on the first approach. Excluding bumper sensors, airbags, and non-design-related articles, a total of 130 relevant technical articles and 147 patents were identified.

The most common method proposed for *cushioning* the lower limb in an impact uses an energy absorber (plastic foam or 'egg-crate') in front of a semi-rigid (steel or aluminum) beam. There are also proposals for 'spring-steel', steel-foam composites, crush-cans, and plastic beams. The most common method proposed for *supporting* the lower limb in an impact is a secondary lower beam, known as a 'stiffener' or 'spoiler'. Most proposed lower stiffeners are plastic plates or metal beams supported by the engine undertray, the radiator support, or the front-end module. In addition to these concepts, there are a number of design proposals involving a deploying bumper or lower stiffener.

INTRODUCTION

Pedestrian-vehicle accidents are a globally recognized safety concern. Efforts toward modifying vehicle designs to offer more protection for pedestrians began in earnest in the 1970s. In parallel, test procedures to evaluate the performance of the new designs were developed. In industrialized countries pedestrian safety has improved significantly since then. However, as the number of motor vehicles increases rapidly in less developed nations, global pedestrian traffic fatalities remain a major issue.

Beyond the real-world concerns, other incentives for automakers to introduce design features to enhance pedestrian safety are current and planned public domain tests and government regulations.

PUBLIC-DOMAIN TESTS

Pedestrian-vehicle impact tests have only recently become part of the mainstream. Since 1996, the European Union has been subjecting select vehicles to a battery of tests (frontal, side, pedestrian) as part of EuroNCAP [1]. The pedestrian tests consist of bumper impacts with a 'leg-form' impactor, hood edge impacts with an 'upper leg-form' impactor, and hood/fender impacts with two different 'head-form' impactors (see Figure 1). A vehicle is typically subjected to 3 bumper impacts, 3 hood edge impacts, and up to 18 head impacts. Vehicle results are reported with a 4-star rating system. ANCAP[*] tests are identical to EuroNCAP. JNCAP[†] also performs tests simulating pedestrian head impacts onto the hood and fenders, but not lower limb impacts. Vehicle performance in these test series has been improving, so it appears European and Japanese manufacturers are addressing these tests in their designs.

GOVERNMENT REGULATIONS

Pedestrian impact requirements are the subject of two existing regulations in Europe and Japan. Though these requirements differ, there are efforts to introduce a Global Technical Regulation to commonize them [2].

In 2003, the European Parliament and Council approved Directive 2003/102/EC [3], which states that new vehicle introductions must have a specified level of pedestrian impact performance starting in 2005 (see Figure 1).

A recent regulation in Japan specifies vehicle pedestrian head impact protection performance, but not lower limb. New vehicle introductions must meet these requirements in 2005.

In addition to these existing regulations, the European Commission has issued a draft directive regarding the use of frontal protection systems (e.g., bull-bars) [4]. This draft may have an influence on some of the design alternatives identified in this study.

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[*] Australian NCAP, http://www.aaa.asn.au/ancap.htm
[†] Japanese NCAP, http://www.nasva.go.jp/assess/indexe.html

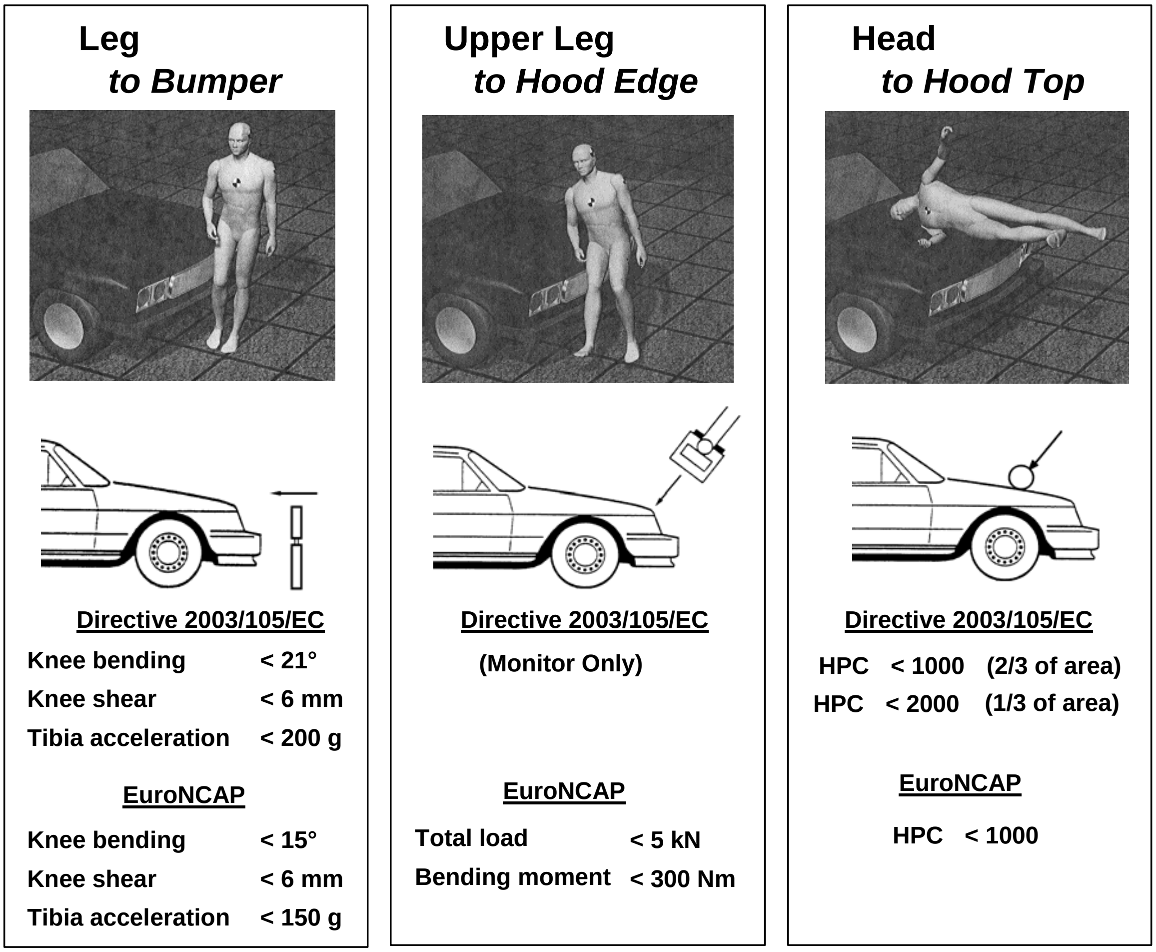

Figure 1: Pedestrian impact test procedures

PEDESTRIAN LEG IMPACT TEST

A brief discussion of the pedestrian leg impact requirements will be helpful before proceeding into the design alternatives found in the literature. The purpose of the pedestrian leg impact test procedure is to reduce the occurrence of lower limb injuries in pedestrian accidents. In the pedestrian leg impact test, a 'leg-form' impactor is propelled toward a stationary vehicle at a velocity of 40 km/h parallel to the vehicle's longitudinal axis. The test can be performed at any location across the face of the vehicle, between the 30º bumper corners. The acceptance criteria are illustrated in Figure 2. The maximum tibia acceleration criterion is intended to prevent tibia fractures. The knee bend angle and shear deformation criteria are intended to prevent knee joint injuries such as ligament ruptures and intra-articular bone fractures.

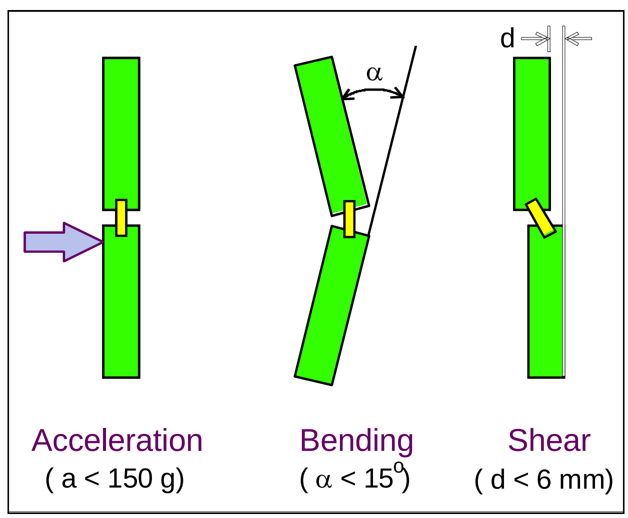

Figure 2: Pedestrian 'leg-form' injury criteria

LIMITATIONS

This study is a review the state-of-the-art (as of January 2005) in the design of bumper systems for pedestrian impact. Because this task relies on work conducted primarily in Europe and Asia, markets with few light trucks, the design trends identified are based on passenger cars.

To focus the study, articles and patents were limited to those specifically describing bumper designs. Articles and patents dealing with the following were *excluded*:

- Other areas of pedestrian impact analysis (e.g. head, torso, and thigh impacts, accident data analysis, impact kinematics and biomechanics, test procedures, and computer simulations)

- Design of other vehicle components (e.g. impact sensors, external airbags, hood, fender, shotgun, headlamps, wipers, windshield)

METHODOLOGY

Standard literature and patent search techniques were used for this study. Keyword searches followed by manual assessment of relevance were used to limit the field to those documents of interest to this study.

LITERATURE SEARCH

In addition to using the standard library database search engines, directed searches were pursued in:

- SAE technical papers (http://www.sae.org)
- 'Enhanced Safety of Vehicles' conferences (http://www-nrd.nhtsa.dot.gov/departments/nrd-01/esv/esv.html)
- IMechE* technical papers (http://www.imeche.org.uk/ils/catalogues.asp)
- UMTRI† library (http://www.umtri.umich.edu/library/simple.html)

The outcome of these searches is believed to be comprehensive in scope. While some technical articles may have been missed, the majority of relevant articles have been identified. Conclusions reached regarding design trends should not be affected by more searches.

Following identification, articles were categorized based on their abstracts. Selected papers were identified for collection and further review. The material presented in this paper is a result of the abstract and selected paper reviews.

PATENT SEARCH

The patent search relied on governmental patent databases, many of which include international patent listings:

- German Patent Office (http://depatisnet.dpma.de)
- European Patent Office (http://ep.espacenet.com)
- Japanese Intellectual Property Digital Library (http://www.ipdl.ncipi.go.jp/homepg_e.ipdl)
- Singapore Patent Office (http://www.surfip.gov.sg)
- US Patent Office (http://www.uspto.gov)
- World Intellectual Property Organization (http://www.wipo.int)

Following identification, patents were categorized based on abstracts and drawings. Selected patents were identified for further review. The trends identified here are a result of the abstract and selected patent reviews.

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RESULTS

LITERATURE SEARCH

A total of 130 relevant articles were identified. Of the 61 recent (published since 1990) articles, approximately 25% were authored by OEM's, 25% by suppliers, and 50% by other groups. Tables 1-3 summarize the number of relevant articles authored by company, and Appendix A provides a list of all articles identified.

PATENT SEARCH

A total of 147 relevant patents (covered by 290 filings) were identified. Tables 1-3 summarize the assignees and types of design solutions identified in these patents, and Appendix B provides a list of all patents.

Table 1: Number of recent non-corporate pedestrian bumper publications and patents

	Recent Articles	Patents
Individuals	9	18
Government Labs	4	2
Universities	9	-
Consultants	5	-
Consortia	4	-
TOTAL:	31	20

Table 2: Number of recent OEM pedestrian bumper publications and patents

		PATENTS								
Company	Recent Articles	Total	Foam	Stiffener	Beam	Egg-crate	Active Bumper	Active Stiffener	Crush-Cans	Other
BMW	-	1					½	½		
DCX	1	6	2½	1½			1	½	½	
Fiat	1	1	1							
Ford/Jaguar	3	17	2	4	2	1	½	2½	1	4
GM/Opel	-	3	1½	½			½	½		
Honda	3	4			½		1	1	1	½
Hyundai	2	1		1						
Kia	1	-								
Mazda	2	8	½	4½			1		1	1
Mitsubishi	-	4								4
Nissan	-	4	1	2½	½					
Peugeot	-	1			1					
Rover	-	1		1						
Subaru/Fuji	1	10	2	3	1				½	3½
Toyota	-	6	1	2		2		1		
Volkswagen	-	3	2		1					
TOTAL:	14	70	13½	20	6	3	4½	6	4	13

Table 3: Number of recent supplier pedestrian bumper publications and patents

Company	Recent Articles	PATENTS								
		Total	Foam	Stiffener	Beam	Egg-crate	Active Bumper	Active Stiffener	Crush-Cans	Other
Adlev S.r.l.	-	1	½		½					
Aisin Seiki	-	1	½		½					
Alcan	1	-								
Atlas Auto	-	1								1
Bayer	-	1						½		½
Benteler	-	1			½					½
Calsonic Kansei	-	2	1		1					
Cellbond	-	2								2
Decoma	-	3	1	2						
Denso	-	1		1						
Dow	3	2	2							
Dynamit Nobel	-	3		1						2
Faurecia	1	-								
FMB Fahrzeug	-	1								1
FPK	-	1								1
G P Daikyo	-	2		1						1
GE Plastics	5	6			1	5				
Inoac	-	1				1				
JSP Corp	3	5	4		1					
Kobe Steel	-	1							1	
Linpac	-	2	1					1		
Man Nutzfahrz.	-	1						1		
Mitsuboshi Belt.	-	1	1							
Netshape	1	3			1	2				
Peguform	-	2		1	1					
Plastic Omnium	-	6	2	2	½	1½				
Raufoss Auto.	-	1			1					
Siemens	1	-								
Solvay	1	-								
SSAB Hardtech	-	1			1					
Tatsuno	-	1					1			
Valeo	-	1				1				
ZF Boge	-	3					2		1	
TOTAL:	16	57	13	8	9	10½	3	2½	2	9

ANALYSIS

OVERVIEW

An assessment of the pedestrian bumper design publications identified two proposed approaches:

- Design the vehicle front-end components to provide the appropriate stiffness to *cushion* the impact while at the same time providing *support* of all parts of the limb to limit knee joint lateral bending. This alternative is the focus of this paper.
- Design an active pedestrian safety system, utilizing sensors and external airbags to cushion and support the lower limb. While there are a growing number of publications in this area, this alternative does not drive bumper design specifically, so is not discussed further here.

CUSHION (ENERGY ABSORPTION)

The cushion function of the bumper in a pedestrian impact is directly related to the acceleration impact criterion shown in Figure 2. It is intended to reduce the severity of bone fractures in a pedestrian impact. This function is not entirely dissimilar from the traditional function of a bumper system (absorbing energy of a vehicle impact). But, there are two key differences: the impact energy and the acceptance criteria.

<u>Impact Energy</u>

A vehicle-to-vehicle impact requires a local energy absorption ‘density’ approximately double that of the pedestrian impact, as can be seen through this brief analysis:

The pedestrian leg-form test device has an effective width of 70-mm. Assuming that a typical bumper energy absorber is 150-mm tall, the contact area is (70)x(150) = 10500-mm^2. The total impact energy at 40 km/h is ½mv^2 = ½(13.4 kg)x(11.1 m/sec)^2 = 825 Joules. As a result, the required energy-absorption ‘density’ of the bumper energy absorber for a vehicle-to-pedestrian impact is approximately (825/10500) = 0.08 J/mm^2.

A pendulum impact engaging only the top 50-mm (typical worst case) of the energy absorber compresses an area (50)x(500) = 25000-mm^2. The total impact energy for a 1500-kg vehicle at 5-mph is ½mv^2 = ½(1500 kg)x(2.22 m/sec)^2 = 3696 Joules. So, the required energy-absorption ‘density’ for a 5-mph vehicle-to-vehicle impact is approximately (3696/25000) = 0.15 J/mm^2.

<u>Acceptance Criteria</u>

For the leg-form impact, the acceleration of the test device must be 150-g or less. For the vehicle impact, the cascaded requirements are maximum force at the frame rail (to prevent damage to the structure) and maximum intrusion (to prevent damage to other components).

The maximum force allowed for vehicle low-speed impact is significantly higher than that tolerated by the human lower limb (as measured by the acceleration criterion). In addition, the intrusion limit, combined with the desire to limit the front-end vehicle length, tends to drive the bumper stiffness as high as possible while still meeting the allowable force limit. This difference between the acceptance criteria is the main cause for conflict between the two impact requirements.

The goal in the design of bumper components to cushion a pedestrian impact is to limit the 'leg-form' acceleration without either (a) sacrificing vehicle damageability, or (b) significantly increasing the depth of the bumper system.

Cushioning Methods

The literature and patent review identified different approaches to perform the cushioning function. These are summarized below in order of decreasing popularity, as measured by the number of patents describing each proposed solution. An example patent is listed for each.

Foam Energy Absorbers – 35 collected patents describe alternative methods for absorbing pedestrian impact energy using plastic foams. The goal of all of these designs is to improve the energy absorption efficiency of existing foam absorbers, and therefore minimize the increase in vehicle length to meet both pedestrian impact and vehicle impact requirements:

- Foam dimensions (13 patents, see EP 1422110) – by changing the contacting shape of the foam, the response of the leg-form device can be tuned. For example, the foam does not have to absorb all the impact energy, it can convert some into leg rotation.

- Multi-density foam (7 patents, see EP 1046546) – by placing low- and a high-density foams in sequence in front of a bumper beam, bumper stiffness can be tailored to different impacts.

- Fluid-filled foam (7 patents, see WO 9725551) – These patents describe alternative fluid-foam composite materials to improve energy efficiency.

- Depression in beam (5 patents, see US 6764117) – by providing an area within the beam for the compressed foam to sit, more of the foam depth can be used for energy absorption. This is important since typical foams only compress 70%.

- Foam coring (3 patents, see JP 2004224106) – by removing material on the backside of the foam, the effective energy-absorption efficiency can be improved.

Molded Plastic Energy Absorbers – 21 patents describe plastic structures to absorb the impacts. In general, these structures replace existing plastic foams, and are intended to improve the energy absorption efficiency for both vehicle and pedestrian impacts:

- 'Egg-crate' molded shapes (13 patents, see US 6726262) – Relatively complex molded plastic structures can be used to deflect and crush in low- and high-energy impacts. Early versions of these designs resemble the inside of an 'egg-crate.'

- Variable stiffness concepts (4 patents, see US 6554332) –Plastic structures that provide different stiffness for different contacting objects have been proposed. For example, a thin object encounters stiffness *X*, while an object four times as thick might encounter a stiffness of *16X*.

- Open shell & other shapes (4 patents, see EP 1365945) – Replacing the energy-absorber with empty space and a simple bumper cover can provide enough stiffness to stop a pedestrian leg-form. However, these designs do not necessarily address vehicle impacts.

Air-filled Energy Absorbers – 11 patents describe air bladders used as energy absorbers, as a means to improving the efficiency. In five of these (see DE 2645823), the stiffness is the same for all impacts. In the rest (see JP 09020192), valves are used to vary the stiffness varies based on the object struck.

Flexible or Plastic Beam – 8 patents describe changes to the bumper's structural member to make it more compliant for a pedestrian impact (see US 6494510), with or without an additional absorber.

Deploying Bumper – 7 patents describe bumpers that provide for additional energy absorber depth without increasing vehicle length by retracting the bumper under normal conditions, and only pushing it out when an impact is predicted (see GB 2368565).

Crush-Cans – 7 patents describe deformable bumper beam attachment structures such as crush cans or pistons. This allows for the impact energy to be absorbed not just in front of a beam, but also behind. In four of these (see DE 3434844), the stiffness is fixed. In the remainder (see JP 2000025540), the stiffness is varied based on the type of impact.

Add-ons – 6 patents describe separate deformable structures added outside the vehicle to protect the pedestrians (see EP 0797517). These structures appear similar to 'bull-bars' but are designed specifically to provide energy absorption and protection of pedestrians.

Foam-encapsulated metal – 3 patents describe methods of encapsulating a metal bumper beam inside the energy-absorbing foam (see US 6793256). The goal is to optimize the interaction between the two pieces and reduce the required foam depth.

Steel energy absorbers – 2 patents describe steel spring structures to store impact energy from different impacts (see US 6398275). These may be used in conjunction with or independent of plastic foams.

SUPPORT (LOAD DISTRIBUTION)

The support function of the bumper system is directly related to the knee bend angle criterion illustrated in Figure 2. It is intended to reduce the risk of severe knee joint injuries such as ligament ruptures and intra-articular fractures. The goal is to provide enough support below and/or above the main bumper to limit the bending moment at the knee joint during an impact. This situation is complicated by two vehicle design requirements:

- The vehicle damageability standard for bumpers requires the front bumper to be located at approximately the same height as the pedestrian 'leg-form' knee. So without other support, the greatest bending moment would occur at the knee. This standard also mandates no damage to other vehicle components, limiting their location.

- The ground clearance and approach angle requirements limit how low to the ground any components can be located.

The goal in the design of bumper components to support the lower limb during a pedestrian impact is to limit the 'leg-form' bending without either (a) sacrificing vehicle damageability, or (b) violating vehicle approach angles.

The literature and patent review identified different approaches to meet this goal. As above, these are summarized in order of decreasing popularity, as measured by the number of patents describing each solution. An example patent is listed for each.

<u>Fixed Lower Stiffeners</u> – 41 patents describe a new stationary component to be positioned below the bumper system to prevent the lower part of the 'leg-form' from intruding further than the knee. This is typically called a 'lower stiffener' or 'spoiler,' though occasionally is referred to as a 'cow catcher' based on its functional resemblance to that device. The differences in these design proposals have mainly to do with manufacturing and attachment:

- Metal beam (11 patents, see GB 2069940) – a metal structural beam (often fronted with foam) can provide the required stiffness.

- Plastic tray (11 patents, see EP 1409295) – a plastic plate is an alternative method for this component.

- Extended structure (8 patents, see US 6676179) – the lower front structure of the vehicle (especially if a molded front-end module) can be extended forward and fronted with foam.

- Reinforced cover (5 patents, see JP 2002144988) – the lower edge of a plastic bumper cover can be reinforced, either through inserts, add-on components, or injection molding.

- Engine undertray (3 patents, see US 6540275) – an existing engine undertray can be extended forward.

- Damper-mounted (3 patents, see EP 557733) – any stand-alone structural stiffener can be mounted to dampers to limit the force applied to the leg-form.

<u>Deploying Lower Stiffeners</u> – Ten patents describe stand-alone lower structural members that deploy forward before impact. Deployment is based on either object detection or speed (see JP 2004074972).

<u>Mechanical Linkages</u> – Three patents describe a lower stiffener that is connected by a mechanical linkage to the bumper face. Pressure on the bumper face forces the lower stiffener forward (see GB 2321624)

<u>Deploying Upper Structures</u> – Two patents describe a deployable stiffener mounted above the bumper system, to prevent excessive knee bend angle by stopping the upper part of the leg-form and pedestrian (see US 6447049).

<u>Broad Face Bumpers</u> – Two patents describe bumpers with a tall front-view height to provide support without additional structures (see GB 2336812).

Note that in addition to these specific design features, the patent and literature search also indicated that designs that provide improved 'cushioning' of the lower limb (e.g., foam shape/profile, multi-density foam, and pedestrian 'bull-bars') can also be used to help reduce knee bend angle during the pedestrian impact.

DISCUSSION

DESIGN TRENDS

Several common design trends can be identified based on the results of this survey. These represent alternative approaches to meeting the requirements of pedestrian leg impact. As bumper systems meeting these requirements are only beginning to hit the market in Europe, Australia, and Japan, it is too early to state definitively which approaches will eventually be the most common. However, the preponderance of certain types of designs in the patent archives can provide some assessment of the likelihood of each trend to be implemented. A list of the key trends follows, in order of the probability of implementation.

<u>Lower stiffeners (deploying or static)</u>. Most bumper designs for pedestrian impact include some type of lower stiffener. There are many ways of delivering the function of this part, as reflected by the breadth of design proposals in this area. The key challenges faced by all of them are durability and vehicle styling. The location of the component virtually ensures contact with curbs, and results in visible changes to the vehicle's front end. Deploying stiffeners are less likely to find

broad implementation in vehicles, although they may be used for more styling-critical vehicles.

Alternative energy absorbers. Between multi-density or ‘tuned’ shape foams and a large number of molded plastic energy absorbers, this is a growth area. The prevailing data suggests that some type of energy-absorber will be necessary between the bumper beam and the pedestrian (structural beams alone being too stiff). There are a few proposed designs that propose modifying the bumper beam to be an energy absorber or adding a crush-can behind the beam. Basically, any design that improves the efficiency of energy absorption will enable vehicle designers to deliver both pedestrian and vehicle impact performance in a more compact package. The more aggressive alternative designs attempt to achieve greater differences in stiffness between the two types of impact. Alternative foam and plastic energy-absorbers will probably be the lead contenders in this area for the foreseeable future.

Beam design. The design of the bumper beam in a beam-absorber system (traditional passenger car) has also received some attention. In particular, there are several proposals to change the shape of the face of the beam to eliminate foam ‘bottoming-out’ and reduce leg-form knee bending. In addition, molded plastic absorbers often require additional attachment points on the face of the beam. This represents a common—though minor—design trend that is really just part of good design practice.

Flexible beams. There are some indications that a flexible (usually plastic) beam can be used to improve pedestrian impact performance. At present, this does not represent a significant trend.

‘Add-on Structures.’ A few structures mounted on the front of the vehicle have been proposed to provide additional energy absorption and support of the lower limb during a pedestrian impact. Although a ‘bull-bar’ is not in general a device that would enhance pedestrian safety – a proposed European regulation on bull-bars assumes they are a detriment to pedestrians – a properly designed energy absorbing add-on structure may protect a pedestrian from more severe impact with the vehicle structure. The design proposals in this area predominantly use plastic materials. This is a minor trend that is unlikely to affect most vehicles.

Bumper-mounted sensors and/or bumper airbags. Although these were not included in this study, they do represent a major design trend. The major benefit of this approach is that protecting for pedestrian impact would result in virtually no change to vehicle styling. In addition, any type of bumper system could be used with an airbag cover – the energy absorption of the bumper is irrelevant. The key disadvantages are cost, durability, and feasibility of the system. Sensors and airbags are much more expensive than most components in other proposals, and their durability outside the vehicle is unknown. In addition, no sensor has yet demonstrated the performance required to deliver this system. As these technologies were not reviewed in-depth in this study, insufficient data exists to predict how likely implementation will be. Major patent activity is on-going in the supporting technological areas, but the remaining technical hurdles and costs are significant. In the author’s opinion, implementation will likely be limited to styling-critical vehicles.

PATENT TRENDS

In addition to looking at design particulars, it is illuminating to look at the growth of ‘pedestrian protection’ bumper patents over time (Figure 3). A modest increase in patents in this area started in 1995, when EuroNCAP began performing and publicizing pedestrian impact tests. But the more striking part of the figure is the extraordinary increase starting in 2001, when the European ‘negotiated agreement’ on pedestrian protection was being publicly discussed. It appears that the increased publicity and apparent progress toward mandated standards has significantly increased the number of new ideas generated in this area.

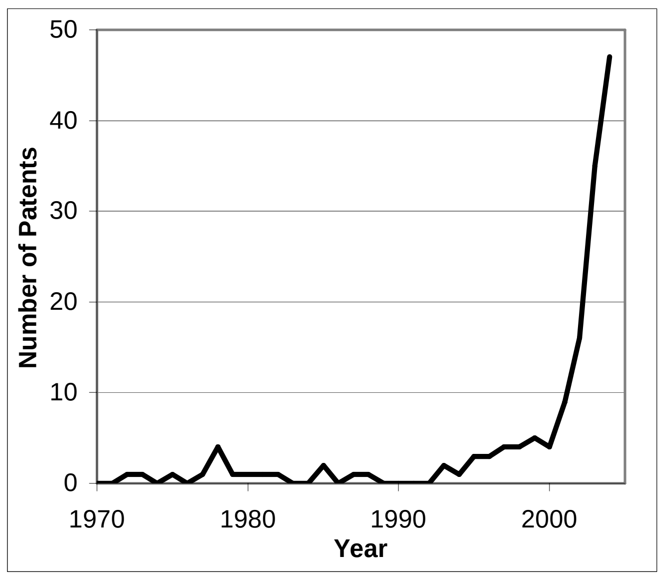

Figure 3: Pedestrian bumper patents over time

CONCLUSION

Over the past 35 years, two approaches have been proposed for protecting a pedestrian’s lower limbs during an impact with a motor vehicle. The deployable approach is to implement advanced impact sensors into the bumper and deploy airbags or structures over the surface just prior to impact. The static approach aims to provide appropriate cushioning and support of the lower limb using the bumper energy absorber and a new component, called a lower stiffener.

130 technical articles and 147 patents were found describing alternative designs within the static area. While the technical articles provide information on the

preferred shape and stiffness of the bumper system, the patents provided specific details on designs delivering those features. An analysis of the data found that some bumper design trends for pedestrian impact, in order of implementation likelihood, are: lower stiffeners, alternative energy absorbers, beam face features, flexible beams, and add-on structures.

ACKNOWLEDGMENTS

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APPENDIX B: RELEVANT PATENTS

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