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**A STRATEGIC ASSESSMENT OF ALTERNATIVE ENGINEERING
CONCEPTS FOR A LOW VOLUME SPORTSCAR MANUFACTURER
TO MEET EUROPEAN STAGE II PEDESTRIAN HEAD IMPACT
LEGISLATIVE REQUIREMENTS**

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**This Thesis is submitted in partial (40%) weighting fulfilment of the requirements for the
degree of:**

Master of Science in Automotive Technology Management

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Abstract

The Lotus Elite concept car was revealed at the Paris motor show in September 2010 and is a two-door 2+2 Sports Grand Tourer planned to compete in the High Luxury Sportscar vehicle segment and is part of a revolutionary model strategy based on a new platform to revitalise Lotus Cars into a profitable and sustainable business through increased margins and volumes.

Future Lotus vehicles will therefore have to comply with any future legislative requirements. These are primarily focussed on vehicle and occupant safety crash performance and these requirements are an important attribute of the proposed Lotus Elite design and development programme.

Road traffic fatalities are a worldwide issue according to a report by the World Health Organisation, an estimated 1.2 million people lost their lives and 50 million non-fatal injuries were due to Road Traffic Accidents. Over the past decade automotive safety initiatives have grown in scope to not only include the vehicle occupants but also to pedestrians. Legislation relating to Pedestrian Protection currently exists in the European Union with further requirements and stricter targets planned for introduction in 2012 and beyond.

These new requirements pose a quandary for Lotus due to the fact that aesthetic style is an important attribute of delivering Lotus core brand values and legislation requirements relating to pedestrian protection may drive a need to compromise and potentially degrade the impact of this key attribute. These compromises are driven by the potential physical geometric changes that maybe required to the front end surfaces to meet targets.

A review of current literature was extensively performed to benchmarking of competitors, identifies industry trends and market landscape to determine what has been, is, and is going to be possibly done in the future to meet pedestrian protection requirements. A set of requirements and targets were defined to enable a more structured review of what technology automotive vehicle manufacturers and suppliers are offering and whether these technologies or strategies could meet the needs of the Lotus Elite to meet requirements.

The current status of the Lotus Elite showcar relating to the achievement of pedestrian protection head impact requirements was derived. Identifying the head impact landscape of the vehicle geometry and highlighted areas of the vehicle that require further analysis and engineering focus to meet pedestrian protection targets.

Both legislative and consumer test regime validity to ‘real’ world accident injury data are reviewed and discussed with a view that existing test criteria and methods do not address the primary causes of injury to pedestrians in the windscreen and ‘A’ pillar areas.

Conclusions draws on research and CAE testing carried out by the Lotus Cars Engineering team to recommend that Elite must meet pedestrian protection requirements in order to support its growth strategy. The adoption of a passive pedestrian protection design strategy is also proposed by the Elite programme team, potentially allowing a lower technical risk and a faster time to market with reduced cost compared to active systems.

Contents

List of Figures	v
List of Tables	viii
List of Equations	viii
Nomenclature	ix
Acknowledgements	x
1 __ Introduction.....	1
1.1 Overview and Background	1
1.2 Problem Statement:	3
1.3 Aims and Objectives	4
1.4 Thesis Content	6
2 __ Commercial Justification – The ‘Need’	8
2.1 Future Lotus Product Placement	8
2.2 Lotus Elite Vehicle Overview	10
2.3 Market Analysis	12
2.4 Alternative Scenarios and Commercial Justification	16
2.4.1 Do nothing	17
2.4.2 Small Series	18
2.4.3 Meet PP EU2 legislative requirements	19
2.4.4 Commercial Justification Summary	19
3 __ Pedestrian Protection Review of Current Literature	20
3.1 Literature Review Objectives.....	20
3.2 Introduction.....	21
3.3 Motivation - Road Traffic Accidents	22
3.3.1 The Accident Environment.....	24
3.3.2 Pedestrian Responses to a Vehicle Impact	29
3.4 Background Vehicle Research and Development.....	33
3.5 Production Vehicle Market Landscape	38
3.6 Competitor Analysis	40
3.6.1 HLS segment analysis	41
3.6.1.1 Passive solutions.....	42
3.6.1.2 Active solutions:.....	45
3.7 Framework and Requirements	47
3.7.1 Pedestrian Protection Outlook	48

3.7.2	Pedestrian Head Impact Requirements	50
3.7.3	Head Protection Hard-point Clearances	54
3.7.4	PP Test Methods and Governing Bodies	57
3.7.4.1	PP Legislative Test Methods	58
3.7.4.2	In Market EuroNCAP Testing.....	59
3.7.4.3	High EuroNCAP scores:.....	62
3.8	Pedestrian Protection Enabling Technologies.....	64
3.8.1	Introduction	64
3.8.2	Passive Countermeasures.....	65
3.8.2.1	Changes in Vehicle Geometry	66
3.8.2.2	Stiffness Optimisation	67
3.8.3	Adaptable Vehicle Structures	68
3.8.3.1	AVS System Considerations	71
3.8.3.2	AVS sub-system componentry	72
3.8.4	Deployable Exterior Airbags	75
3.9	Technology Assessment and Methodology	81
3.9.1	Methods of Assessing Technologies	81
4	Lotus Elite Pedestrian Protection Requirements	84
4.1	Head Impact Zone Requirements.....	84
4.2	Vehicle Attribute Considerations.....	90
5	Results and Findings.....	94
5.1	Current State Elite.....	94
5.1.1	HI Clearances	94
5.1.2	HIC Status.....	97
5.1.3	Current State Elite – Key Observations.....	101
6	Discussion and Future Work	103
6.1	Legacy Integration	104
6.1.1	Product - Alternative Engineering Architecture Solutions for Elite	104
6.1.1.1	Passive System Impact Assessment	104
6.1.1.2	Geometry changes	105
6.1.1.3	Stiffness considerations:.....	105
6.1.1.4	Active System Impact Assessment.....	106
6.1.2	Process	109
6.1.3	Governance.....	112
6.2	Future work and Next Steps.....	114
7	Conclusions.....	116
8	Bibliography	119

List of Figures

Figure 1 – Lotus NEP proposed core vehicle product range	2
Figure 2 – Current and future Lotus volume and pricing versus competitors	8
Figure 3 – Potential future Lotus product positioning within the HLS segment	9
Figure 4 – Lotus Elite Coupe – Paris show car 2010	11
Figure 5 – Lotus Elite predicted competitor set (as of 2011)	12
Figure 6 - PESTEL analysis of drivers influencing the HLS market segment	13
Figure 7 - Porters five forces model applied to the Lotus NEP strategy	15
Figure 8 - Killed or seriously injured casualties by road user UK 1994-2007 (5)	23
Figure 9 - Vehicle impact zones in pedestrian to car accidents (8)	25
Figure 10 – Sources of pedestrian injuries in the front zone of a vehicle.....	26
Figure 11 – Pedestrian to vehicle frontal crash event at 40km/h (13)	27
Figure 12 –Factors associated with Pedestrian crash risk and/or injury severity (15)	28
Figure 13 – Distribution of injuries suffered by pedestrian resulting from RTAs (9).....	30
Figure 14 – Percentage of hospitalised pedestrians – Pronounced dead during hospital stay indicating injury type and body area location (5).....	31
Figure 15 – Percentage of hospitalised pedestrians – Discharged alive post hospital stay indicating injury type and body area location (5).....	32
Figure 16 - BL Marina based ‘SRV2’	34
Figure 17 – BL Mini Clubman based ‘SRV4’	35
Figure 18 – Austin 1300 based ‘SRV5’ demonstrating first active PP system	36
Figure 19 –Austin Metro based PP design study (TRL developed) circa 1985 (20).....	37
Figure 20 – First example of production deployable bonnet, Jaguar XK 2006.....	38
Figure 21 – PP bonnet technology implementation timeline.....	39
Figure 22 - Ferrari California 2010 (Front Engine, 2+2 GT)	42
Figure 23 – Audi R8 (2008) (Mid Engine, 2 seater)	42
Figure 24 - Maserati Gran Turismo 2009 (Front engine, 2+2 seater)	43
Figure 25 – Mercedes SLS 2010 (Front engine, 2 seater)	43
Figure 26 – Bentley Continental GT 2011 (Front engine, 4 seater)	44
Figure 27 – Aston Martin Vanquish 2012 (Front engine, 2+2 seater).....	44
Figure 28 - Jaguar XK 2006 (Front engine, 2+2 seater).....	45
Figure 29 – Mercedes SL 2012 (Front Engine, 2 seater).....	46
Figure 30 – PP Legislative elements	47
Figure 31 –Global PP regulatory requirements landscape (2010).....	49
Figure 32 – Global PP legislation introduction timeline	49

Figure 33 – AIS Scale of injury entity and corresponding fatality percent (23)	51
Figure 34 – PP EU2 legislative test requirements (head and lower leg shown).....	53
Figure 35 – Example ‘Adult’ PP EU2 test head-form (CAD model shown)	54
Figure 36 – Cross relationship between under bonnet clearance and intrusion (29).....	55
Figure 37 – Bonnet head-form tests performed at BASt in Germany, 40km/h impact speed (31)	56
Figure 38 - Graph of absorption versus Z clearance requirements.....	57
Figure 39 –Schematic of PP EU2 Head impact test criteria.....	58
Figure 40 – Legislative PP EU2 head impact test equipment installation.....	59
Figure 41 - EuroNCAP PP HI test criteria and targets overview (34).....	60
Figure 42 - Example of consumer EuroNCAP PP test results (35).....	62
Figure 43 – BMW 5 series, 2010.....	63
Figure 44 – BMW 5 series 2010 EuroNCAP PP results (35).....	63
Figure 45 - Overview schematic of PP enabling technologies groups	64
Figure 46 – TASS ‘Ecofront’ concept study, 2001 (36).....	66
Figure 47 – Collapsible fender bracket concept (37).....	67
Figure 48 – 2011 landscape of vehicles with deployable bonnet PP system.....	69
Figure 49 – Venn diagram of a bonnet deployed AVS system	69
Figure 50 - AVS system 3 stage activation lifecycle.....	70
Figure 51 – Example of a fully deployed active bonnet system (31)	71
Figure 52 – AVS sub-system vehicle schematic (Source Nissan).....	72
Figure 53 – Schematic of an active bonnet actuator	73
Figure 54 – Single link deployable bonnet hinge as used in the Jaguar XF	74
Figure 55 – Multi link hinge concept (Source Anonymous)	74
Figure 56 – Example of a resettable active hinge mechanism.....	75
Figure 57 – Example of development testing for early bonnet deployed airbag (49)	76
Figure 58 – Development prototype of bonnet airbag system (40)	77
Figure 59 – Toyota Gosei exterior airbag concept car (41).....	78
Figure 60 –Volvo V40 Pedestrian Protection Airbag system (42)	79
Figure 61 – Typical technology roadmap example (43).....	82
Figure 62 – Overview of Vehicle assessment for PP (44).....	83
Figure 63 – Elite bonnet rear reference line schematic	85
Figure 64 – Elite bonnet forward reference line schematic	86
Figure 65 – Elite bonnet side reference line schematic	86
Figure 66 – Resulting EU2 head impact test zones for Elite (½ area shown)	87
Figure 67 – Resulting legal test zones for PP EU2 for Elite concept vehicle.....	88
Figure 68 – Cross section of bonnet to hardware clearance Zone (33)	89
Figure 69 – Potential attribute effects of PP to core Elite programme	92

Figure 70 -Cross section of Elite bonnet PP EU2 HI target envelope.....	95
Figure 71 –100mm Z internal clearance target overlaid to Elite package and PP zones.....	96
Figure 72 - Example of a high z intrusion area selected for CAE HIC analysis	97
Figure 73 – Selected CAE PP HI points for Elite concept bonnet area.....	98
Figure 74 – CAE derived HIC results for Elite concept bonnet hinge area	99
Figure 75 –CAE derived HIC results for Elite concept bonnet around headlamp area	100
Figure 76 – Passive system changes required to concept Elite under bonnet components	104
Figure 77 - Proposed active hinge deployed bonnet Elite PP system.....	106
Figure 78 - Bonnet cross section showing lift requirements in Z at trailing edge.....	107
Figure 79– Timeframe for Elite hinge deployed bonnet PP countermeasure event	108

List of Tables

Table 1 – Distribution of Pedestrian to Vehicle RTAs by collision partner type (10)	23
Table 2 – EuroNCAP PP test relationship between points scored and star rating (34)	61
Table 3 – Summary table of Lotus PP EU2 head impact targets.....	90
Table 4 – CAE derived HIC results for selected high impact points for Elite concept	99
Table 5 - CAE derived HIC results for high scoring areas in the bonnet hinge area	100
Table 6 – First run CAE derived PP EU2 HIC status for Elite showcar concept.....	101
Table 7 – Example of technology assessment matrix for PP active actuators.....	110
Table 8 –PP technology strategy assessment matrix for Lotus Elite.....	111

List of Equations

Equation 1 – HIC expression relating to PP head impact	52
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Nomenclature

AIS	Abbreviated Injury Scale
AVS	Adaptable Vehicle Structure
BL	British Leyland
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CATIA	Computer Aided Three-dimensional Interactive Application
DVL	Downward Vision Legislation
ECE	Economic Commission for Europe
EC SSTA	European Commission Small Series Type Approval
ECWVTA	European Community Whole Vehicle Type Approval
EEVC	European Enhanced Vehicle-safety Committee
EU	European Union
Euro NCAP	European New Car Assessment Programme
GT	Grand Tourer
GTR	Global Technical Regulation
HI	Head Impact
HIC	Head-form Impact Criterion
HLS	High Luxury Sportscar
MADYMO	MAThematical DYnamic MOdels
NEP	New Era Platform
NHSTA	National Highway Traffic Safety Administration
NPI	New Product Introduction
OEM	Original Equipment Manufacturer
PESTEL	Political Environmental Technology, Economic Legislative
PP	Pedestrian Protection
RTA	Road Traffic Accident
SRV	Special Research Vehicles
SSV	Safety System Vehicle
TASS	TNO Automotive Safety Systems
TRL	Transport Research Laboratory
UK	United Kingdom
US	United States
VAG	Volkswagen Audi Group
WAD	Wrap Around Distance
WG17	Working Group 17
WHO	World Health Organisation

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The author (at the time of writing) was the Chief Programme Engineer of the Lotus New Era Platform responsible for front engine programmes. He is a degree qualified engineer in Automotive Engineering Design with 17 years' experience in the automotive industry, working at companies such as Aston Martin and Jaguar Land Rover primarily within the Product Development Programme Management function.

1 Introduction

1.1 Overview and Background

Lotus Cars was founded in 1952 by Colin Chapman is a manufacturer of low volume, niche Sportscars based at Hethel in Norfolk, United Kingdom (UK) and is part of Group Lotus Limited which also owns the engineering consultancy Lotus Engineering. It a global company, with facilities in the UK, United States (US), Malaysia and China.

Vehicle dynamics and intelligent design through lightweight principles have been the core elements of the Lotus brand since its creation, these philosophies still remain relevant to Lotus core values today and continue to define Lotus's current product range. These brand values will also be realised in a new generation of vehicles to be launched from 2014 onwards based on a new vehicle platform and architecture known at the New Era Platform (NEP).

Lotus's current vehicle range is not based on this NEP architecture and is therefore not considered in the scope of this thesis. The NEP will consist initially of 3 discrete model lines - the Esprit Super Sportscar, the Elite Sports GT and the Eterne 4 door sports saloon as depicted in Figure 1 All these 3 NEP vehicles will compete together in the High Luxury Sportscar (HLS)¹ vehicle market segment.

¹ The HLS vehicle market segment is defined as large multi-cylinder coupe and convertible vehicles with European premium brands, such as BMW, Mercedes, Ferrari and Aston Martin.

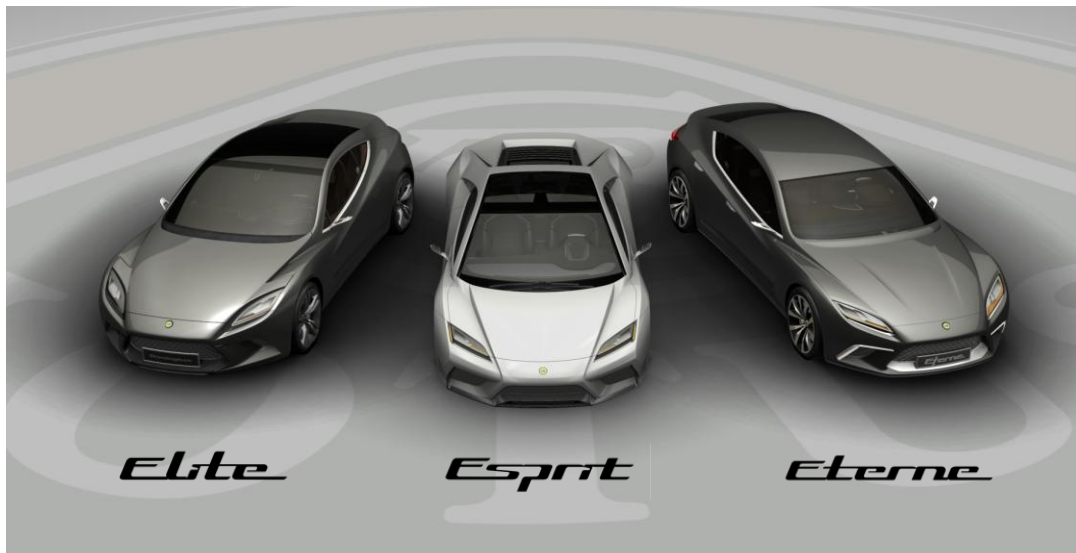


Figure 1 – Lotus NEP proposed core vehicle product range

The proposed NEP strategy was created in 2010 and forms the basis of all future mid and front engine Lotus vehicle products. It comprises two key elements in its strategy; at its core is a bonded monocoque structure consisting of a mixture of aluminium pressings, castings and extrusion sections centred on a common front occupant package and crash structure. This element provides a high level modularity to enable different wheelbases, body styles and wheel tracks to be designed and configured around this nodal architecture, whilst maximising component commonality.

The second element refers to cross-vehicle line supporting systems such as air-conditioning, Powertrain and Electrical architectures that are sourced as modules from a variety of automotive international suppliers. These components and systems are tailored and then integrated into each vehicle configuration to meet specific customer driven requirements, hence reducing development and variable piece costs and also reducing vehicle launch time to market.

These 3 new models mark a significant change point in the timeline of Lotus as an automotive vehicle manufacturer. They are part of a major companywide Lotus strategy to enable the brand to elevate its current 'purist' market place positioning to a more premium level akin to Aston Martin, Porsche and Ferrari to ultimately become more profitable and sustainable.

1.2 Problem Statement:

In order to meet these company aspirations to grow volume and shift to a higher market segment to maximise revenue margins, future Lotus vehicles will need to be sold in existing and new market territories and must therefore comply with any future legislative requirements. These are primarily focussed on vehicle and occupant safety crash performance and these requirements are an important attribute of the NEP engineering development programme.

Over the past decade automotive safety initiatives have grown in scope to not only include the vehicle occupants but also to pedestrians. Legislation relating to Pedestrian Protection (PP) currently exists in both European Union (EU) and Japan with further requirements and stricter targets planned for introduction in 2012 and beyond (3).

The key driver for these incremental requirements according to Fredriksson (4) is a rising trend in non-life threatening pedestrian injuries. Crandall et al (5) concluded that the increase in pedestrian injuries relating to traumatic neck, brain or facial injuries can result in long term disability or impairment. Fredriksson (4) also suggests the most

common upper-body injuries are caused by the windscreen area of a vehicle, with head related injuries being the most dominant result. As will be concluded these areas are not currently covered in the scope of existing or future safety legislation.

These new requirements pose a quandary for Lotus and its future vehicle strategy due to the fact that aesthetic style is an important attribute of delivering Lotus core brand values and legislation requirements for PP may drive a need to compromise and potentially degrade the impact of this key attribute. These compromises are driven by the potential physical geometric changes that maybe required to the front end visible surfaces and supporting inner structure of the vehicle to meet PP targets.

1.3 Aims and Objectives

The primary aims of this thesis are to:

- Conduct a literature review of alternative engineering concepts available to Lotus to meet European Stage II PP legislative 2012 targets, specifically relating to head impact criteria utilising its proposed NEP architecture as a base (the Elite vehicle derivative is chosen in this case due to the authors knowledge of the programme and also the mechanical layout of the vehicle being more relevant to PP strategies, i.e. a front-engine package layout).
- Review how these concepts can be evaluated from a technology implementation perspective and how this process could be integrated into the Lotus business model to assess future technology applications.

The resulting objectives of this thesis are:

- Quantify the drivers, sources and mechanics of pedestrian fatalities and serious injuries to determine how the vehicle could be modified to reduce injury severity.
- Review existing legislative and consumer testing relating to PP and assess correlation to ‘real world’ accident data.
- Assess current and future automotive competitor activity and identify trends relating to PP Head Impact (HI) countermeasure strategies.
- Propose and assess potential alternative engineering concepts specific to the Lotus Elite vehicle in order to meet PP requirements.
- Discuss legacy integration relating to proposed product and process impacts to Lotus Cars NEP strategy.
- Conclude and propose future workstreams and next steps.

The resulting scope of this thesis is to review and strategically assess potential engineering concepts to enable Lotus to manufacture, retail and register its Elite product in the EU by meeting PP impact legislation due to be implemented at the end of 2012.

The structure of this thesis contains both technical and strategic process elements relating to how a low volume vehicle manufacturer such as Lotus Cars could approach, assess and implement PP enabling technologies. This thesis is unique to others as it discusses and reports the influence of exterior aesthetics specific to vehicles in the HLS market sector in meeting PP requirements. In this sector vehicles have a much lower stance to the ground, in side profile have long bonnets and a lower windscreen angle compared to other more commonly tested vehicle sectors.

1.4 Thesis Content

This thesis begins by answering the commercial question of “why do Lotus products need to change in order to fulfil the growth aspirations and resulting financial stability future state of the Lotus business and what are the main driving factors and forces for this change?” By utilising existing literature relating to road traffic fatalities and injuries and industry technology trends, a case leading to the need for Lotus products to change is built.

Following on from defining a need for change, a review of current literature is performed to determine the governance structure, introduction timeline and technical requirements of the PP framework and associated test regimes. This literature review conducts a benchmarking of competitors, identifies industry trends and market landscape to determine what has been, is, and is going to be possibly done in the future to meet PP requirements.

A part of this literature reviews the sources and causes of pedestrian injuries coupled with a deeper review of the enabling PP technologies to determine the important design parameters that should be considered when implementing a PP strategy into the Lotus Elite vehicle.

From a review of literature a set of requirements and targets are defined to enable a more structured review of what technology automotive vehicle manufacturers and suppliers are offering and whether these technologies or strategies meet the needs of the Lotus Elite to meet PP requirements.

Chapter 4 reviews the current status of the Lotus Elite showcar relating to the achievement of PP HI requirements is derived in chapter 5. This identifies the PP HI landscape of the vehicle geometry and highlights areas of the vehicle that require further analysis and engineering focus to meet PP targets.

Discussion and future work in chapter 6 collates all learning to date based on current literature to evaluate and propose a direction on how the Lotus Elite could meet PP requirements and what approach can be taken to perform this assessment. Alternative engineering concepts for Elite, both are explored to quantify any constraints, influencing factors and risks/challenges/opportunities to determine a technology assessment matrix which can be applied to identify alternative workstreams to meet PP requirements with an assessment justification.

Both legislative and consumer test regime validity to ‘real’ world accident injury data is discussed with a view that existing test criteria and methods do not address the primary causes of injury to pedestrians.

The conclusion draws on research carried out literature review within the previous chapters to recommend that Lotus must meet PP requirements in order to support its growth strategy. The adoption of a passive PP design strategy is also proposed to the Elite programme team, potentially allowing a faster time to market and reduced cost to be realised. HLS segment vehicles with package layouts and geometry such as the Elite may require further amended PP test procedures particularly in the windscreen and ‘A’ pillar area to replicate ‘real world’ sources of severe head injuries.

2 Commercial Justification – The ‘Need’

This chapter provides an overview of future Lotus products, where they will compete and provides an insight into what the drivers are for meeting PP legislation and how they relate to and may impact the Lotus future NEP product strategy.

2.1 Future Lotus Product Placement

Lotus as an automotive company is relatively small in terms of overall resources and leverage within its industry sector, current production manufacturing volumes are also low compared to its main competitors, such as Porsche, Maserati, Aston Martin, Jaguar and Bentley. The company has a revised strategy to grow to deliver a more significant profit margin, not only through increased volume but also a shift in market position (see Figure 2).

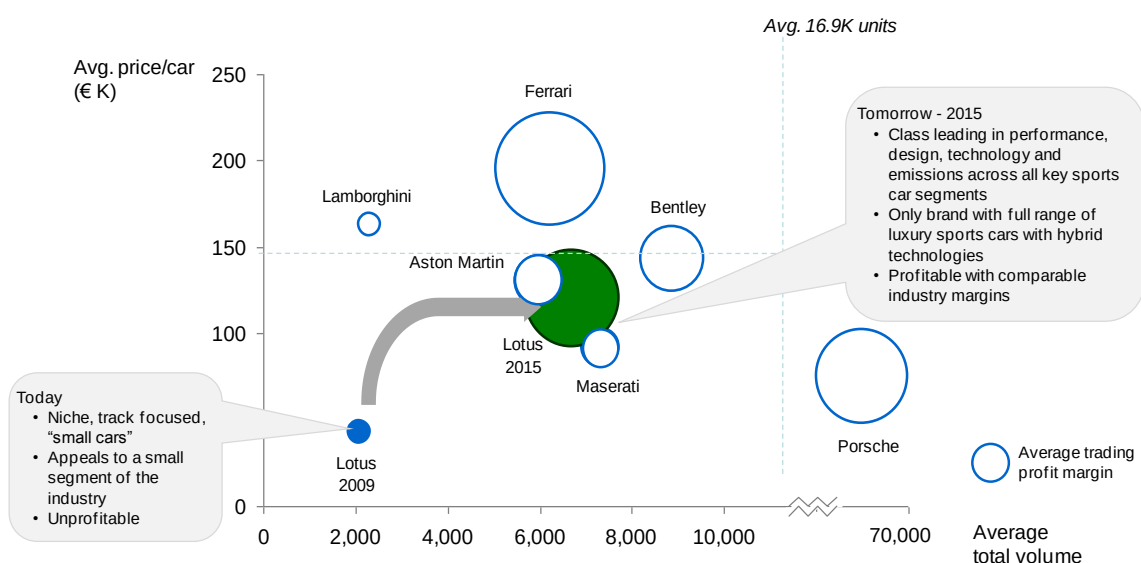


Figure 2 – Current and future Lotus volume and pricing versus competitors

As discussed in chapter 1 the proposed NEP based Lotus vehicles are to be positioned in the HLS market segment as shown in Figure 3, this also places HLS sector vehicles into sub categories relating to price, use and sportiness.

The current range of Lotus products can be seen in the bottom left area of the chart in the ‘purist’ category. In order to attain higher profit margins and volume future Lotus NEP vehicles must shift category (Esprit, Elite and Eterne are shown).

The HLS market segment is relatively volatile in comparison to other automotive vehicle sectors. Rapid changes in customer requirements related to emerging fashion trends coupled with shifts in expectation levels, lead manufacturers to implement product actions swiftly in order to achieve competitive advantage, or even maintain their existing position within the marketplace.

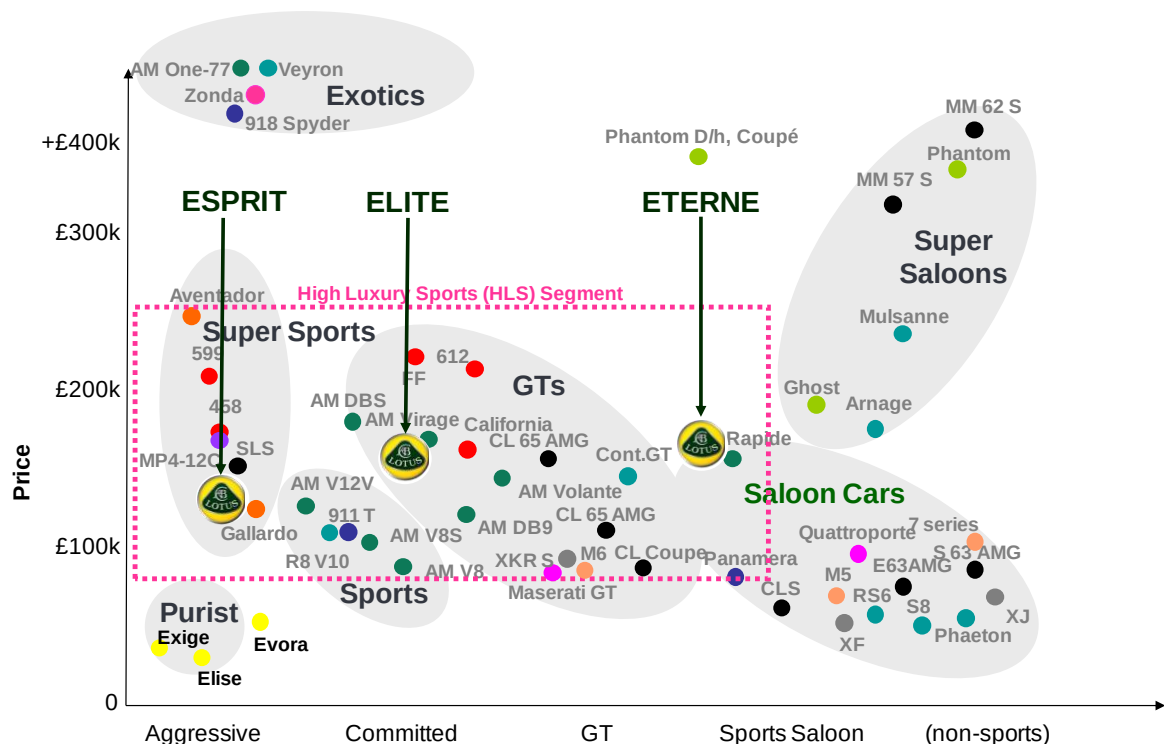


Figure 3 – Potential future Lotus product positioning within the HLS segment

Vehicle development and time to market introduction therefore need to be as short as possible, but robustly delivered in order to reap the benefits in term of sales reward and ultimately continued sustainable revenue generation.

As previously discussed Lotus needs to reposition itself within the market segments in order to become a profitable, self-sustainable vehicle manufacturer but, being present in the EU market is also vital to the success of this shift as it currently accounts for over 30% of total consumer sales and hence contribution margin. This market is also currently expanding as a growing number of legacy ‘Eastern Bloc’² countries make the financial transition into the western industrial world economy to join the Euro.

2.2 Lotus Elite Vehicle Overview

The Elite vehicle is planned to be a high luxury, high performance and aesthetically styled Sportscar. As a result it has a long, low bonnet line, for the basis of this thesis the exterior surfaces used will be based upon the concept Elite concept car revealed at the Paris motor show in September 2010 (as shown in [Figure 4](#)).

The resulting space underneath the bonnet to package a relatively high capacity normally aspirated V8 engine and its associated supporting hardware is maximised. This may result in clearances possibly being less than the internal clearance targets in places within the HI zones as depicted by Figure 68 in chapter 4.

² Eastern Bloc countries refer to the former communist states of Eastern and Central Europe

The Elite programme at the time of writing is carrying out an in-depth concept study exercise with a view to understanding the technical and commercial feasibility of the 2010 Paris showcar.



Figure 4 – Lotus Elite Coupe – Paris show car 2010

The Lotus Elite concept is a two-door 2+2 Sports Grand Tourer (GT) with a front-mid-engine, rear transmission and rear wheel drive mechanical package layout. Core competitors for this vehicle can be seen in Figure 5, as described earlier Elite will compete in the luxury sports orientated HLS vehicle segment.

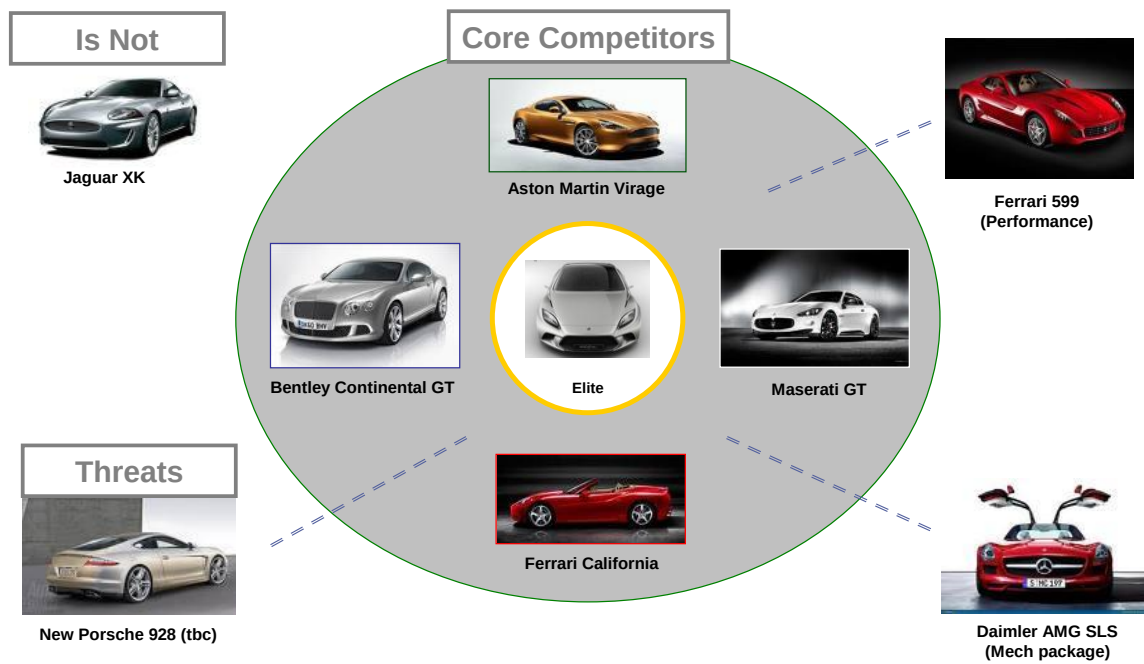


Figure 5– Lotus Elite predicted competitor set (as of 2011)

2.3 Market Analysis

In order to assess which strategies could be deployed to support the revised direction for Lotus future products, an understanding of both the external business environment and of the internal resources, capabilities, and culture is required.

This section examines the most commonly used frameworks for analysing the external environment in which Lotus is placed. The purpose of this analysis is to understand what factors may affect the future of the business as a whole from an outside perspective.

1. General changes in the business environment
2. Changes within the industry
3. Known activities of immediate competitors and other events

Political

- US CAFE Standards
- EU CO₂ Financial Penalty
- Emerging Market Stability (China & Russia, Brazil)

Technology

- Hybrid
- Government Research Funding for CO₂ reduction
- Lightweight body structure
- Core Powertrain and transmission architecture

Law

- Tailpipe emissions Level
- Occupant Safety
- Pedestrian Safety
- Fuel Economy
- Recyclability

Environmental

- Environmental leader

HLS Marketplace

LOTUS CARS

Economic

- Disposable income
- Global Financial Health and Volatility
- Interest Rates
- Residual Value (Lease Deals)

Social

- Image Projection
- Environmental Pressure Groups
- Reliability
- Status symbol

13

The PESTEL for Lotus in the HLS market can be seen in Figure 6, this enables an insight into the industry and the market in which Lotus will compete to be better understood.

Drivers for customers to purchase vehicles from the HLS segment have several external influencing factors as depicted in Figure 6, these factors revolve around the technology, social and legislative drivers. Consumers in the HLS market expect vehicles to be visually appealing, portray a credible responsible image and must deploy the latest technologies to be successful. Vehicles must also meet legislative requirements not only occupant safety but also those of pedestrian safety.

This legislative safety factor is starting to mould the exterior physical shape and construction of today's HLS vehicles. Legislation relating to PP requirements has been introduced over the past few years and this subject is increasing in public awareness. Lotus needs to address this key driver through the assessment and application of new technologies if it to continue to produce vehicles that consumers crave visually and can actually register legally in market.

However according to Macmillan et al (1) PESTEL is not a rigorous analytical tool to identify the strength and nature of influencing forces on a market but, it can be used to identify change and address the drivers for change.

In order to understand these forces in more detail a review of the external competitive environment and an assessment of the attractiveness of the market sector in which Lotus aims to compete in with its future products is required. It is important to understand the factors which have a direct or indirect influence on the business performance of Lotus.

An important tool used to identify these factors or economic forces as described by Michael Porter is the Porters five forces model (2). This model can provide a complete picture of the local competitive dynamics of the industry and particularly how it influences the profitability of the business.

Porter (3) also states this model can assist the business to understand which positions can make it more profitable by identifying the following strategies:

- Position the company where forces are weakest
- Exploit changes in the forces that affect the business
- Reshape forces in favour of gaining competitive advantage

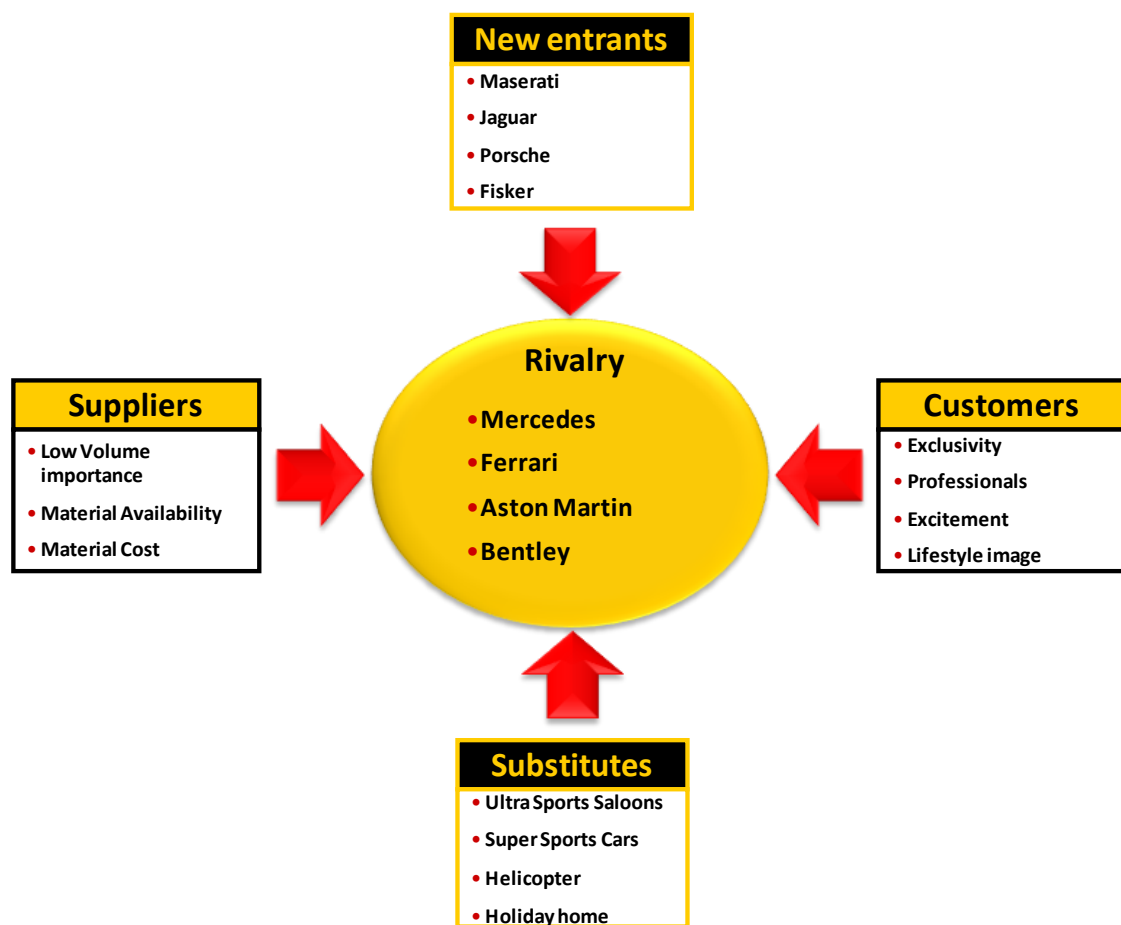


Figure 7 - Porters five forces model applied to the Lotus NEP strategy

Figure 7 shows the Porter's five force model applied to the Lotus Cars business in relation to the HLS market segment and provides an indication of the forces that have a direct or indirect influence on the performance of the NEP vehicles. The strongest force is exerted from new entrants into the segment, these provide additional pressure to an already crowded market thus Lotus products must offer an alternative 'why-buy' unique selling point.

The weakest force comes from substitutes, Lotus products are distinctive and have a true motoring lifestyle, this focused customer base can either afford other leisure activity alternatives or would not exchange there focused motoring orientated pastime.

2.4 Alternative Scenarios and Commercial Justification

This section identifies and reviews which alternative pathways are available to Lotus, relating to the adoption of PP European phase II (to be known as EU2) legislative requirements and their potential impact on market penetration, presence and ultimately profit growth viability. Scenarios considered wrt Lotus adopting the PP framework for its future NEP based Elite product are as follows:

1. Do nothing
2. Adopt a small series³ homologation route for the EU market
3. Meet EU legislative requirements relating to PP legislative requirements

³ Small series is an element of EU legislation tailored to low volume car manufacturers

2.4.1 Do nothing

This scenario proposes that no product action is taken on the Elite vehicle. From an initial desktop analysis of the Elite showcar exterior geometric surfaces it was concluded that the current shape would not be compliant with PP requirements. If these requirements and resulting design actions are not developed, validated and introduced it would result in the Elite vehicle not being able to be homologated in the EU-27⁴ zone and hence would not permit sales or registrations to be completed.

The result of this would effectively mean that over a third of the planned sales and resulting contribution margins for Elite would not be realised creating a significant degradation in the overall programme business case and financial viability (if substitution volume in other non EU-27 markets could not be sourced).

The associated dealer network sustainability would also have to be brought into question as they would not have any new model Lotus products to sell and would only be supporting in-service customers which may not be a commercially viable option in the medium to long term.

So the net effect to Lotus of Elite not meeting PP EU2 legislation would be:

- Lost direct sales, reduced contribution margin
- Dealer network retention risk
- Reduced customer (existing and future) satisfaction
- Loss of market confidence and presence

⁴ EU-27 is defined as the European Union member state as of 2007

2.4.2 Small Series

European Commission Small Series Type Approval (EC SSTA) has been created for low volume car producers of M1⁵ class passenger vehicles only. Similar to full European Community Whole Vehicle Type Approval (ECWVTA), EC SSTA will enable EU-27 wide sales but, with technical and administrative requirements that are more adapted to smaller scale businesses. PP EU2 requirements are currently not included within these technical requirements for EC SSTA.

However, if this route is chosen for approval, the number of vehicles that can be manufactured within the approval year is limited. The limit for cars produced is 1000 per type each year in the whole of the EU-27 network. Non EU-27 countries such as Switzerland also require full ECWVTA to be obtained in order to secure sales in that market. Therefore the effects of adopting this route can be summarised as:

- **Positive:**
 - PP EU2 requirements are no longer required to be met
 - Sales in EU-27 countries can continue, however limited to 1000 cars per type per year
- **Negative:**
 - Limited sales due to lost markets, resulting in profit contribution degradation
 - Dealer network impact and resulting customer in service impact, due to lost market presence

⁵ Denotes the EU general classification category M1 as a motor vehicle with 4 wheels and no more than eight seats in addition to the driver's seat

2.4.3 Meet PP EU2 legislative requirements

The third alternative is for the Lotus Elite vehicle to be designed and engineered to meet PP EU2 requirements contained within the ECWVTA (4) legislation thus enabling sales to continue unaffected in all European countries. This ensures the programme financial model profitability is met.

2.4.4 Commercial Justification Summary

Based on the financial implications (not disclosed) that the loss of unit contribution margins and associated existing customer base and dealer impacts would offer, this thesis recommends that meeting PP EU2 targets is a must for the Elite vehicle in order to support the future financial success and sustainability of the Lotus Cars company.

This thesis now also recommends researching in more depth into defining the exact requirements of the PP framework, its associated targets and test methods governing certification being granted.

Current academic literature is used to develop a landscape of existing and future PP enabling technologies both by HLS segment Lotus Elite competitors and the wider automotive related supplier base.

3 Pedestrian Protection Review of Current Literature

3.1 Literature Review Objectives

This literature review aims to provide an interpretation and synthesis of current published academic work relating to the PP framework, governing strategies and associated PP enabling technologies.

This literature review begins with quantifying and the physical mechanics relating to pedestrian injuries, their nature and source. Following this a review of the PP framework and associated test regimes leads to PP EU2 technical requirements being identified.

The market landscape for PP HI countermeasures currently in use or being developed for vehicles not only in the HLS segment where future Lotus products will compete but also encompasses higher volume mainstream vehicles segments. Trends and suitable PP enabling technologies that could be assessed for deployment into the Elite vehicle in order to meet PP EU2 HI targets are also reviewed.

This chapter concludes with a summary of its findings that should be considered when assessing the implementation of alternative PP enabling technologies into the Lotus Elite vehicle.

3.2 Introduction

As discussed previously technologies relating to preventing the accident known as preventative safety, i.e. to mitigate the crash event happening in the first place, such as collision avoidance, roadway infrastructure and pedestrian detection are not reviewed and are out of the scope of this thesis. Only technologies that minimise the consequences of an accident that has actually occurred known as passive safety are researched.

Sufficient energy absorption needs to take place in order to reduce pedestrian injuries during impact. This energy absorption can be achieved by applying one or more of the following PP technology strands to the front end geometry of a vehicle.

1. Active PP:

- A hinged deployable bonnet system.
- Inflating a protective external airbag in the bonnet and/or windscreen areas to protect a pedestrian during impact (these also deploys the bonnet).

2. Passive PP:

- Relocating components to be out of the PP clearance zone, either by increasing clearances below the bonnet surface or raising the bonnet surface.
- Or by modifying the mechanical properties of the front end structure of the vehicle to manage effective energy absorption during impact.

3.3 Motivation - Road Traffic Accidents

This section identifies and details the key drivers for the PP frameworks being created and implemented. The primary goal of the PP legislation framework is targeted to reduce:

- Pedestrian fatality risk
- The risk of serious pedestrian injuries, permanent impairment or disability

An insight into what type of Road Traffic Accident (RTA) occur and to which users is given along with the resulting types of pedestrian injuries and which part of the vehicle is the source of said injuries. The pedestrian to vehicle accident event and influencing factors are also defined. An understanding as to how the human body reacts biomechanically during a vehicle impact and what parts of the vehicle it interacts with is also identified.

Road traffic fatalities are a worldwide issue according to a report by the World Health Organisation (WHO) (5), an estimated 1.2 million people lost their lives and 50 million non-fatal injuries were due to Road Traffic Accidents (RTA). WHO in a World Bank report in 2009 (6) also suggested by 2020 that this fatality figure would increase to about 2.4 million.

A study by Naci, H et al as documented by Rosen et al (7) indicates that pedestrians struck by a motorised vehicle are the largest road user group to suffer fatalities in terms of years of life lost, Crandall (8) also concluded in the UK, pedestrians are twice as likely to be killed in accidents as a vehicle occupant.

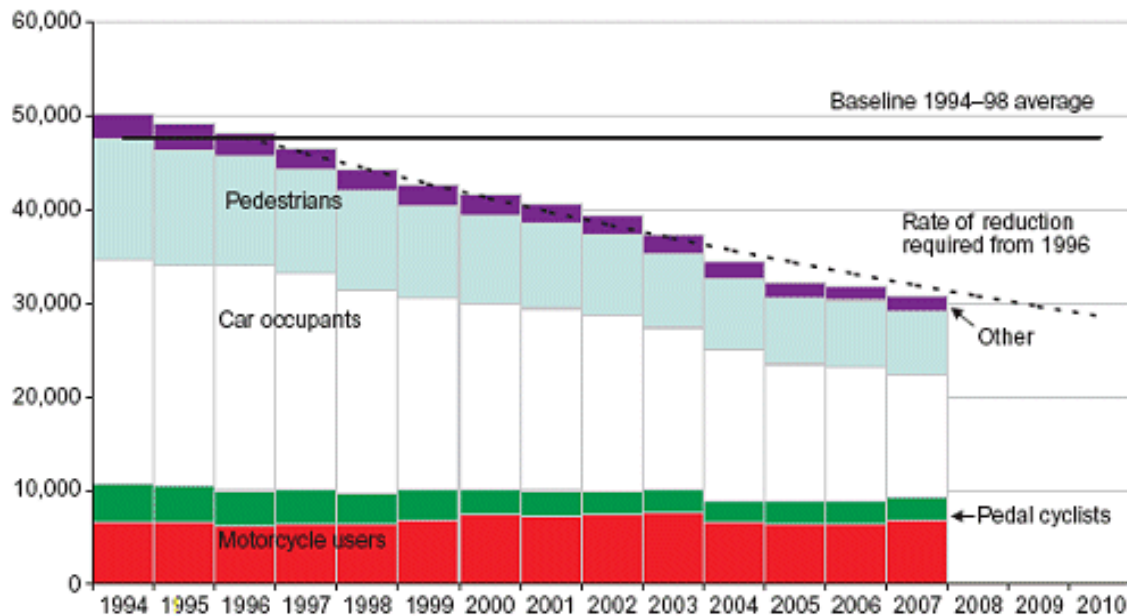


Figure 8 - Killed or seriously injured casualties by road user UK 1994-2007 (5)

Pedestrians are becoming a higher proportion of RTA victims (as depicted by Figure 8) and the car is the major source of pedestrian injuries (see Table 1). The fatalities of pedestrians due to vehicle accidents in developed countries such as the UK has seen a downwards trend as discussed by Shogo (9).

Collision partner	Pedestrians (Germany)		Pedestrians (Norway)		Cyclists (Norway)	
	Fatally injured	All injured	Fatally injured	All injured	Fatally injured	All injured
Car	72 %	76 %	79 %	86 %	83 %	89 %
Truck	17 %	6 %	11 %	3 %	11 %	3 %
Motorcycle	3 %	3 %	1 %	2 %	1 %	2 %
Bus	2 %	2 %	4 %	4 %	1 %	1 %
Cycle	2 %	11 %	1 %	2 %	2 %	4 %
Other vehicle	4 %	2 %	4 %	3 %	2 %	1 %

Table 1 – Distribution of Pedestrian to Vehicle RTAs by collision partner type (10)

This reduction also discussed by Shogo (11) is mainly due to various initiatives such as road improvements, lower speed limits and stricter enforcement of alcohol and drug related laws. However as fatalities have declined the number of overall accidents has increased along with a rising trend in non-life threatening injuries.

During research for this thesis published literature relating to pedestrian mortalities was common but papers covering non-fatal but serious outcomes from pedestrian-vehicle collisions are less common and were mainly focused on specific geographic areas.

Therefore in order to develop effective countermeasures to save pedestrian lives and reduce the risk of serious injury, it is important to examine the accident environment, human responses to impact and mechanisms that cause injuries.

3.3.1 The Accident Environment

According to Haddon (12), there are three factors that are needed to fully understand a RTA;

- The vehicle
- The environment
- The road user.

It is therefore important to understand under what conditions these RTA events occur in order to develop mitigation solutions to reduce the severity of pedestrian injury.

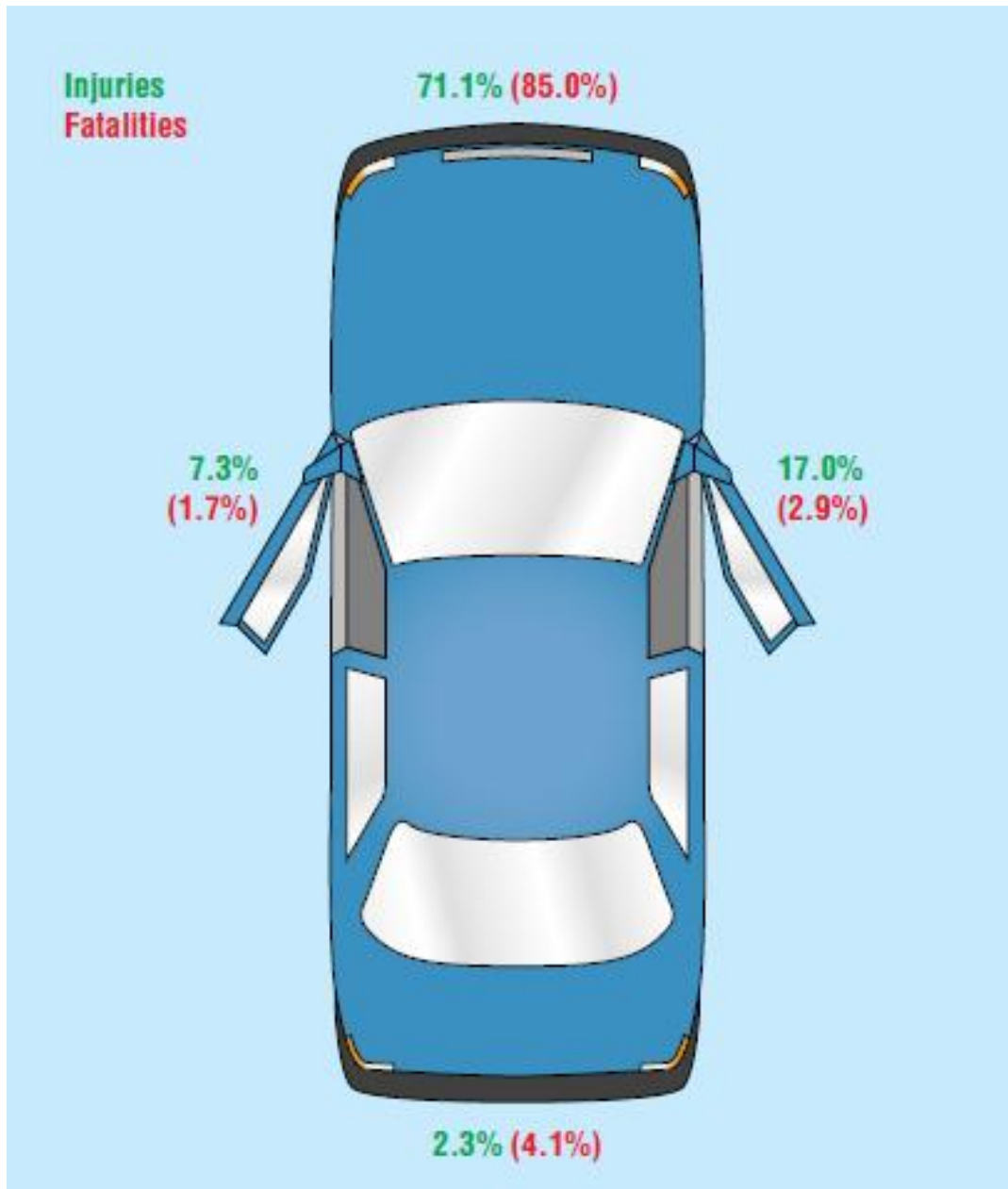


Figure 9 - Vehicle impact zones in pedestrian to car accidents (8)

As previously seen in Table 1, Erke et al (10) identify most pedestrian crash events involve a car. Figure 9 indicates which zones of the car are impacted by a pedestrian during pedestrian to vehicle accidents. As can be seen the vast majority of pedestrian fatalities (80%) and injuries (over 71%) occur in the front zone of the vehicle.

Further analysis by Crandall (8) into the frontal car zone showed the lower bumper, bonnet and windscreen area of the vehicle are the three main sources of injury as is depicted in Figure 10.

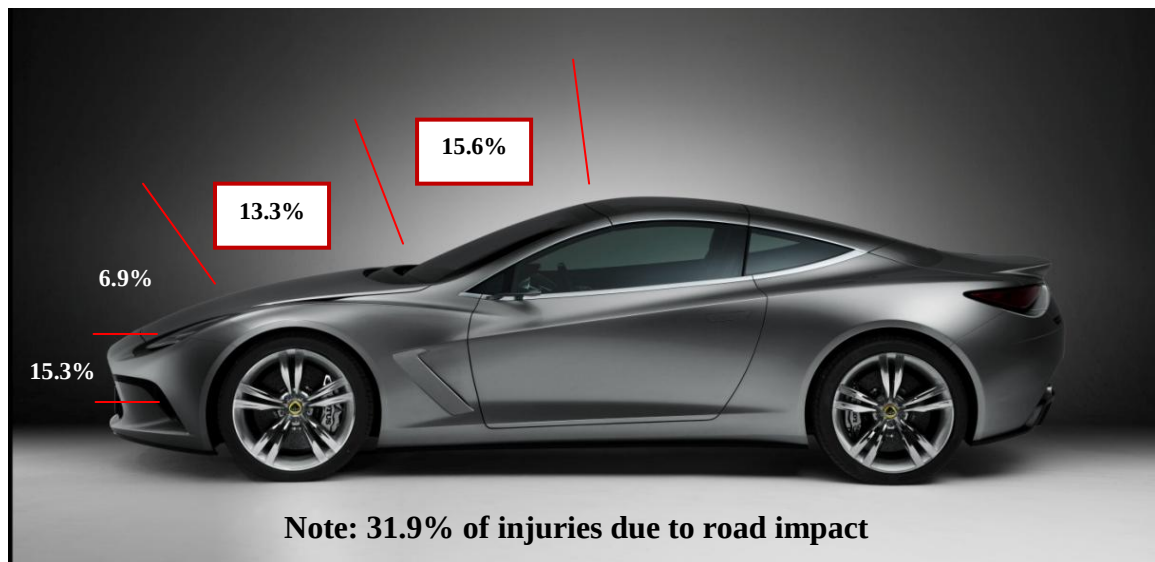


Figure 10 – Sources of pedestrian injuries in the front zone of a vehicle

It is therefore important that the biomechanics of a pedestrian to car frontal collision is understood. In a pedestrian to car crash event (as shown in Figure 11), a standing or walking pedestrian is struck and accelerated to the speed of the vehicle and then continues forward as the driver brakes the vehicle to a stop. Although the pedestrian is impacted twice, first by the vehicle and then by the ground, evidence by found by Crandall (8) shows that most of the fatal and life threatening injuries occur due to the interaction with the vehicle.

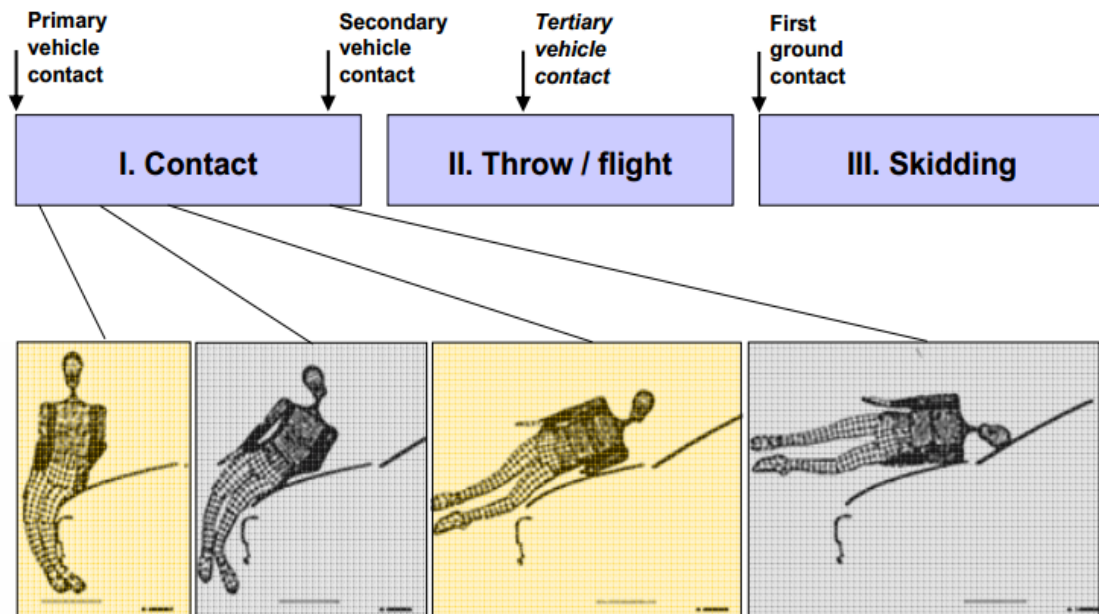


Figure 11 – Pedestrian to vehicle frontal crash event at 40km/h (13)

As described by Gandhi et al (14) during a frontal pedestrian to car impact as shown graphically in Figure 11 the bumper contacts the lower leg, the leading edge of the bonnet strikes the proximal lower limb or pelvis (dependant on the stance, approach angle and percentile of the pedestrian).

Finally the head and upper torso hit the top surface of the bonnet or windscreen of the vehicle. In essence the pedestrian body wraps around the front of the vehicle until the pedestrian and vehicle are travelling at the same speed, as the vehicle brakes the pedestrian continues to move forward while the vehicle decelerates. The eventual contact with the ground often then produces further pedestrian injuries.

The precise trajectory and injuries to the pedestrian rely heavily on the relative size of the pedestrian, the orientation of the pedestrian before impact and the impact speed of the vehicle (which is not covered in the scope of this thesis), also of more importance is the actual physical geometry of the vehicles front profile surfaces.

Figure 12 shows the potential factors that are associated with pedestrian-vehicle impact events. As can be seen there are numerous sources and factor areas which cover a broad spectrum ranging from the physical vehicle to social elements.

The scope of this thesis will only look at factors associated with the vehicle, relating to geometric design, material properties and associated PP enabling technologies.

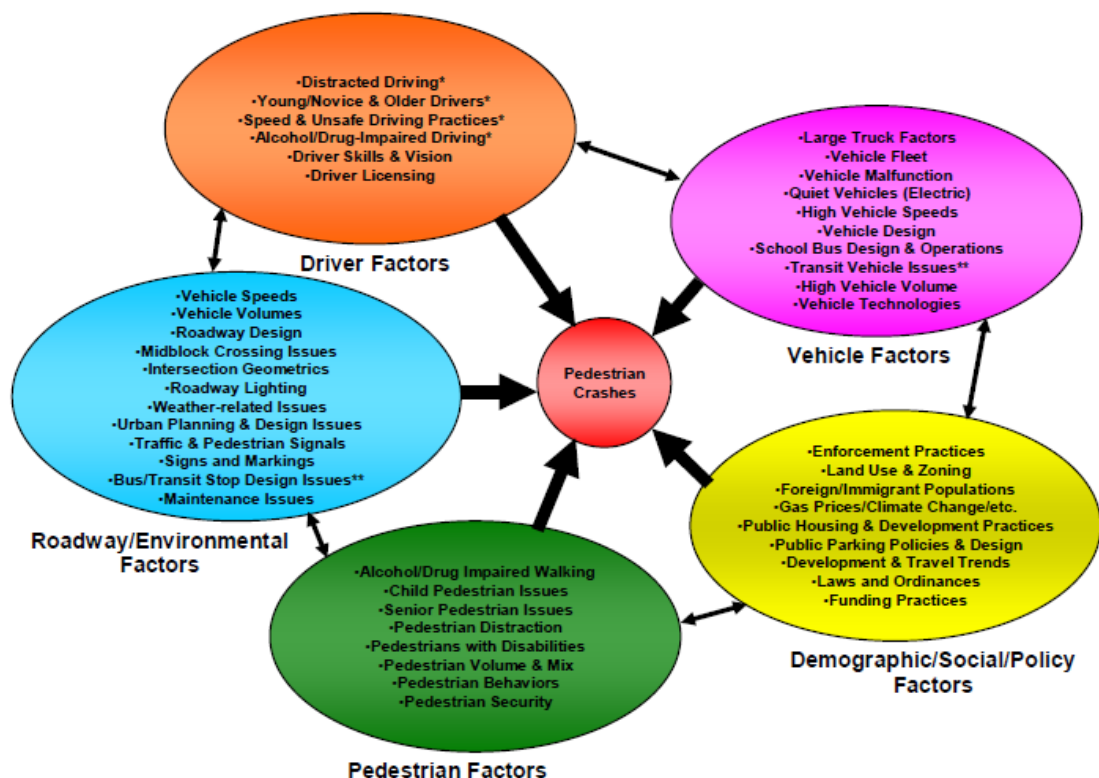


Figure 12 –Factors associated with Pedestrian crash risk and/or injury severity (15)

In summary this section has identified:

- What areas of a passenger vehicle cause most pedestrian accidents
- Which parts of the vehicle cause injuries
- Factors that influence pedestrian injury risk
- What actually mechanically happens during this event
 - to the vehicle
 - and to the pedestrian

In order to understand how these injuries can be mitigated it is important to investigate how the human body reacts to these events and the resulting forces during a pedestrian to vehicle impact.

3.3.2 Pedestrian Responses to a Vehicle Impact

This section reviews how the human body reacts to a frontal pedestrian to car impact to specifically identify where and what type of resulting pedestrian injuries are inflicted and to highlight the injury source.

According to Crandall (8) these injuries can result in long term disability or impairment, particularly those attributed to head or neck trauma.

Figure 13 shows the distribution of pedestrian injuries resulting from an RTA; this highlights the head area to be the highest overall single source of injuries. Shogo (9) also relates these effects to the increased number and density of road vehicles in use particularly in highly populated urban areas.

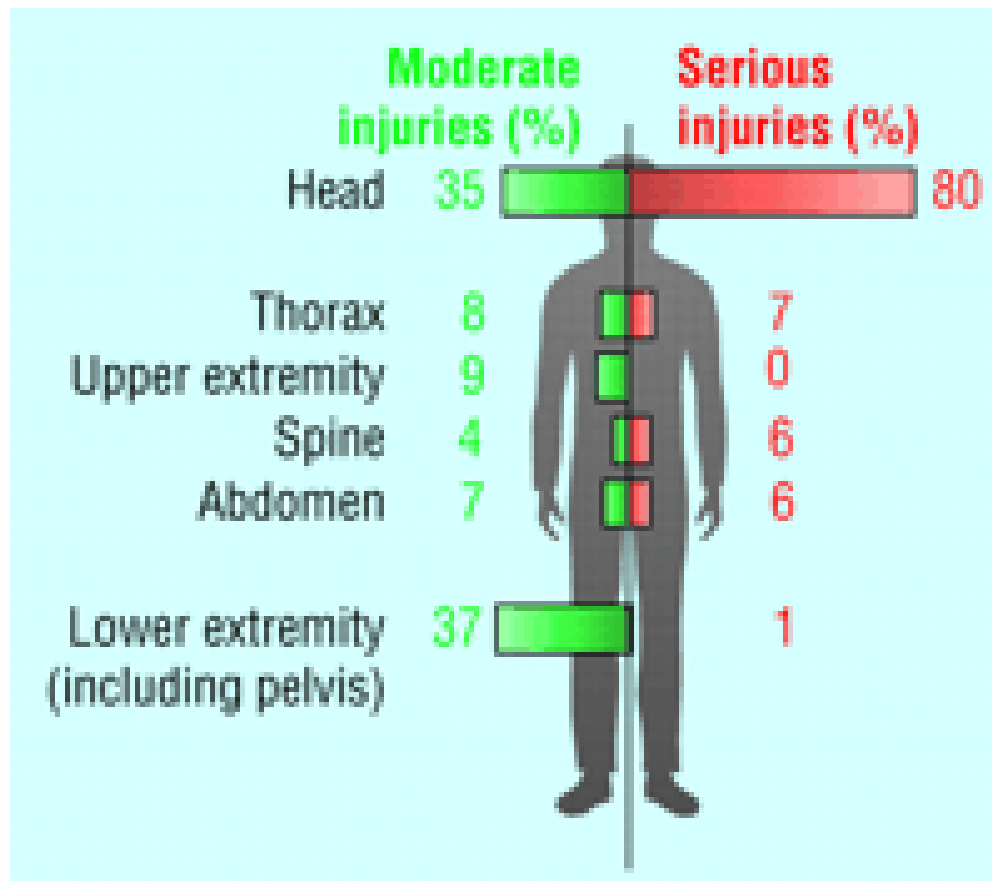


Figure 13 – Distribution of injuries suffered by pedestrian resulting from RTAs (9)

The human body according to the European Road Safety Observatory (ERSO) (16) the human body has limited tolerance to the kinetic forces it experiences during a RTA. The resulting injury levels are related to how much of this kinetic energy is directly applied to the human frame during a pedestrian to vehicle impact event.

Analysis carried out by Svoboda and Cizek (17) also indicates the severity and risk of a pedestrian fatality resulting from a vehicle accident is high, with most accidents occurring in densely populated areas with impact velocities ranging from 30 to 50km/h. The resulting fatalities were found to be attributed to head injury caused in the majority of cases by the bonnet, windscreen and ‘A’ pillar areas of the impacted vehicle.

The following graphs (Figure 14 and Figure 15) provide an indication of the part of the pedestrian body that is injured during an RTA (covering both pedestrian fatalities and injuries) and the source type of injury inflicted.

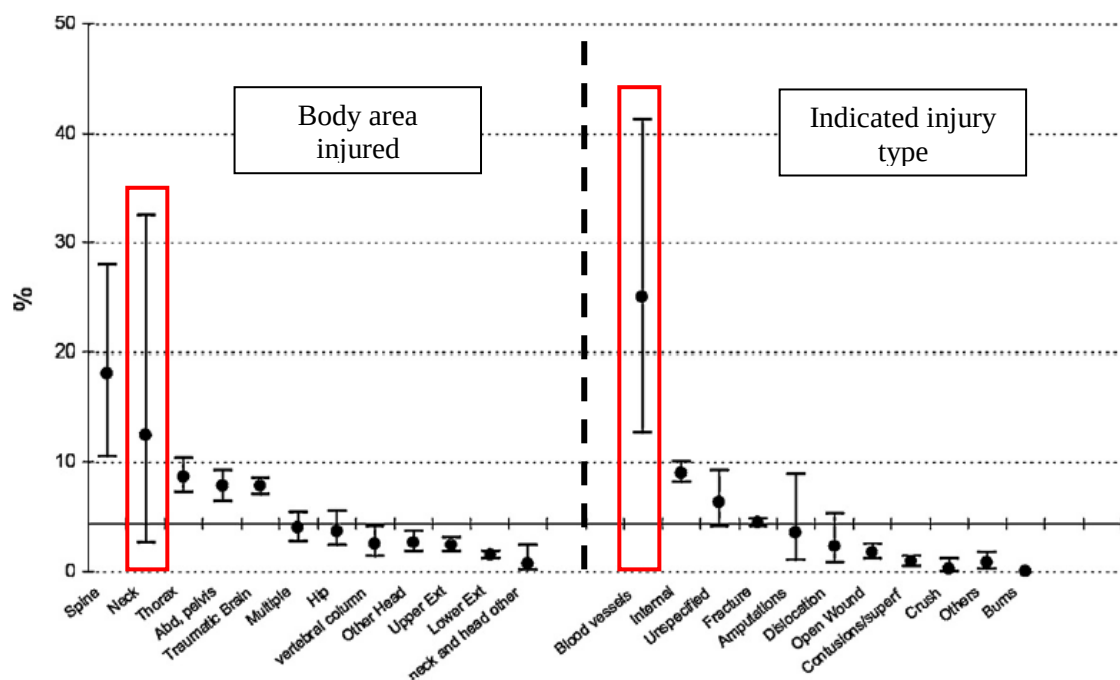


Figure 14 – Percentage of hospitalised pedestrians – Pronounced dead during hospital stay indicating injury type and body area location (5)

As can be seen the neck area has the largest contribution standard deviation to pedestrian deaths but, it is the spine that has the highest overall percentage. Blood vessels are the largest percentage and spread relating to the indicated injury type. All other areas and types have relatively minor contribution to pedestrian deaths, indicating the neck and spinal areas as the primary source of pedestrian deaths.

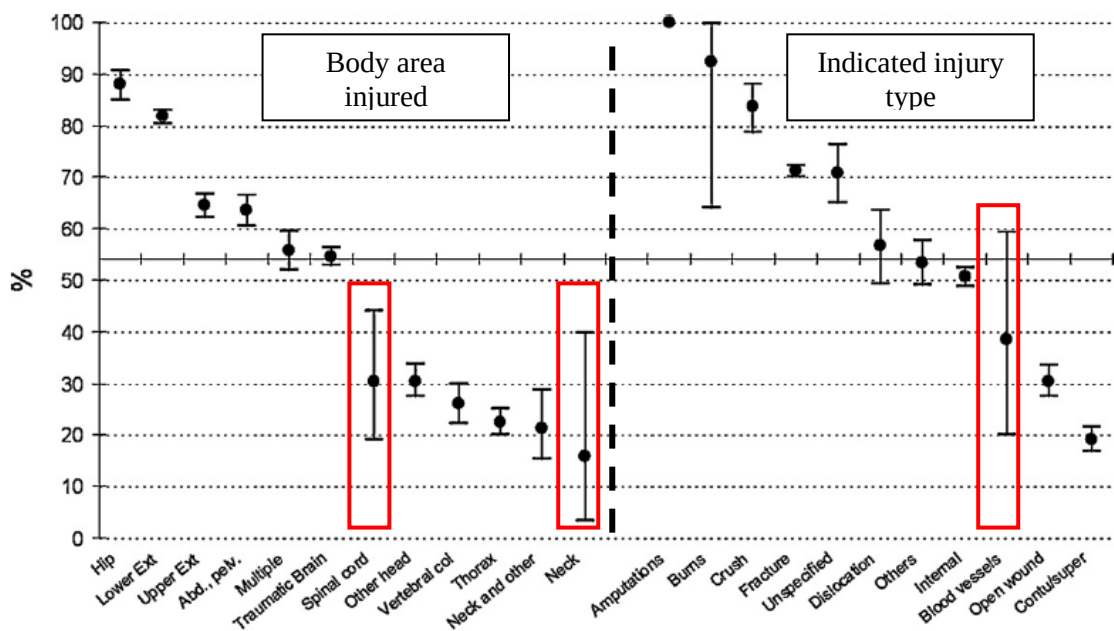


Figure 15 – Percentage of hospitalised pedestrians – Discharged alive post hospital stay indicating injury type and body area location (5)

Discharged alive pedestrian accident data indicates a different landscape to that of pronounced dead pedestrians. Data in Figure 15 shows that it is the lower areas of the body that are injured, as seen by higher percentage contributions. However the standard deviation data for the spine and neck are the largest.

It is now understood what happens to the human body during a pedestrian impact with a vehicle relating to the type and distribution of injuries. Also the time and severity effect of these injuries to the pedestrian, being either death at the accident scene, death during hospital stay or post hospital discharge.

Based on the study of accident data as discussed, it can be concluded that the majority of fatalities and the serious injuries are caused by a collision between the pedestrian and the vehicle bonnet, with the head area being the largest single source of pedestrian death due to the resultant neck and spinal trauma. These areas also contribute to injuries sustained to post hospitalised accident victims.

Due to this increase in pedestrian injury risk, various strategies and frameworks have been introduced as legislation by governments in various countries or regions across the globe. The objective of these PP frameworks are to drive automotive manufacturers to design and homologate vehicles that reduce the severity of injuries incurred by pedestrians during a frontal impact and are discussed in further detail in the following sections.

3.4 Background Vehicle Research and Development

This section provides an overview of the history of PP enabling technologies to date, identifying key milestones and technology implementation dates or vehicles to ascertain if any trends relating to the direction of PP countermeasures exist.

One of the earliest PP initiatives was to basically slow down the vehicle speed by having a man with a red flag walk in front of the vehicle, this practice was initiated in the early 1800's and was only removed in 1896. A more recent physical change to vehicles has been the removal of bonnet ornaments since the early 1950's.

Significant research and development activities in PP strategies started in the 1970's. The car manufacturer British Leyland (BL) embarked on a programme to explore the future of car safety technology, leading to the development of the MGB GT based Safety Systems Vehicle (SSV) in 1972.

BL continued to expand its knowledge of PP and produced a series of prototype Safety Research Vehicles (SRV) (examples are shown in Figure 16, Figure 17 and Figure 18) over the next few years with assistance from the Transport Research Laboratory (TRL).



Figure 16 - BL Marina based 'SRV2'

Each of these early SRV prototypes focused on passive approaches by creating sufficient clearance to the vehicle engine-bay components to reduce the risk of pedestrian injury.

These clearances were basically created by altering the geometry and physical exterior appearance of the vehicle resulting in the sloping bonnet effect. It can also be seen in Figure 16 that ‘SRV2’ has concealed wipers and lower windscreen area.



Figure 17 – BL Mini Clubman based ‘SRV4’

However as Figure 18 shows, the first record of an active PP system can be seen on a modified BL Austin 1300 (SRV5). The method was relatively simple in what now seems a primitive system, a spring loaded bar mounted at the front of the vehicle raises to literally catch the pedestrian during an impact event.



Figure 18 – Austin 1300 based ‘SRV5’ demonstrating first active PP system

Towards the end of the 1970s PP gained more visibility as part of a wider growing automotive safety campaign based on the back of a successful drive to reduce vehicle occupant safety (via drivers airbags, pre-tensioning seatbelts) and momentum was building behind the technology enablers to deliver potential solutions that could be incorporated into mainstream passenger vehicles and future legislation.

Appel (18) showed a PP system in the form of a lower windscreen airbag in 1977. As early as 1978 the concept of a deployable bonnet to increase the energy absorption distance in the event of an accident was also released by Volkswagen Audi Group (VAG) (19). However it would take a further two decades for these two concepts to become reality in mainstream production vehicle.

During the 1980's more data was understood from the BL SRV initiative and work continued to bring more aesthetic solutions to mitigate the PP issue. Shown in Figure 19 is an example of a PP design study conducted in 1985, as can be seen the geometry of the bonnet exterior surfaces is such that it creates a greater deformation distance to the rigid components below it.



Figure 19 –Austin Metro based PP design study (TRL developed) circa 1985 (20)

Also of note is the overlap of the bonnet at its side to the fenders to create a clamshell effect, thus reducing local stiffness's in this area and the concealed wiper arms, PP countermeasures that are seen on modern vehicles today.

It was not until 2005 when EU legislation relating to PP was introduced that vehicle manufacturers started applying and introducing solutions to significantly improve PP. The first active deployable bonnet system was introduced on the Jaguar XK Sportscar in 2006 (see Figure 20).

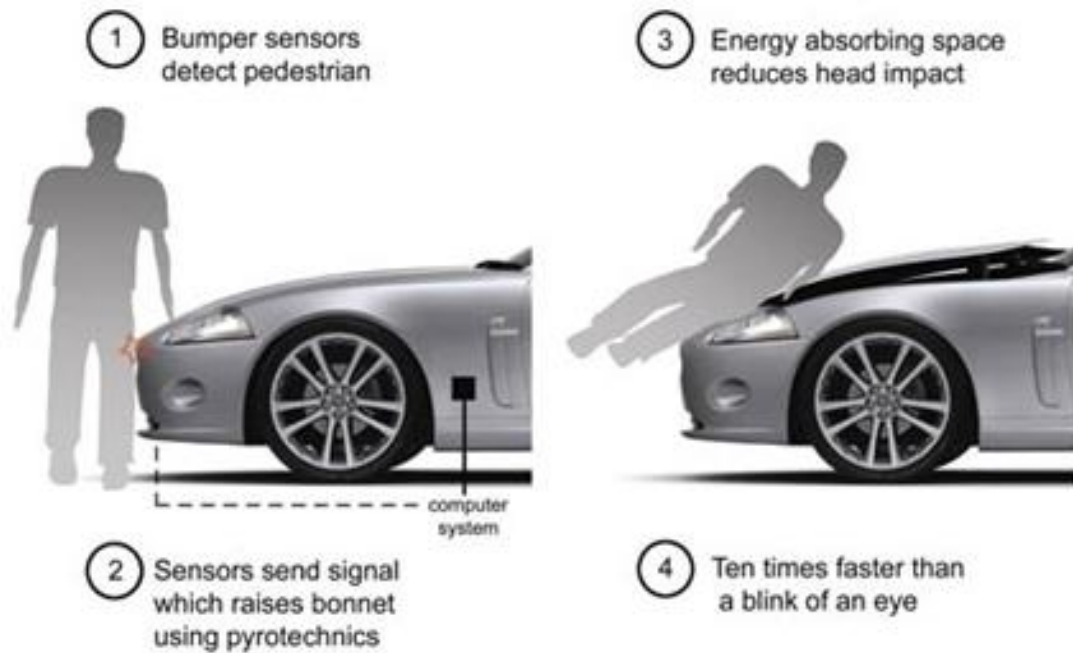


Figure 20 – First example of production deployable bonnet, Jaguar XK 2006

3.5 Production Vehicle Market Landscape

The implementation timeline of major Original Equipment Manufacturers (OEM) that have adopted active PP countermeasures over the past decade is shown in Figure 21 along with a future prognosis of which strategies may also be adopted.

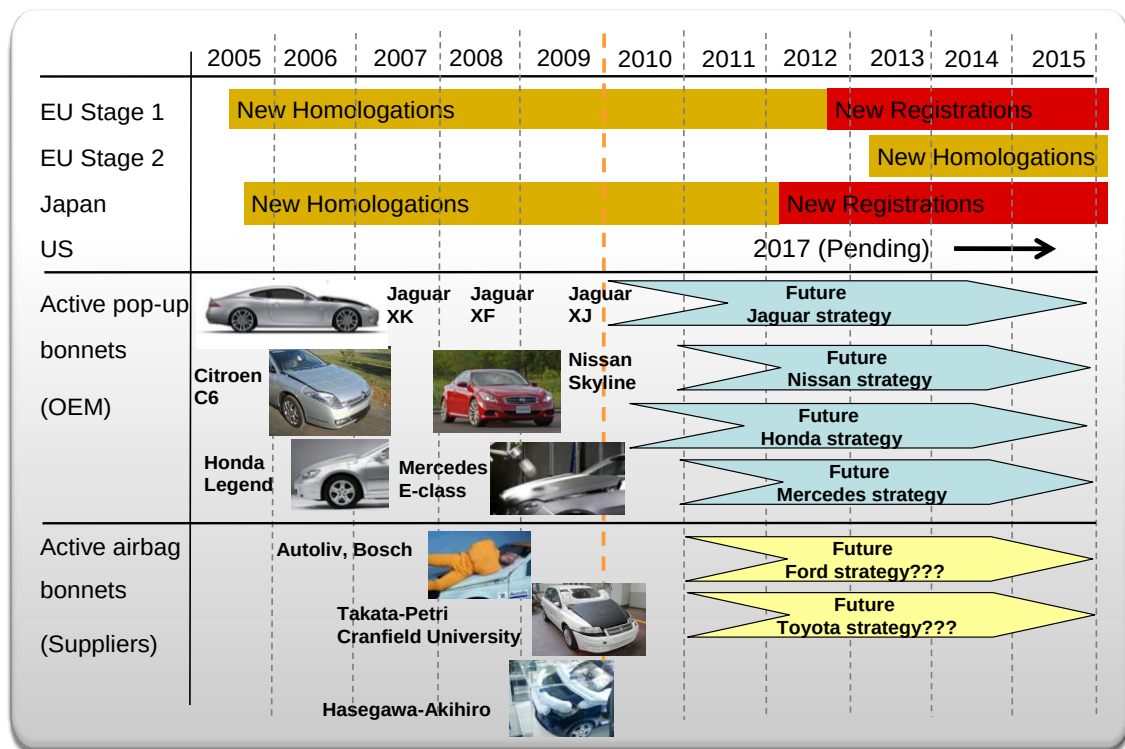


Figure 21 – PP bonnet technology implementation timeline

Bonnets airbags technology is very much at the development stage, with technology collaborations exist between automotive safety systems suppliers Autoliv, Bosch and OEMs such as Ford and Toyota with no set date for future vehicle implementation. The only production OEM to offer bonnet airbags at the time of writing is Volvo (Sweden), with the V40 series vehicle that was recently launched at the Geneva Motor show in March 2012.

The next section looks at these vehicles in more detail relating to the type and nature of the specific PP technology strategies being used with an aim to discover what initiative are being deployed and why these may have been chosen over alternative technologies and by whom they have been developed by.

3.6 Competitor Analysis

This section reviews the competitor landscape in more detail relating to PP enabling strategies and technologies in order to answer the following questions:

- Who is doing what and why?
- What types of technologies are being used and how are they integrated?
- Are there any emerging trends? If so what are they?

In order to gain an insight into the competitor landscape styling features incorporated into existing pedestrian protection compliant vehicles are reviewed and where possible European New Car Assessment Programme (EuroNCAP) scores have been included to indicate the level of protection offered.

The vehicles selected for analysis in this section fall into one of the following categories:

- Direct competitor vehicles sold in similar HLS market segments to future Lotus NEP products, with similar configurations to Elite of front engine, 2+2 GTs.
- Vehicles with features of particular interest relating to PP countermeasures.
- Vehicles with high EuroNCAP scores.

3.6.1 HLS segment analysis

The HLS market segment can now be analysed to understand the current landscape relating to how competitor vehicle brands approach meeting the PP requirements.

Active ‘pop-up’ bonnets have been adopted by some of the vehicles within the HLS sector that future Lotus NEP products will compete in such as Jaguar and Mercedes. However direct market place competitors to future Lotus NEP products from other lower volume OEMs such as Porsche, Lamborghini, Aston Martin and Ferrari do not currently deploy specific PP technology. These vehicle manufacturers have adopted passive design driven changes that may subjectively compromise aesthetic style to meet PP targets.

Many of these HLS segment competitor vehicles also have rear or mid-engine vehicles which do not have major hard-point clearance zone issues due to the major hardware being located away from the frontal pedestrian impact zones.

The following images (see figures 22 to 27) provide an overview of some of these competitors and the theme, strategies that they have adopted to meet PP targets.

3.6.1.1 Passive solutions



Figure 22 - Ferrari California 2010 (Front Engine, 2+2 GT)

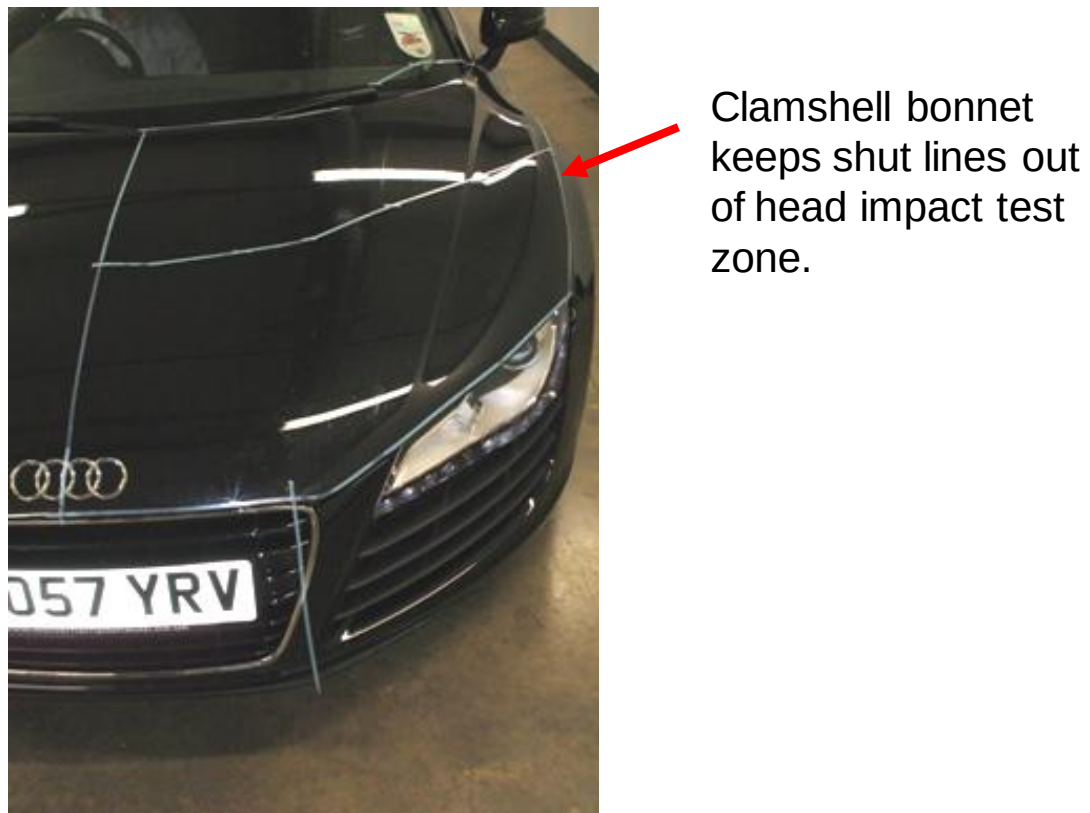


Figure 23 – Audi R8 (2008) (Mid Engine, 2 seater)

Steeply angled fenders allows side reference line to follow crease. Bonnet shut lines with 20mm of crease



Figure 24 - Maserati Gran Turismo 2009 (Front engine, 2+2 seater)

Relatively long bonnet, dry sump engine (low), has sufficient under-bonnet clearances



Figure 25 – Mercedes SLS 2010 (Front engine, 2 seater)



Optimised under-bonnet clearance to existing hardware

Mounting strategy of under-bonnet components design to break away under impact

Figure 26 – Bentley Continental GT 2011 (Front engine, 4 seater)



Optimised under - bonnet clearance to existing hardware

Bonnet stiffness and headlamp mounting strategy recalibrated

Figure 27 – Aston Martin Vanquish 2012 (Front engine, 2+2 seater)

In summary the competitor HLS segment landscape that adopt passive PP countermeasures do by either generating sufficient under-bonnet clearances (i.e. locating the engine and engine-bay hardware relatively low and rearward, away from PP test zones as in the Mercedes) or by locating front panel shut-lines and headlamp ornamentation in such a way that it results in the PP test zones being favourable to the existing vehicle package (Maserati headlamp location, Audi clamshell bonnet).

3.6.1.2 Active solutions:

A small minority (but growing proportion) of HLS market segment vehicles currently adopt active ‘pop-up’ bonnet technology to provide sufficient clearances to under-bonnet components during a pedestrian to vehicle impact event.

Active PP countermeasures have only been adopted by Jaguar XK and Mercedes SL, (as shown in Figure 28 and Figure 29) and this technology is part of a wider cross product OEM strategy that encompasses other non HLS segment models (all Jaguar products have this feature, thus gaining in technology knowledge and economies of scale).



Figure 28 - Jaguar XK 2006 (Front engine, 2+2 seater)



Figure 29 – Mercedes SL 2012 (Front Engine, 2 seater)

The competitor landscape for PP countermeasures is mainly dominated by passive measure. New entrants into the HLS market such as Mercedes are however adopting active PP technology to counteract any potential aesthetic compromises but, the integration of this technology bring gains in design freedom at the expense of additional weight, complexity and technology delivery risk.

With the competitor market analysis complete to understand the landscape for PP countermeasures, focus can now be turned to reviewing how PP requirements are defined, tested and governed.

3.7 Framework and Requirements

The objective of the PP framework is to reduce the frequency of pedestrian fatalities and the injury severity sustained during a collision with the front of a motor vehicle. This is governed by law relating to the application of legislative targets within the EU and Japan that vehicle manufacturers must meet in order to homologate vehicles and thus sell in the associated market region or country.

The PP legislative framework consists of 2 discrete elements (see Figure 30); Lower leg and Head injuries. The purpose of the PP framework is to reduce the severity of these injuries to the pedestrian and can be categorised by the following sequence of events:

- **Lower leg**, where the vehicle bumper first contacts the lower limbs of the pedestrian and then the leading edge of the bonnet hits the upper thigh or pelvis.
- **Head**, where the head and upper torso are struck by the top surface of the bonnet and/or windscreen.

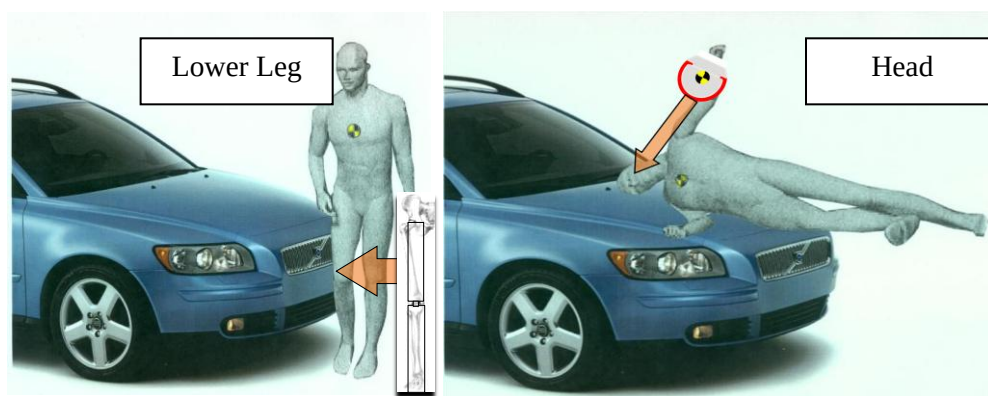


Figure 30 – PP Legislative elements

The following sections provide an overview of the major elements of the overall PP framework, its definitions, the associated test methods and constraints automotive manufacturers such as Lotus must adhere to in order to comply with the relevant legislative requirements.

As will be shown in the following sections PP zones are highly dependent on the vehicle exterior front end surface geometry and underlying hardware package layout, as a result there is a strong link between vehicle exterior style, package layout and the feasibility of meeting the legal PP requirements.

3.7.1 Pedestrian Protection Outlook

Figure 31 shows how varied the existing PP landscape and associated legislative frameworks that exist throughout the globe in 2010 are. This landscape currently consists of five framework zones:

- Green No current or proposed involvement in PP criteria
- Orange No legislative PP requirements but are actively participating in the creation of a Global Technical Regulation (GTR) to cover PP
- Blue Covering the EU PP legislation
- Yellow Countries that are observing but not participating in GTR activities
- Red Japan whom are the primary driver for a PP GTR

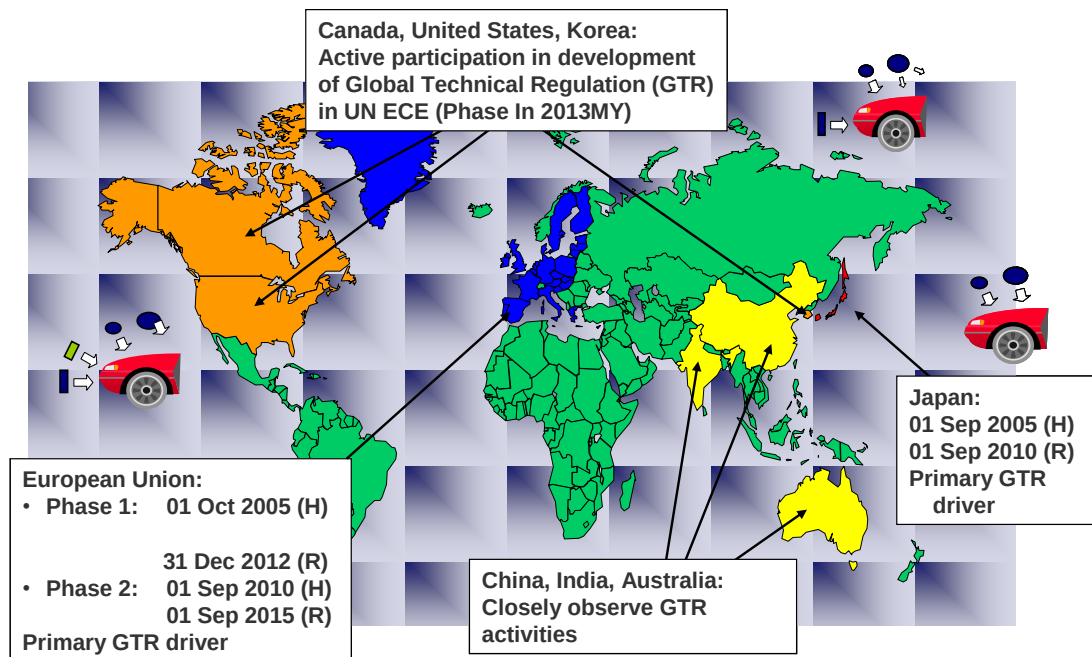


Figure 31 –Global PP regulatory requirements landscape (2010)

Where H denotes Homologations⁶ and R denotes Registrations⁷ in the associated market. The associated timelines for the adoption of existing and future PP legislation for the EU, Japanese and potentially US markets is depicted by Figure 32.

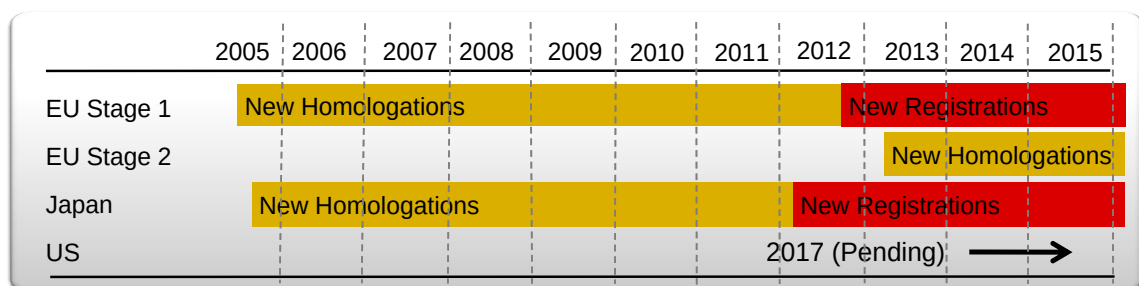


Figure 32 – Global PP legislation introduction timeline

⁶ Homologations refer to the process by which vehicles are approved by public agencies to assure that they meet standards for such things as safety and environmental impact.

⁷ Registrations refer to physical vehicles that are registered for use on the public highway.

As previously discussed in the EU-27 market represents approximately a third of all global Lotus vehicle sales and over 40% of its dealer network is located in this region, these sales generate a significant percentage of the overall contribution margin for the company.

As a result EU-27 markets are very important for Lotus in terms of the continued and future growth of revenue generation, profit contribution and marketplace presence to continue vehicles sales in this vital market.

The majority of research and knowledge bank information relating to PP enabling technology deployment is also concentrated in this region, spread not only in OEMs but also amongst a strong tier 1 supply base and various academic institutes.

The scope of this thesis will therefore focus on the EU-27 market zone PP EU legislative timeline relating to stage II targets (to be known as EU2) and as previously discussed due to head related injuries being the major contributor to death and severe injuries only the associated HI requirements of the legislation will be assessed. The following sections describe the specific requirements and targets for these criteria.

3.7.2 Pedestrian Head Impact Requirements

In 2005 the first legal requirements for PP were introduced as legislation in countries governed by EU law under directive 2004/90/EC (21), covering both lower leg and head injury criteria.

Head injury severity is often classified using the Abbreviated Injury Scale (AIS) (see Figure 33) which according to Carter et al (22) is based on the probability of death as a result of that injury on a scale of AIS1 (very slight) to AIS6 (almost certainly fatal). Several epidemiological studies by have found the head to be the most common site of fatal injuries to pedestrians struck by passenger cars and the most common site for injuries greater than AIS2.

<i>AIS</i>	<i>Injury entity</i>	<i>Fatality percent</i>	<i>HIC index values ranges</i>	<i>Head Injury</i>
0	None	0	0 - 134	none
1	Minor	0 - 7	135 - 519	Headache or dizziness
2	Moderate	7 - 18	520 - 899	Unconscious less than 1 hour; linear fracture
3	Serious, without life danger	18 - 42	900 - 1254	Unconscious 1 to 6 hours Depressed fracture
4	Severe, with life danger	42 - 70	1255 - 1574	Unconscious 6 to 24 hours; Open fracture
5	Critical (uncertain survival)	70 - 87	1575 - 1859	Unconscious more than 24 hours; large haematoma.
6	Fatal	87 - 100	> 1860	Non-survivable

Figure 33 – AIS Scale of injury entity and corresponding fatality percent (23)

The test methods and associated impactors related to this European directive (3) were derived from the European Enhanced Vehicle-safety Committee (EEVC) Working Group 17 (WG17) report (24) published in 1998 relating to AIS2+ and to some extent 3+ injuries.

The acceptance metric for the PP HI test is reported as Head Impact Criterion (HIC) and must not exceed a threshold specific to a given ADULT or CHILD head-form in order to pass the legislative test.

HIC is a standardised value of the maximum integral value of head deceleration and as discussed relates to the probability of the pedestrian sustaining severe head injuries. In this PP application it relates directly to the physical distress the pedestrians head will be exposed to during an impact with the front end of a vehicle during an accident event.

HIC has no units and is calculated from the head acceleration time history as the maximum using the following expression in Equation 1 (25). Where ‘a’ is the resultant head acceleration in g’s and t1 and t2 are two time constants during the impact event.

$$HIC = \left\{ \left[\frac{1}{(t_2 - t_1)} \cdot \int a(t).dt \right]^{2.5} (t_2 - t_1) \right\}_{\max} < 1000$$

Equation 1 – HIC expression relating to PP head impact (25)

The HIC for PP HI requirements as shown by Prasad and Mertz (26) is only calculated for a time period of < 15 ms and is denoted as HIC₁₅. This time correlates to the impact severity being critical for head injuries such as skull fractures or concussions.

Work conducted by the US based National Highway Traffic Safety Administration (NHTSA) in 1995 (27) determined the HIC value of 1000 to equate to the risk of a serious (AIS3+) or more severe head injury of 53%. The higher HIC value of 1700 equates to a risk of 94% for AIS3+ head injury.

These HIC targets provide a maximum threshold level for both legislative and consumer testing. Any components hit by the impactor must translate or deflect to allow a controlled deceleration of the head-form to within the specified HIC target.

In 2009 PP EU2 requirements (21) were introduced with a single heavier child head-form mass of 3.5kg and a reduced higher level HIC value to reflect latest level accident information. The homologation test relating to PP EU2 consists of firing a head-form against the outer surface of the test vehicle bonnet whilst the vehicle is static (28). Figure 34 shows the types of homologation test requirements for PP EU2.

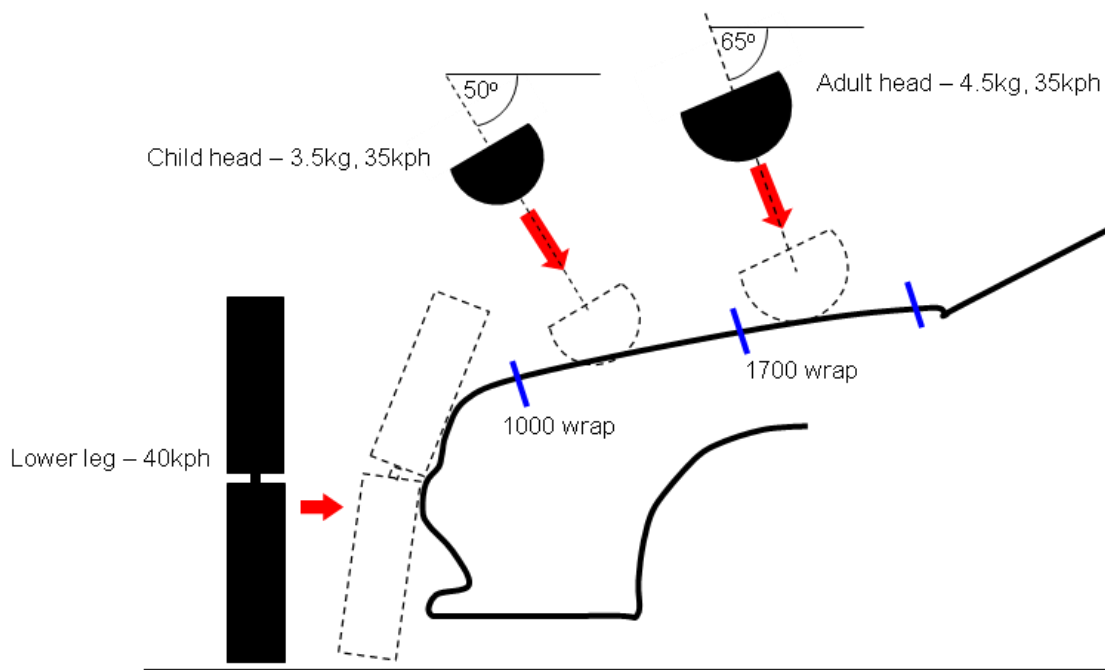


Figure 34 – PP EU2 legislative test requirements (head and lower leg shown)

The head-form impactor consists of an aluminium base plate and sphere covered in a thick rubber skin (see example in Figure 35). The test head-form mass is determined by

the location on the bonnet to which they are fired, these are known as ‘ADULT’ (4.5kg) and ‘CHILD’ (3.5kg).

The definition of which head-form (an example can be seen in Figure 35) is used and where it is impacted into the vehicle during the legislative test is determined by the specific exterior geometry of the vehicle.

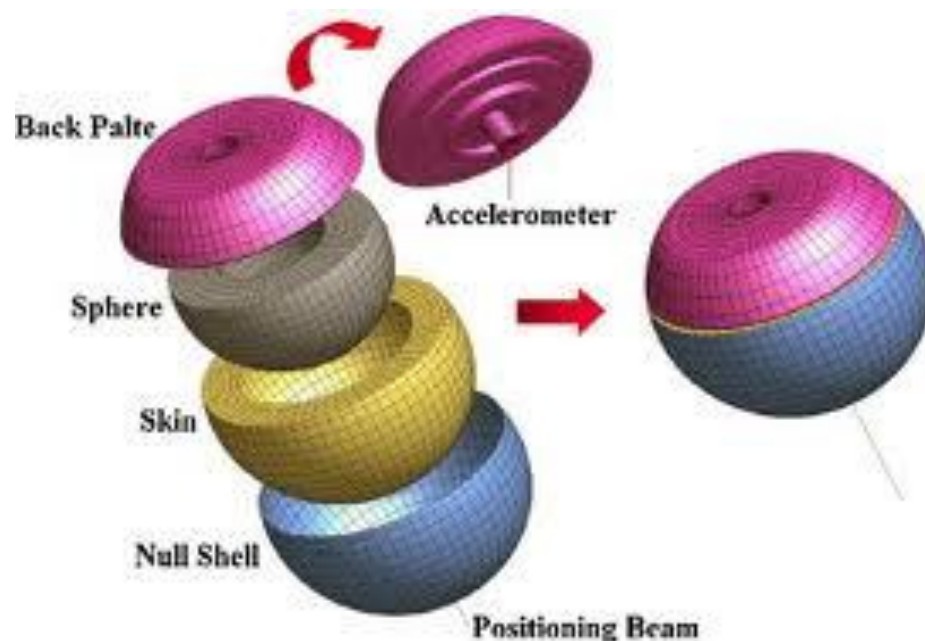


Figure 35 – Example ‘Adult’ PP EU2 test head-form (CAD model shown)

3.7.3 Head Protection Hard-point Clearances

As discussed previously, in order to meet the desired HIC targets a level of energy absorption through deformation must take place by the bonnet. However, this level may be reduced by the proximity of the bonnet to components packaged inside the engine compartment.

Therefore, it is desirable to maximise the under-hood clearances for pedestrian protection to be achieved. Figure 36 shows the relationship between under-bonnet clearances, intrusion and its vertical component as discussed by Liu et al (29).

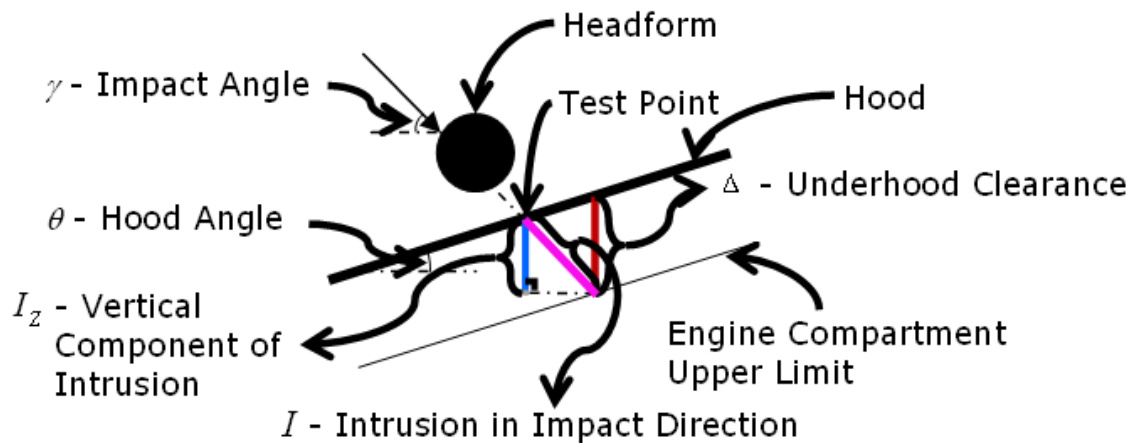


Figure 36 – Cross relationship between under bonnet clearance and intrusion (29)

Work conducted by Zellmer and Glaeser (30) on head-form to bonnet impacts experimentation concluded that 70mm (ADULT) and 50mm (CHILD) of stopping space was required to limit the HIC value to <1000 at speeds of 40km/h in order to absorb the energy resulting from a pedestrian head impact event (see Figure 37).

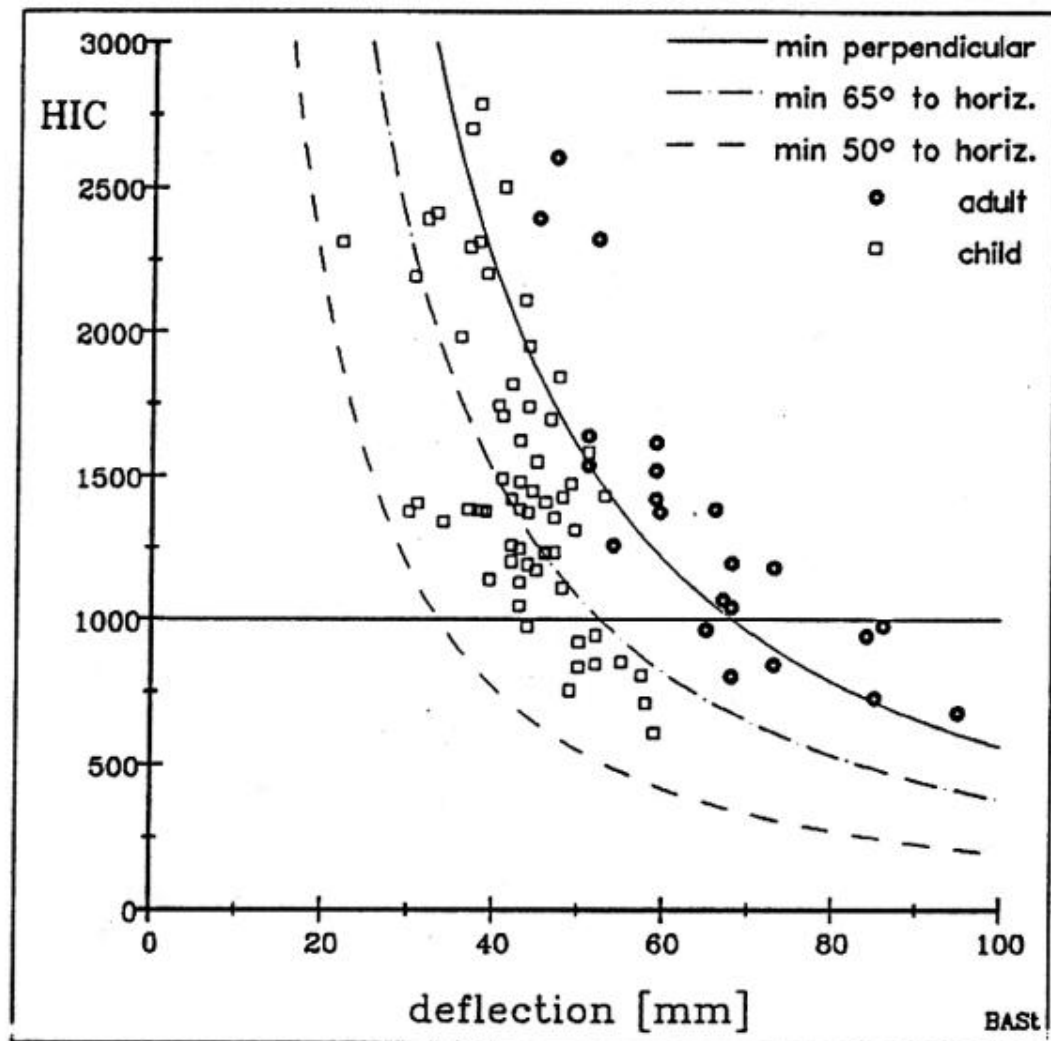


Figure 37 – Bonnet head-form tests performed at BAST in Germany, 40km/h impact speed (31)

Using the HIC expression as defined previously by Equation 1, it is possible to plot theoretical curves showing the resultant HIC against available displacement space (as shown is Figure 38).

A perfect energy absorber can achieve 100% energy absorption efficiency but, in reality every impact will be short of this value and a greater amount of clearance will be required than the theoretical minimum.

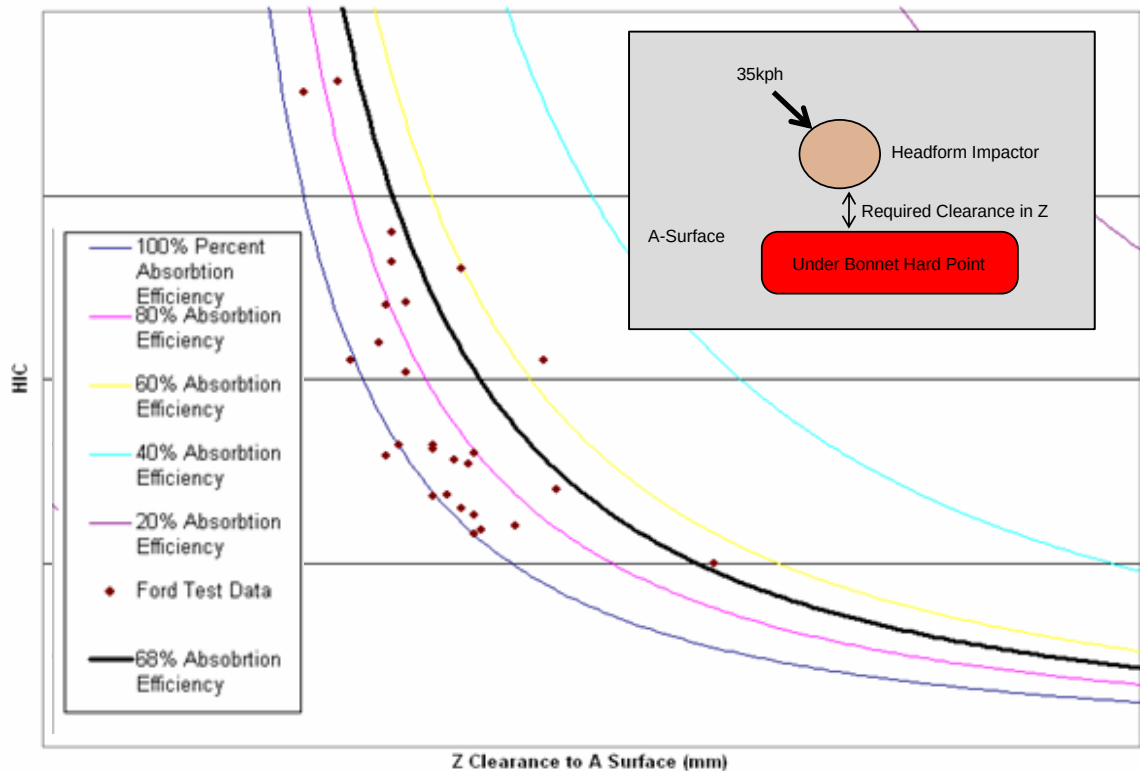


Figure 38 - Graph of absorption versus Z clearance requirements

3.7.4 PP Test Methods and Governing Bodies

This section describes the development and legislative test methods and customer focussed testing that exists to determine if a vehicle passes the PP acceptance criteria. The output of the EEVC WG17 report as previously discussed, defined the basis for the pedestrian regulatory test regime, these methods can now be defined in more detail.

3.7.4.1 PP Legislative Test Methods

EU2 PP HI regulations relate to injury risk assessments where a pedestrian head impacts onto the vehicles bonnet area. As previously discussed sub-system impactors (see Figure 35) instead of crash test dummies are used to represent the head of a child pedestrian and the head of an adult pedestrian (32).

These impactors are propelled onto the vehicle bonnet with a velocity of 35km/h (equivalent to a vehicle speed of 40km/h) and the resultant HIC values calculated must comply with the regulation requirements (as depicted by Figure 39).

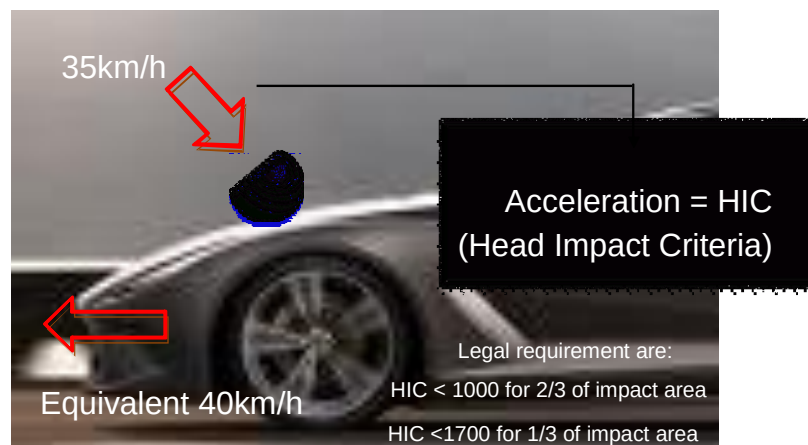


Figure 39 –Schematic of PP EU2 Head impact test criteria

Figure 40 shows the legislative HI test apparatus, the head form impactor in its unfired position, it is moved across the PP zone surface and various impacts are performed and resultant HIC values recorded.

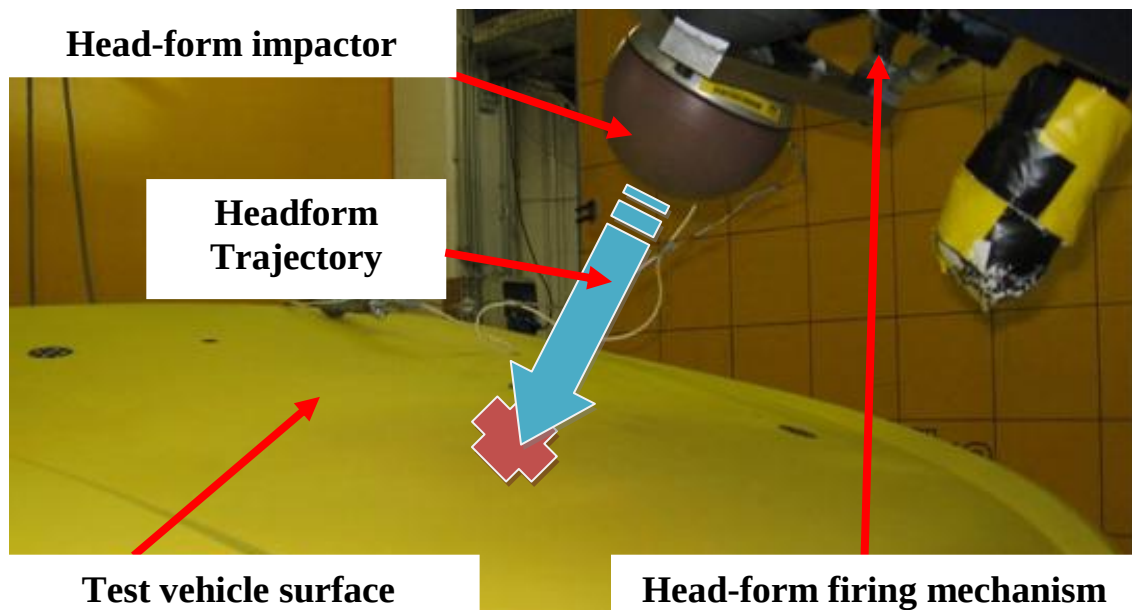


Figure 40 – Legislative PP EU2 head impact test equipment installation

3.7.4.2 In Market EuroNCAP Testing

This section provides information relating to in market consumer group testing relating to PP requirements. It is thought by Ponte et al (33) that a consumers' perception of pedestrian safety may affect the actual vehicle purchase decision. Across the world various agencies exist to promote vehicle safety including pedestrian-safe vehicles and hence publish into the public domain results relating to how new vehicles perform relating to pedestrian safety.

The EuroNCAP is one such agency that promotes both occupant and pedestrian-safe vehicles (34) and was developed in the UK with the aim of improving vehicle safety; it provides an independent objective evaluation of the protection offered by a vehicle to a pedestrian. Legislative safety standards set a vehicle manufacturer a minimum

threshold level to attain, basically a pass or fail result; EuroNCAP seeks to quantify that pass result.

The EuroNCAP PP protocols were established in 1996 and up to November 2011 EuroNCAP have tested over 400 discrete models to assess their PP performance and published results for consumers to openly view (at present Lotus products have not been tested or assessed). The consumer test (as depicted by Figure 41) differs slightly from the legislative test, in that the bonnet zone rear limit is not defined by the bonnet rear reference line but by a Wrap Around Distance (WAD) of 2100mm (defined as WAD2100).

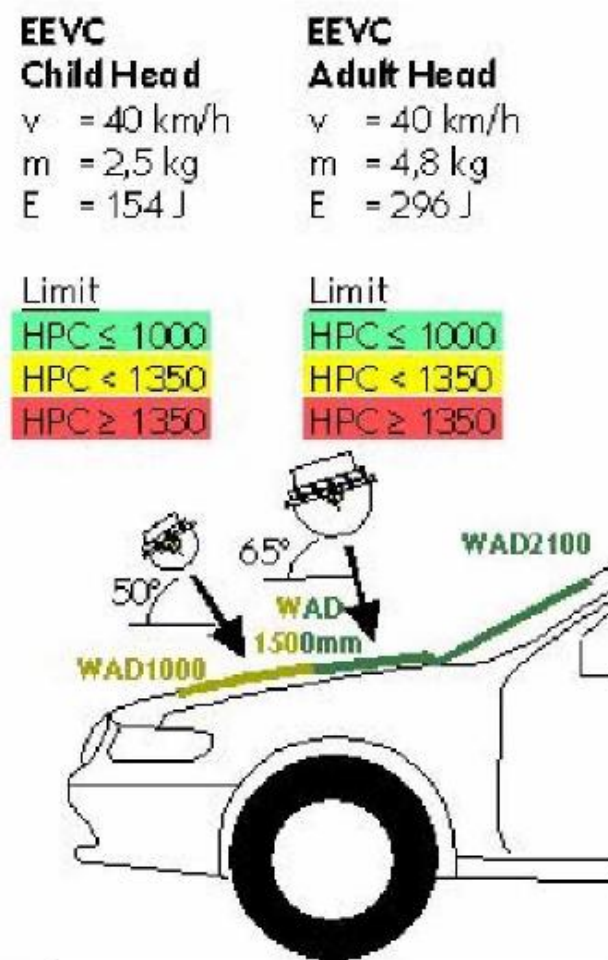


Figure 41 - EuroNCAP PP HI test criteria and targets overview (34)

The EuroNCAP PP assessment criteria consists of a vehicle being awarded up to 36 points, based on the results of a series of HI tests as described in Figure 41, in which sub-system impactors are fired at the front of the vehicle exterior surface.

The vehicle is then given a star rating of between 0 and 4 stars based on the amount of points it has scored (see Table 2).

Points scored	0-0.99	1-9.49	9.5-18.49	18.5-27.49	27.5-36
Star rating	0	1	2	3	4
	Very Poor	Poor	Good	Very Good	Excellent

Table 2 – EuroNCAP PP test relationship between points scored and star rating (34)

In 2009 the PP rating was incorporated into the overall published EuroNCAP vehicle safety rating, Figure 42 depicts a typical example report of how this information is relayed to the consumer in media.

As can be seen in Figure 42 this test report provides the consumer with a simple graphic of the front of a vehicle to indicate the overall PP performance and associated points scored relating to PP element requirements. A total points and percentage score is also published.

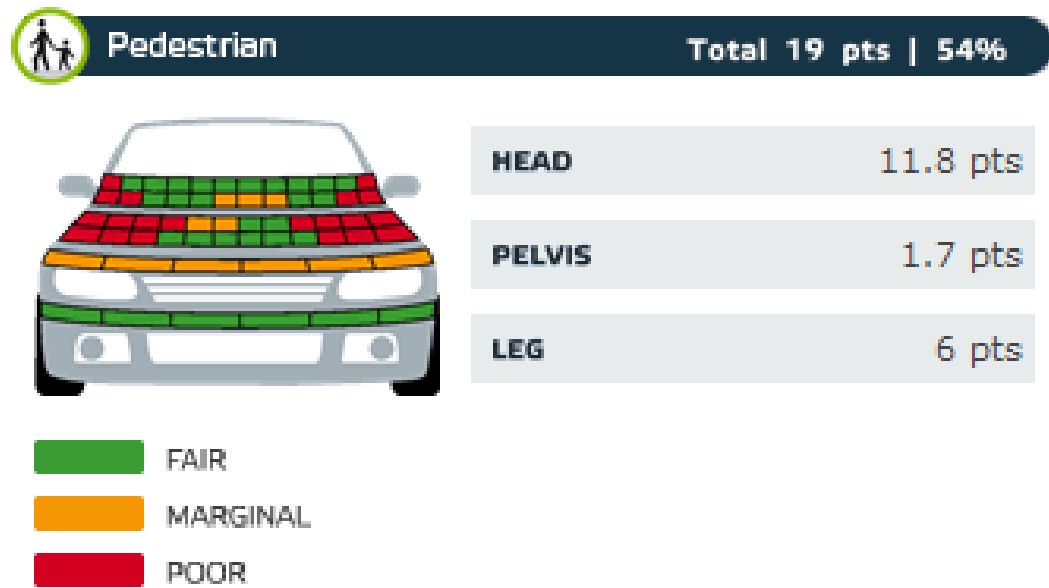


Figure 42 - Example of consumer EuroNCAP PP test results (35)

To emphasis and demonstrate the importance that the consumer industry puts on PP, for 2012 EuroNCAP plans to tighten the award requirements, so a vehicle will not obtain a top five star rating if it does not meet at least a 60% of potential maximum rating in the PP department; at present the minimum percentage in pedestrian marks currently required to obtain a general 5 star rating is 40%. At the time of writing no vehicles in the HLS segment have been tested by EuroNCAP for PP.

3.7.4.3 High EuroNCAP scores:

This section reviews other non-HLS sector vehicles that have scored high within the EuroNCAP assessment to assess if there are any traits and design or technology trends

that maybe of significant value to this study. Vehicles that have scored the highest PP rating during 2011 were reviewed.



Figure 43 – BMW 5 series, 2010

The BMW 5 series (Figure 43) is a 4 door executive saloon launched in 2010 and scored the highest score for PP at the time of writing (January 2012) in the EuroNCAP test. It offers an active bonnet as other luxury executive vehicle manufacturers such as the Jaguar XF and Mercedes E-class but manages the energy more efficiently across the whole bonnet surface (as can be seen by the majority of uniform green sectors in Figure 44).

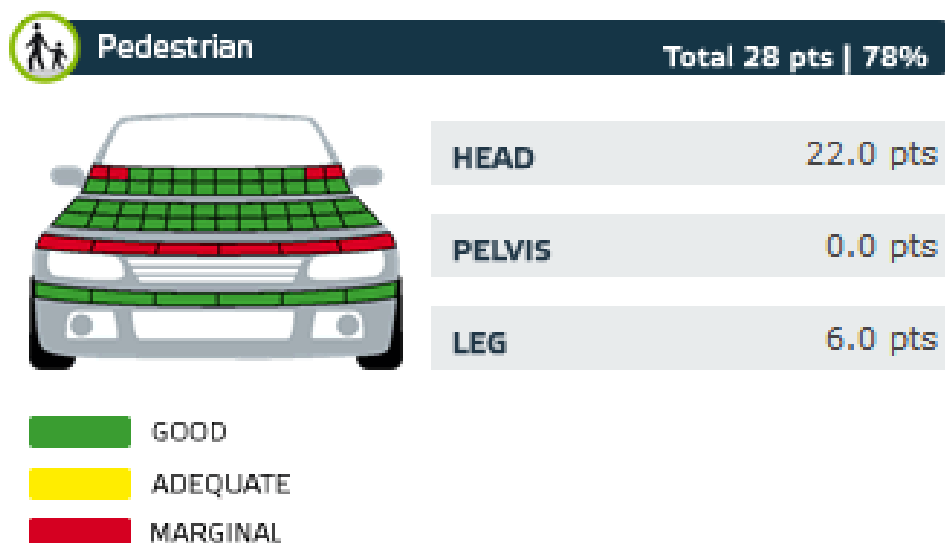


Figure 44 – BMW 5 series 2010 EuroNCAP PP results (35)

3.8 Pedestrian Protection Enabling Technologies

3.8.1 Introduction

As discussed previously research in the area of injury mechanisms to pedestrians resulting from a frontal impact with a car demonstrates that countermeasures can be effective in the avoidance of fatalities and reduce the level of serious injuries to pedestrians.

PP compliant OEM vehicle type examples have been discussed, this section reviews current and future system level technologies available or in development to provide improvements in order for OEMs to meet PP requirements. As previously discussed these system level technologies can be broken down into the following groups as shown in Figure 45.

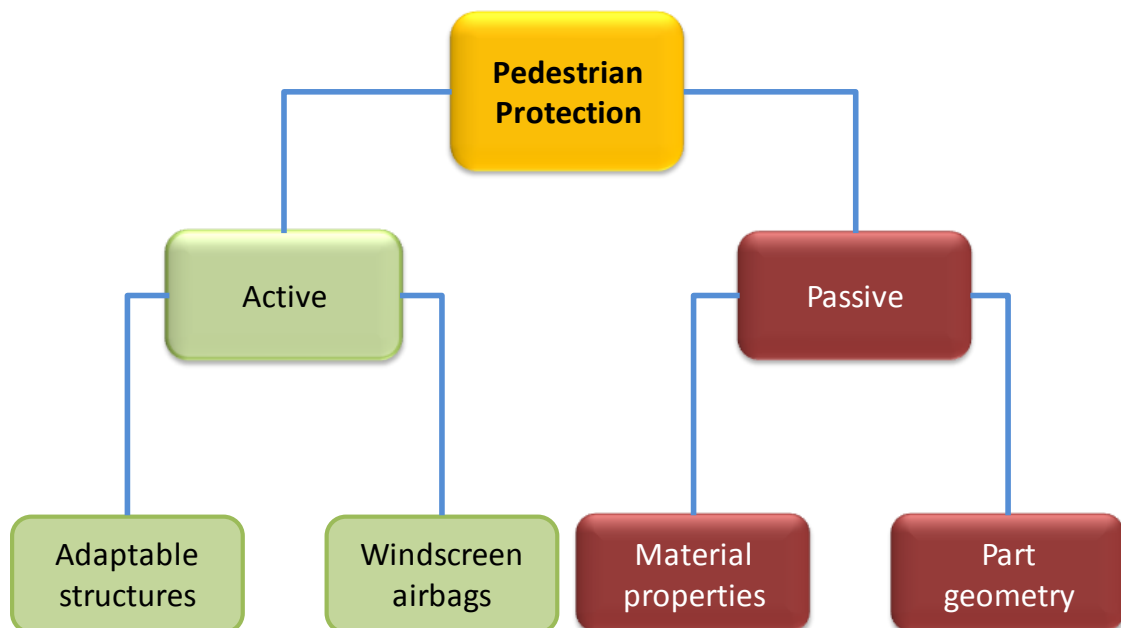


Figure 45 - Overview schematic of PP enabling technologies groups

3.8.2 Passive Countermeasures

Passive countermeasures relating to PP create a design which is made by changes in the structure of the vehicle to allow sufficient deflection to occur whilst still meeting the relevant HIC targets.

This management of kinetic energy dissipation can be achieved by:

- The use of differing materials to manage the energy transfer during the head impact or
- Geometric changes to provide sufficient clearances.

One such study into passive PP countermeasures, the ‘Ecofront’ project (36) (see Figure 46) was an initiative vehicle created by the Dutch research and development foundation TNO Automotive Safety Solutions (TASS) to demonstrate the feasibility of designing a vehicle to meet PP requirements by passive means only.

This concept was developed in 2001 using general design guidelines based on TASS experience from previous pedestrian safety projects and testing. These guidelines consisted of providing the necessary free deformation space under the bonnet surface to provide the associated vehicle package requirements and material stiffness in order to achieve a HIC value <1000 (to meet the anticipated PP EU2 targets).



Figure 46 – TASS ‘Ecofront’ concept study, 2001 (36)

The results of the ‘Ecofront’ study proposed a bonnet consisting of a two layer construction, tuning the offset layer distance to achieve the necessary deformation and proposing styling guidelines to avoid high local stiffness’s (for example between the bonnet and fender shut line, clamshell bonnet and concealed wipers).

3.8.2.1 Changes in Vehicle Geometry

Physical changes in the vehicle geometry to either relocate components to be outside of the HI zone or to improve clearances are a relatively simple solution used to meet PP requirements. These can be in the form of, moving components, lowering the engine and other hard-points or providing deep sections over hard-points such as hinges.

3.8.2.2 Stiffness Optimisation

A passive method of improving PP by stiffness optimisation is to allow component mounting points to fail first during a pedestrian impact thus reducing stiffness and realise lower levels of HIC for those areas affected. Components this strategy is applied to are reservoir bottles for windscreen or coolant fluids, engine air boxes or wiper spindles.

As discovered from competitor analysis, Audi uses a clamshell type bonnet to remove the relatively stiff bonnet to fender shut-line interface caused by the fender location structure. This interface is stiff as to retain the structural integrity of the fender to the body. Alternative mounting strategies have been developed in the form of deformable fender returns to collapse on impact, such as a collapsible bracket development by General Motors Brazil in 2009 (37) as shown in Figure 47

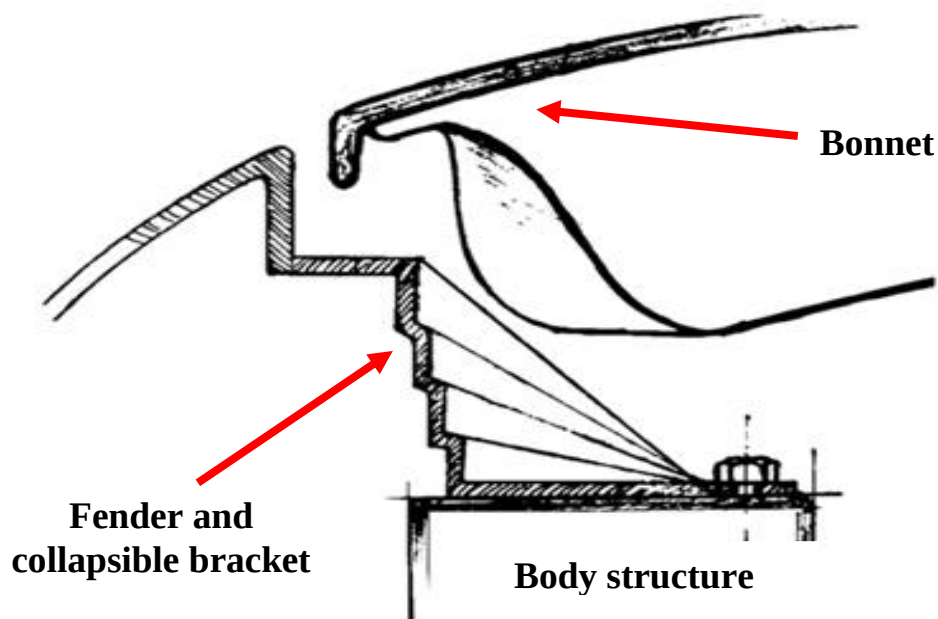


Figure 47 – Collapsible fender bracket concept (37)

3.8.3 Adaptable Vehicle Structures

An alternative to providing a passive PP design structure is that of an Adaptable Vehicle Structure (AVS) which can change its mechanical properties, such as its stiffness or physical geometry, depending on the configuration and severity of the crash experienced.

This approach can optimise the vehicles PP performance to minimise injury risk. AVS systems use ‘pre-crash’ sensing to supply information about the crash configuration to maximise the amount of time available for them to adapt prior to the pedestrian to bonnet impact.

AVS systems are required when there is a lack of under hood space under the desired exterior bonnet surface; this would otherwise create a conflict with the requirement for a sufficient deformation PP zone. By raising the exterior surface promptly at the moment of collision, AVS systems create the necessary space to efficiently absorb the impact energy of the pedestrians head.

Figure 48 shows the landscape of vehicles in 2011 which have adopted an AVS approach over the past decade, these utilise deployable active bonnet technology to achieve PP requirements.

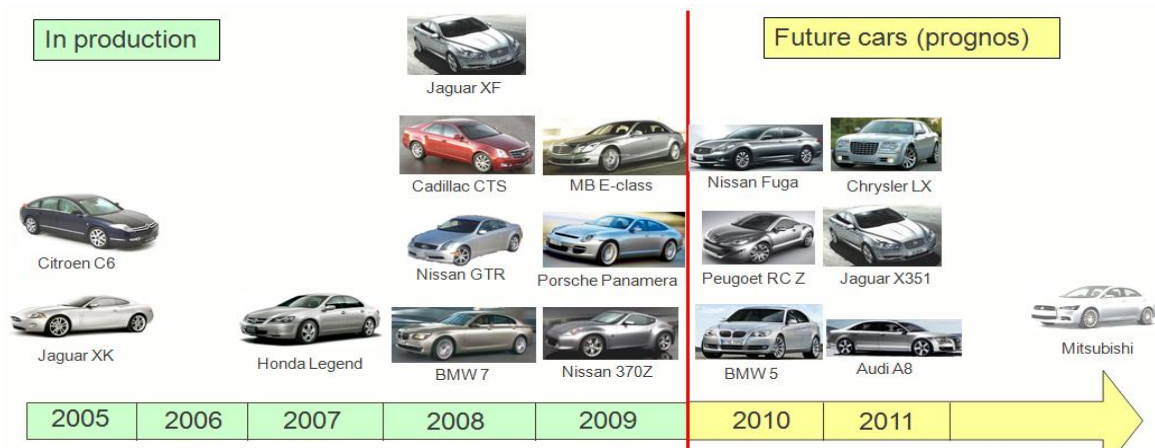


Figure 48 – 2011 landscape of vehicles with deployable bonnet PP system

This alternative PP mitigation approach entails adjusting the geometry of the bonnet before or during the pedestrian to vehicle accident event in such a manner that create the necessary space to efficiently absorb the impact energy of the pedestrians head.. The advantage of these systems is that the desired vehicle exterior aesthetics can be maintained until the pedestrian impact occurs.

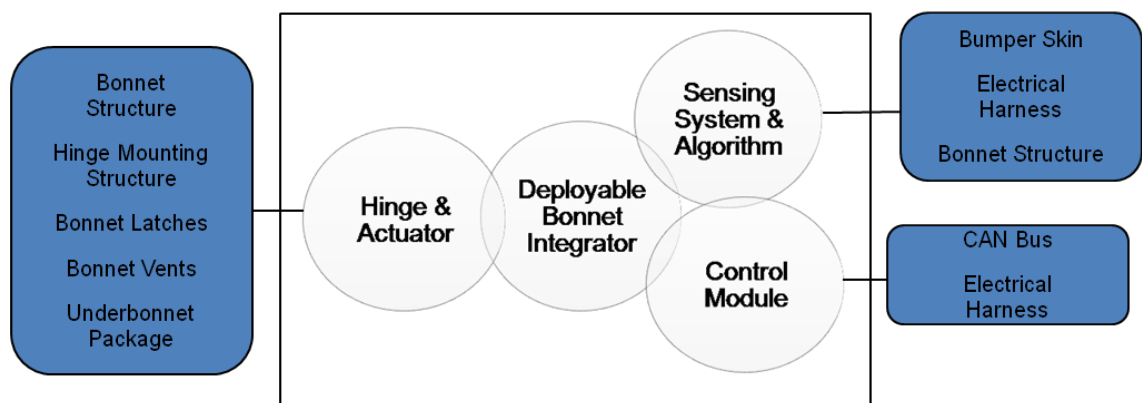


Figure 49 – Venn diagram of a bonnet deployed AVS system

AVS bonnet systems deploy during a pedestrian frontal impact by utilising a sensor array along the front of the vehicle to detect what the object struck is, this is done by a classification algorithm. This determines if the object is a pedestrian or not to prevent the system from deploying by mistake (for objects such as other vehicles or obstacles).

If the sensors calculate that protection can be offered, then the bonnet will deploy into the fired position via springs or a small pyrotechnic charge. Figure 49 shows the elements of a typical bonnet AVS system.

Figure 50 depicts the lifecycle activation event of a PP AVS system; these periods can be defined as sensing, actuation and dwell.

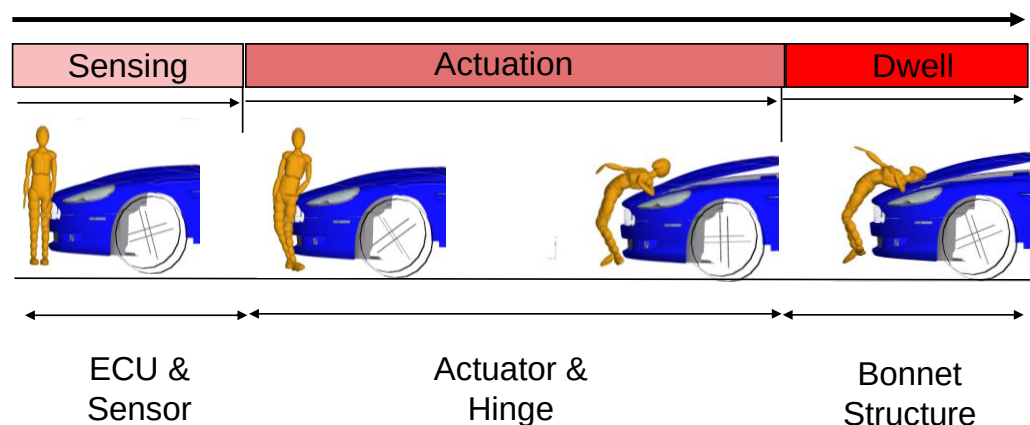


Figure 50 - AVS system 3 stage activation lifecycle

The raised bonnet in its fired position creates a larger clearance between the bonnet and the under bonnet components underneath and reduces the acceleration of the pedestrians head in a controlled manner.

The front and rear of the bonnet both rise to create the necessary space underneath and offer some protection for adults and children impacts in a timely manner. Figure 51 shows the physical system with the bonnet in a fully deployed state post pedestrian impact.



Figure 51 – Example of a fully deployed active bonnet system (31)

3.8.3.1 AVS System Considerations

Considerations relating to the functionality requirements of an AVS system are important to understand and define, these include:

- Hinge functions; motion control, strength / stiffness, conventional hinge operation and delivery condition
- Release; part of hinge system or lifting device?
- Re-latch; force required to reset system, permanent or temporary re-latch
- Braking; deformable (requires replacement?)
- Halting; fully deployed position stop feature, oscillation reduction

3.8.3.2 AVS sub-system componentry

This section reviews the AVS PP vehicle system (see Figure 52) in more detail and identifies component parts and their various types.

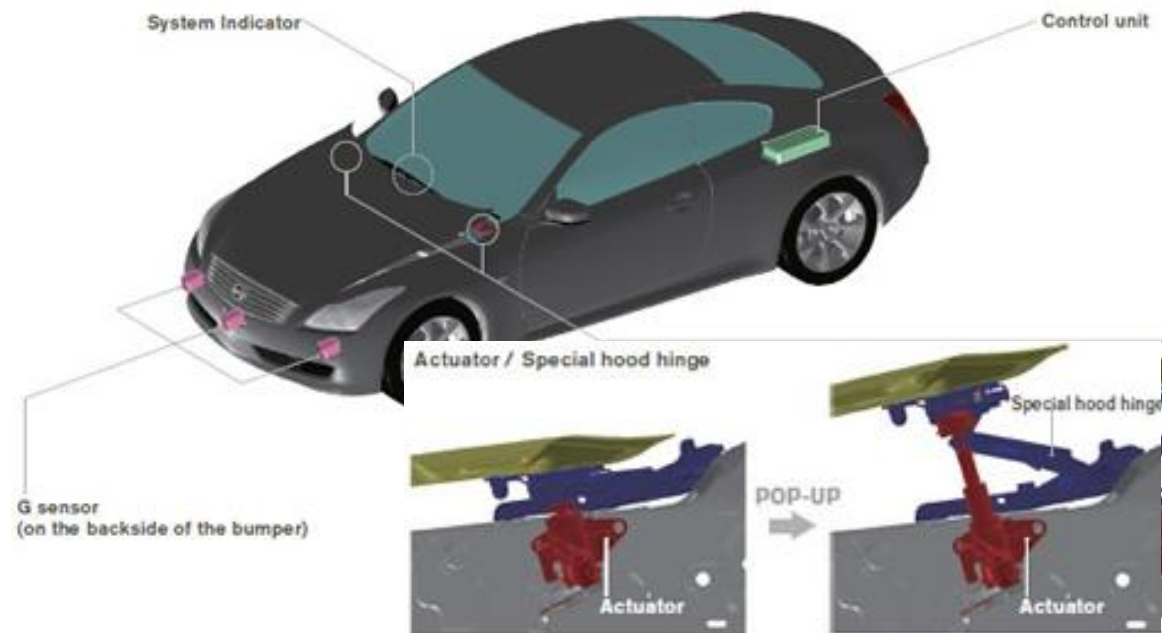


Figure 52 – AVS sub-system vehicle schematic (Source Nissan)

3.8.3.2.1 Actuators:

An active deployment device is required as reviewed to lift the bonnet during a pedestrian impact. There are various means of performing this task by actuator units such as:

- Spring or torsion spring-drive
- Electromagnetic drive
- Hydraulic or pneumatic drive
- Pyrotechnic drive

The most commonly used are those that are pyrotechnic driven, these are mounted toward the rear of the bonnet on the outboard edge and secured to the body structure hidden from view.



Figure 53 – Schematic of an active bonnet actuator

3.8.3.2.2 Bonnet Hinges

Bonnet hinges need to deploy in a controlled manner during the pedestrian impact event to allow the bonnet to rise in the Z direction to create sufficient clearance, whilst still being able to retain their primary function of allowing the bonnet to open in normal use.

Numerous types of active hinge designs exist to support active PP systems and are detailed in this section with both positive and negative considerations noted.

- **Single-link** (as can be seen in Figure 54)
 - + No movement of bonnet in x during deployment
 - + Weight/costs low
 - Integration into the vehicle, rotation point package constraints
 - Release options are limited

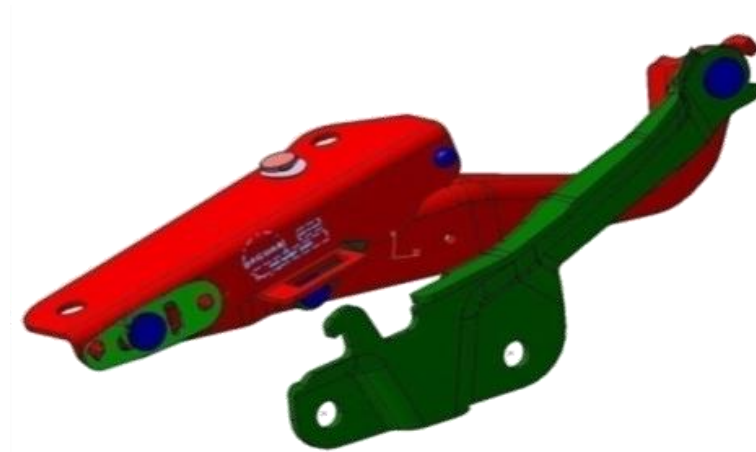


Figure 54 – Single link deployable bonnet hinge as used in the Jaguar XF

- **Multi-link**
 - + More integration and release options compared to single link designs
 - Hard to avoid movement of bonnet in x during deployment

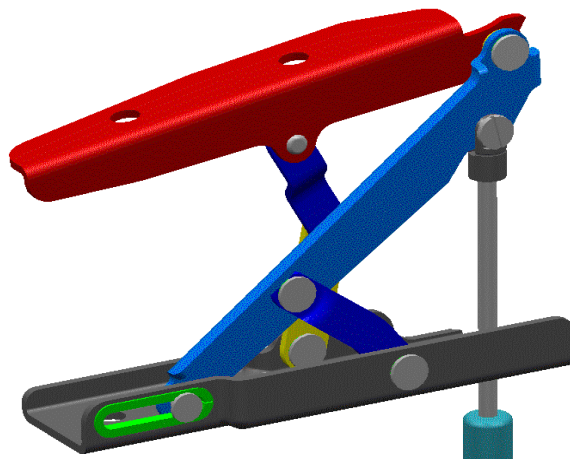


Figure 55 – Multi link hinge concept (Source Anonymous)

- **Resettable hinge**

After deployment, this hinge system can be reset by lifting bonnet to normal full-open position. Gas struts on both sides of the vehicle lock in the compressed position and bonnet can be lowered in normal fashion, the system can be fully reset by the consumer and therefore no service visit is required. This resettable feature is advantageous in relation to cost of ownership reductions not only for the user but to the OEM service department in terms of repair time and cost.

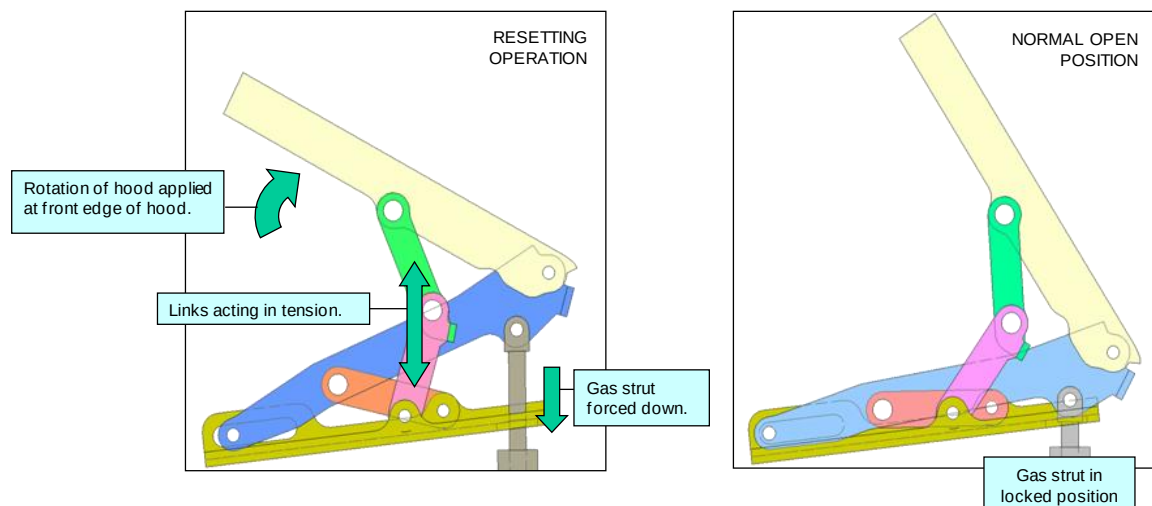


Figure 56 – Example of a resettable active hinge mechanism

3.8.4 Deployable Exterior Airbags

Deployable airbag systems are a relatively new technology enabler for meeting PP requirements. This system consists of a 'U' shaped airbag deployed externally at the base of the windscreen area, the majority of systems include a portion of the A pillar to

be also covered by the airbag. Actuation is as per other AVS systems through a sensing system located at the front of the vehicle.

The airbag is used in conjunction with a deployable bonnet function to increase the head deceleration distance and to offer ‘cushioning’ for pedestrian impacts to help reduce the risk of injury. Research into this area is in its infancy compared to other active technologies however a study completed by Bovenkerk et al (38) demonstrated the potential of a bonnet airbag.

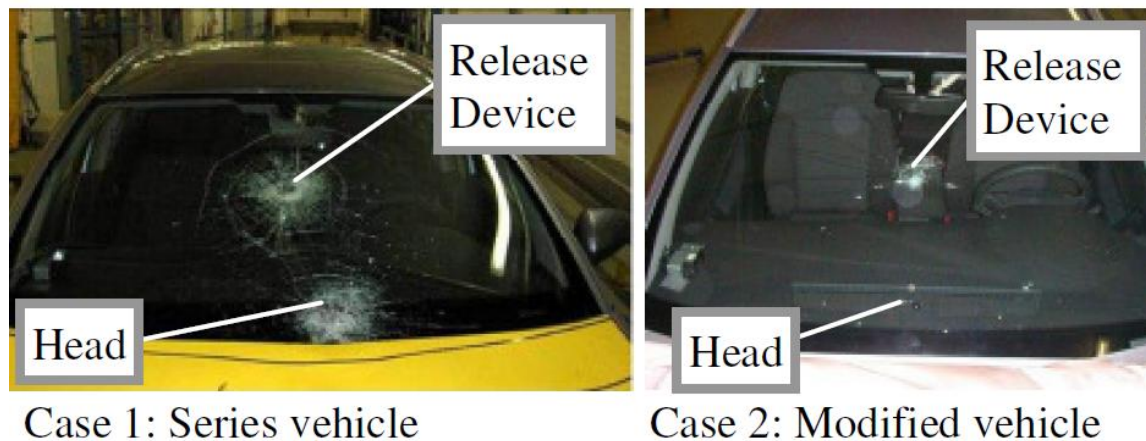


Figure 57 – Example of development testing for early bonnet deployed airbag (49)

Figure 57 shows the windscreen PP HI physical results for a series production vehicle and one that had been modified to include a bonnet mounted airbag (no specific HIC data was available). However as can be seen the resulting damage caused to the windscreen (at its lower section) by the head impactor is considerable less on the vehicle with the bonnet deployed airbag (case 2).

A more recent development as shown in Figure 58 shows a further concept of a bonnet airbag system developed by Cranfield University, UK and the automotive safety system supplier Takata in 2005 (39).



Figure 58 – Development prototype of bonnet airbag system (40)

This Fiat Stilo based vehicle (see Figure 58) was created at the University's 'Cranfield Impact Centre' and uses a forward mounted sensor to “pre-detect” a collision to inflate a ‘U’ shaped airbag hidden at the rear of the bonnet and covers the base of the windscreen area and the lower A pillar areas.

This inflated airbag configuration is to maximise the drivers vision on impact by the pedestrian and to maximise coverage of stiff areas of the body structure). On deployment the airbag also raises the rear edge of the bonnet hence generating increased under-bonnet clearances to dissipate energy.

The test vehicle was not originally designed to meet PP, however with this AVS system installed initial test results indicated that it would achieve the latest PP EU2 lower HIC target of 1000, with a score ranging from 645 to 945 (without any bonnet stiffness modifications) (6).

A further concept for exterior airbags to mitigate and reduce pedestrian injuries was shown by Toyoda Gosei Japan in 2008 (as shown in Figure 59), this concept consisted of two sets of frontal exterior airbags:

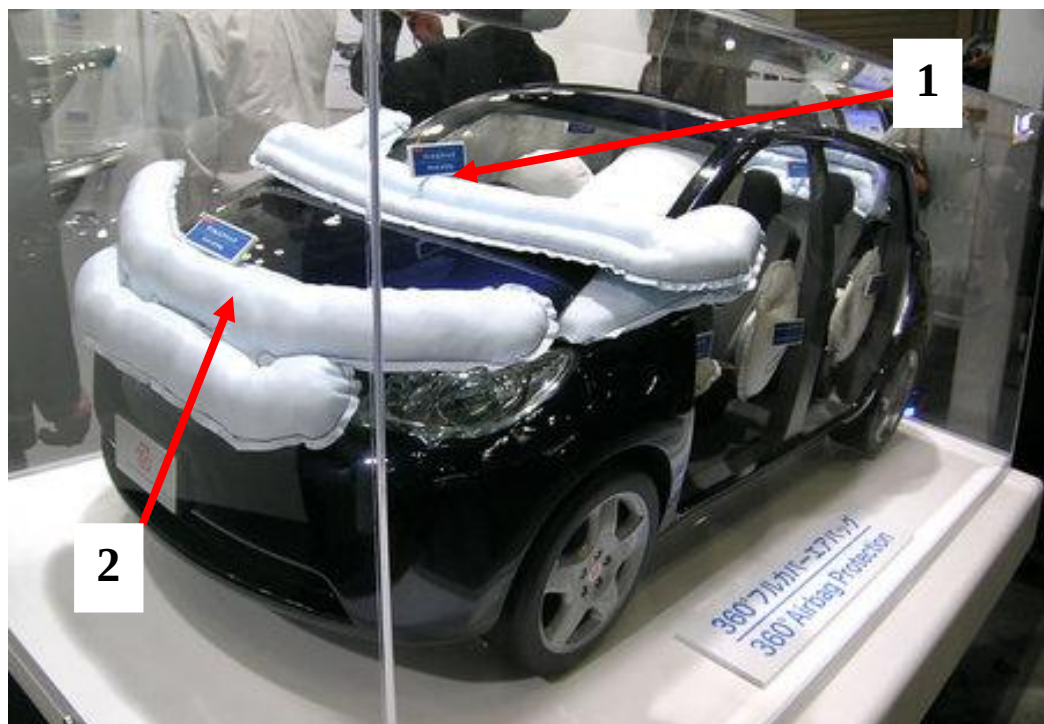


Figure 59 – Toyoda Gosei exterior airbag concept car (41)

1. The bonnet airbag comes out from under the bonnet trailing edge and decelerates an adult head during the impact on the fender or A-pillar areas.
2. Additionally the forward lower airbag deployed out from a front grill to offer protection to the head of a child or the pelvis/torso of an adult.

At the time of writing there is only one series production vehicle application of this technology hardware. Volvo Cars based in Sweden are the first OEM to introduce an external airbag to support its PP strategy (42).

This first application was previewed on the Volvo V40 premium 5 door hatchback at the Geneva show in March 2012 (Figure 60 shows a schematic of the airbag inflated and bonnet deployed).

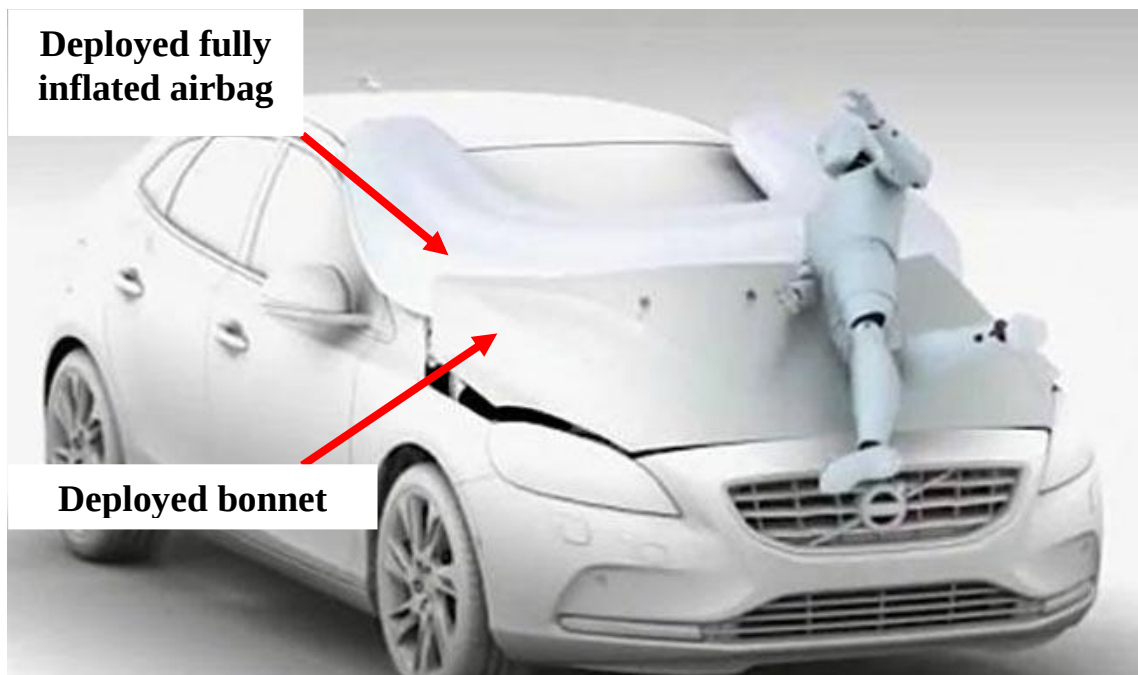


Figure 60 –Volvo V40 Pedestrian Protection Airbag system (42)

The Volvo V40 PP airbag system is similar in principle to that researched and developed by Cranfield University and Takata. It features sensors in the front bumper that register physical contact between the car and the pedestrian at the moment of impact.

The rear end of the bonnet is then released and elevated by the airbag as it inflates to cover the entire area under the raised bonnet as well as around a third of the windscreen. According to Volvo the raised, cushioned bonnet and airbag help reduce the severity of pedestrian injuries (at the time of writing EuroNCAP results were not available).

To demonstrate the importance of this key pedestrian safety technology, Thomas Broberg, Senior Safety Advisor at Volvo Car Corporation commented in March 2012 that the V40 airbag technology is, *"Yet another important step toward our vision that nobody should die or suffer serious injuries in a new Volvo car by the year 2020."*

Just as Jaguar pioneered the use of deployable bonnet PP technology in 2006 with the introduction of the XK, Volvo is now perceived to be the leader in this next phase of PP active development.

It is important to mention how the areas of the vehicle that this new PP airbag technology addresses are not part of existing PP EU2 legislative test acceptance criteria. Research by Bovenkerk et al. (38) showed these areas of the vehicle relating to the lower 'A-pillar' show significant relevance in real-world pedestrian accidents.

3.9 Technology Assessment and Methodology

This chapter explores how these different PP enabling technologies can be assessed, to identify what merits do each have to be adopted by the Elite vehicle programme.

3.9.1 Methods of Assessing Technologies

One approach for assessing these technologies according to Phall et al (43) is to develop a roadmap, which aims to align technology with organisational objectives; this approach is shown graphically in Figure 61 and identifies 3 key elements:

1. Know-why

- To identify what is the objective of the business and what influences it

2. Know-what

- Which mechanisms deliver the objective

3. Know-how

- Which resources are available to develop the delivery mechanisms

This approach can be used to map out the technology strands to deliver PP EU2 requirements, a four elements, know-when is also applied to frame the process within a timeline.

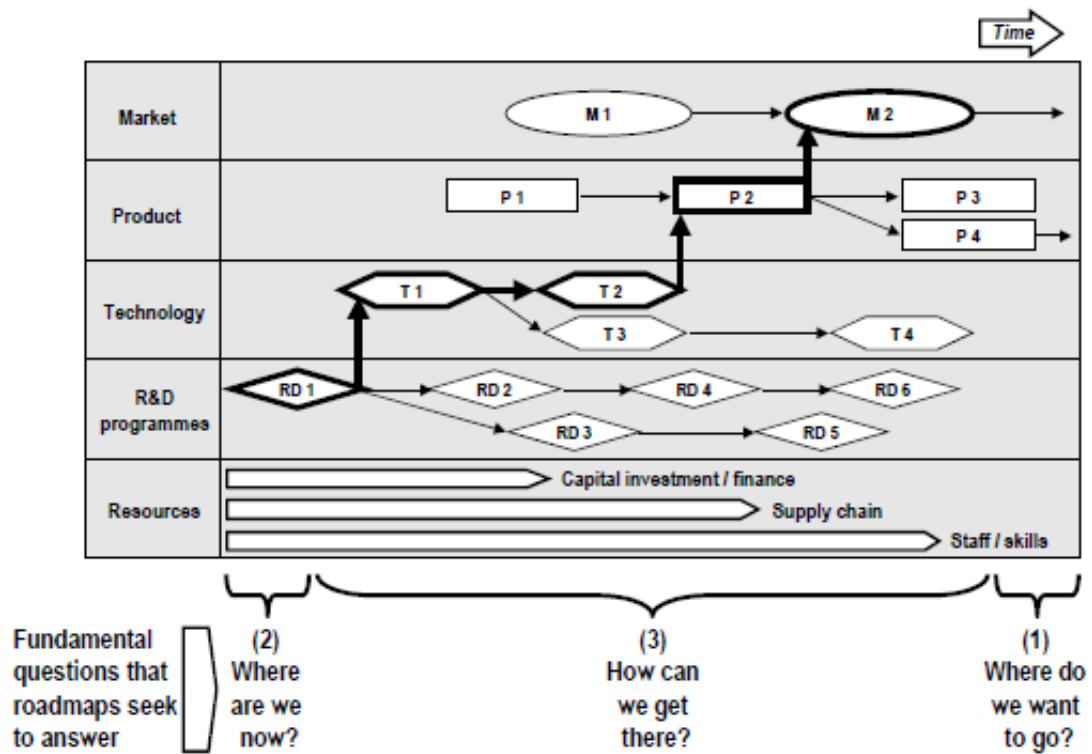


Figure 61 – Typical technology roadmap example (43)

Another more specific and targeted approach to assess and hence compare potential enabling technologies for PP a procedure is required to be developed; it also has to be able to be applied to an existing design.

One such assessment matrix (see Figure 62) has been developed by the German Insurance Association (44) which provides through the use of the vehicle surface, accident research data and front accident kinematics an index value indicating the level of head injury risk for a given vehicle architecture.

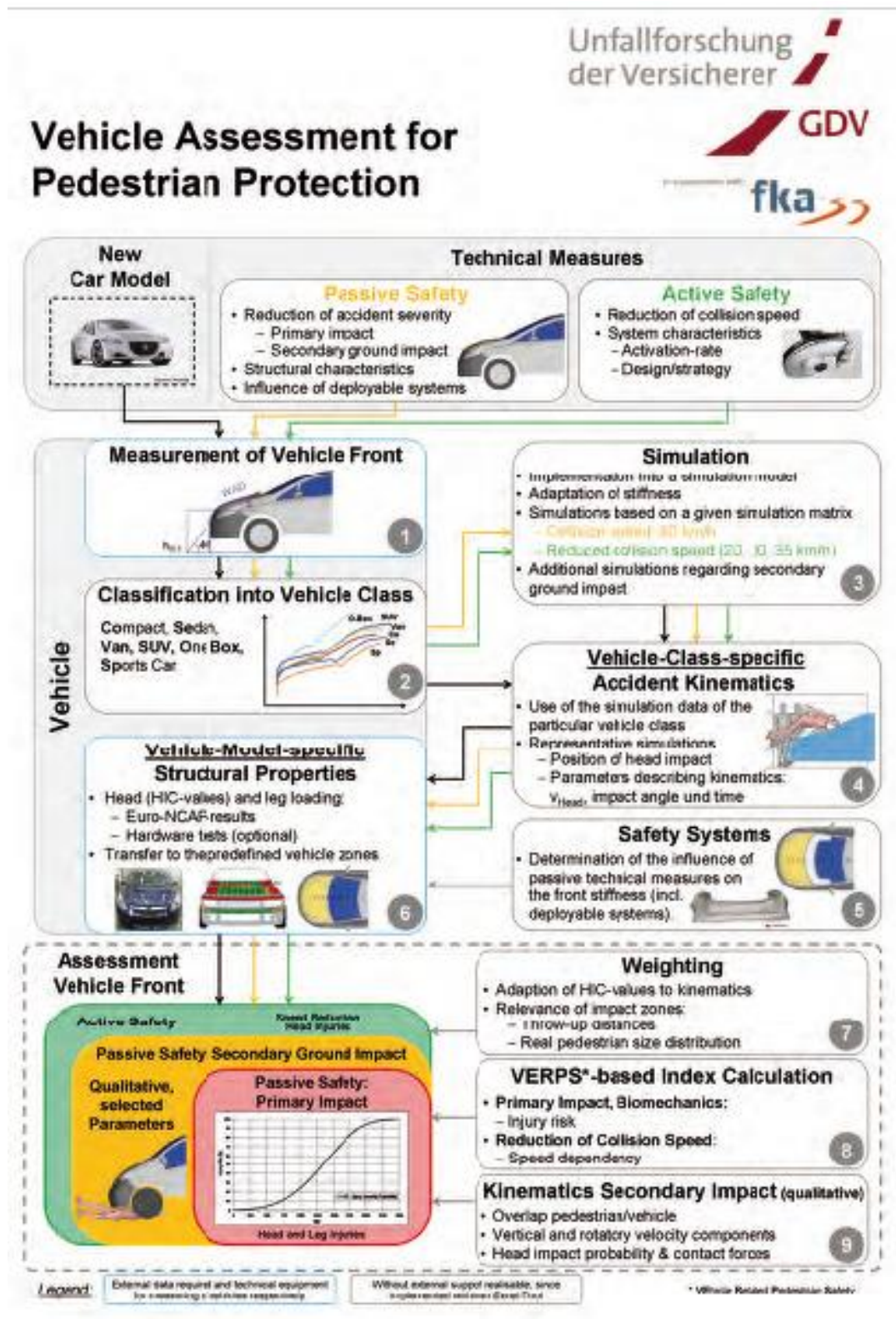


Figure 62 – Overview of Vehicle assessment for PP (44)

4 Lotus Elite Pedestrian Protection Requirements

Having established high level PP requirements and test methodology, this chapter reviews and assesses the current state performance of the Lotus Elite 2010 Paris show car concept in meeting these legislative requirements relating to PP EU2 HI targets.

4.1 Head Impact Zone Requirements

As mentioned previously physical vehicle exterior geometry is used to determine the HI zones in which the acceptance HIC value is measured. This section details the processes used to construct and therefore identify the location of the HI zones for both ‘ADULT’ and ‘CHILD’ head-forms (male and female are not termed differently). These zones can then be used in determining the HIC value of the current Elite bonnet surface against the EU2 PP legislative targets and spatial requirements.

The bonnet rear reference line is determined by rolling a 165mm diameter sphere across frontal upper surface whilst maintaining contact with windscreen as Figure 63 illustrates. The line follows the foremost point of contact (windscreen wipers and wiper arms are removed for this measurement).

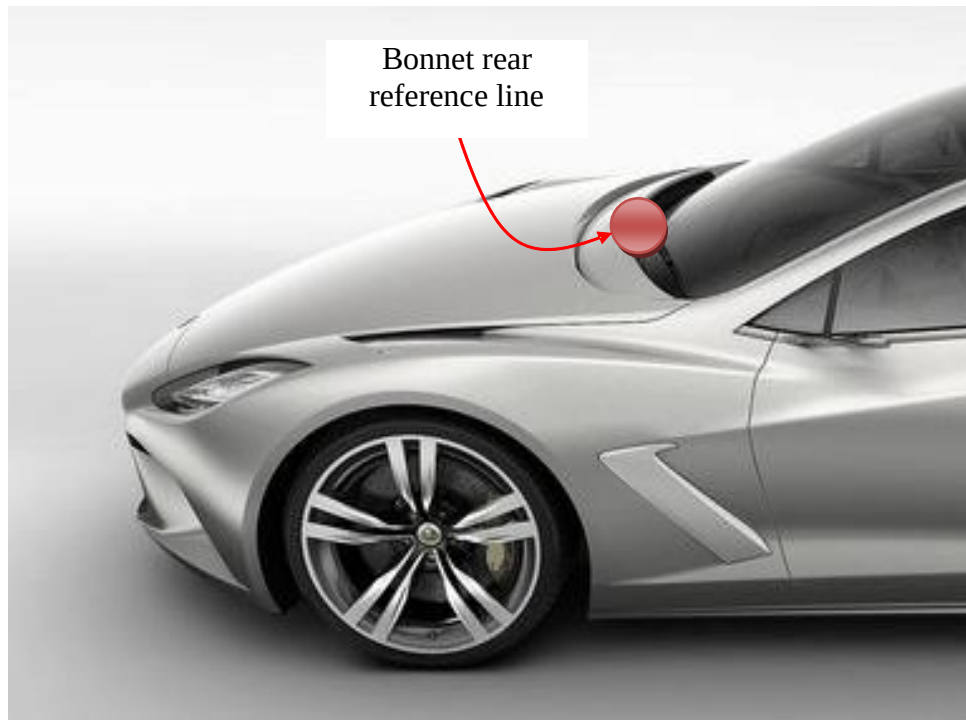


Figure 63 – Elite bonnet rear reference line schematic

Figure 64 shows the 1,000mm (CHILD) and 1,700mm (ADULT) lateral lines known as the WAD and are determined by holding a tape taught and traversing across the width of vehicle and is to kept aligned with X-Z plane throughout.

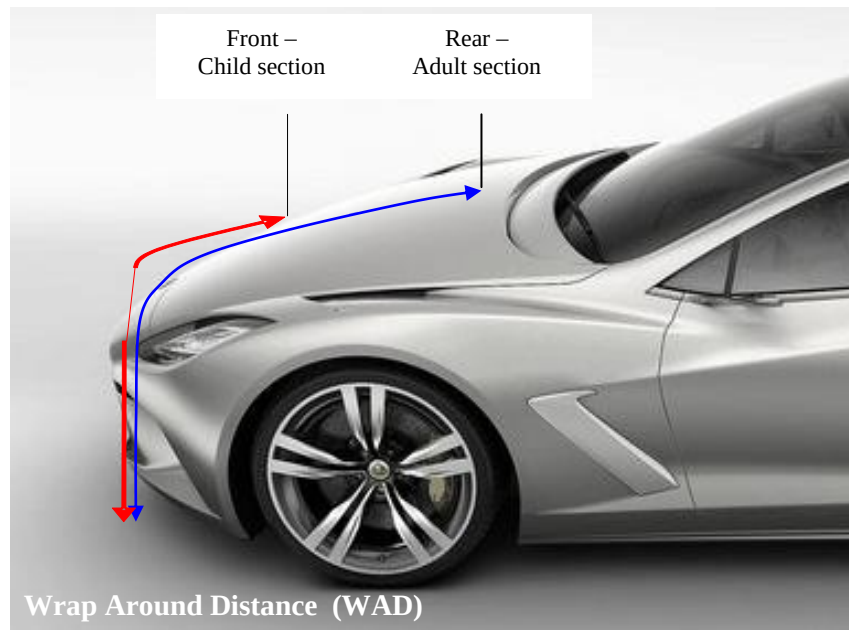


Figure 64 – Elite bonnet forward reference line schematic

The bonnet side reference lines are determined by traversing straight edge held at 45 degrees along the front of vehicle. The resulting line follows the intersection of edge and fender as shown in Figure 65.



Figure 65 – Elite bonnet side reference line schematic

The HI zone is defined by surface bounded by 1000mm wrap line and a line 82.5mm inwards from bonnet rear reference line and bonnet side reference line. This area is divided into adult and child zones by 1700mm WAD.

Figure 66 illustrates the resulting overall head impact test zone for the Elite exterior surface geometry (shown in grey). This forms the basis of where the homologation test head impactors will be fired to attain the resultant HIC value measurements.

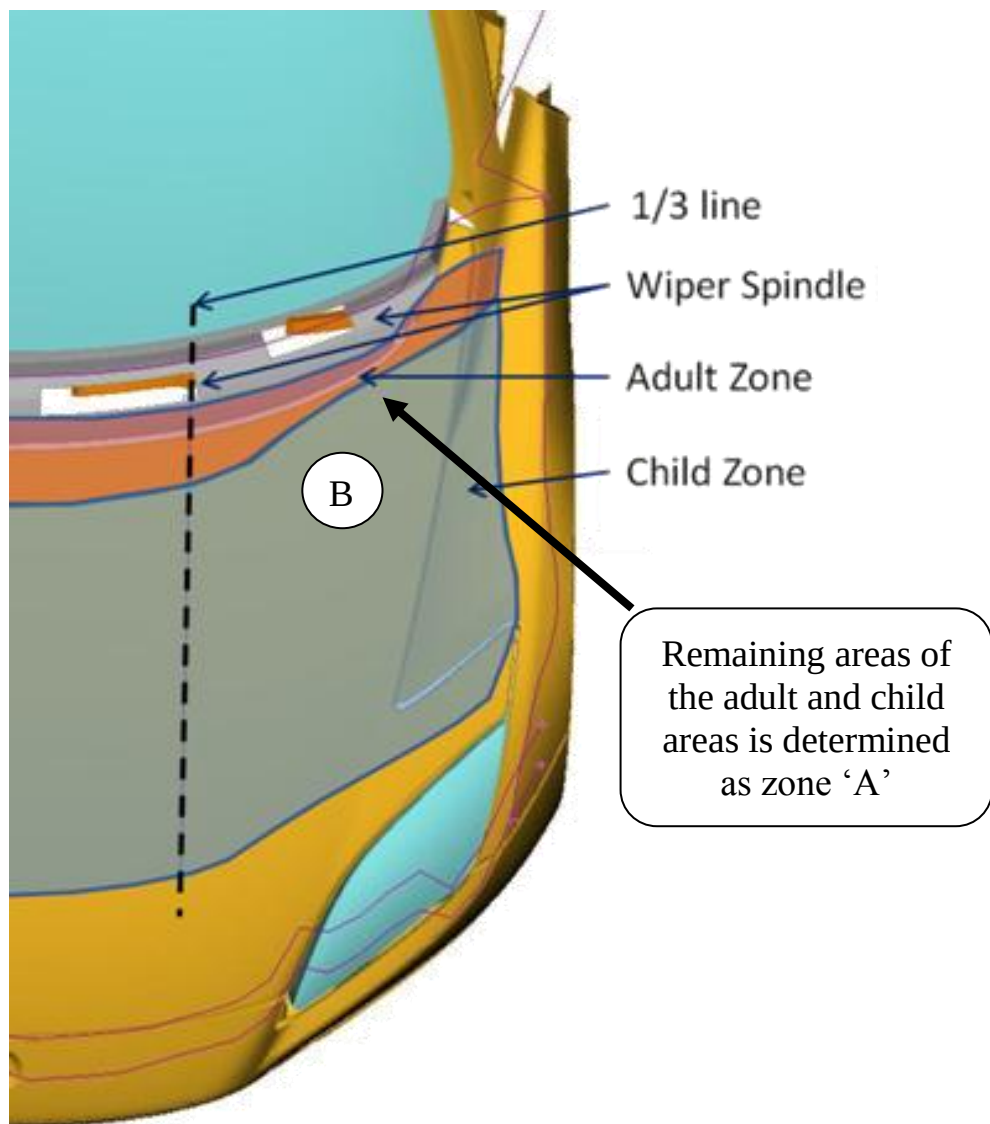


Figure 66 – Resulting EU2 head impact test zones for Elite (½ area shown)

Up to a third of this resulting test area can also be declared as zone B, where the HIC must be $\ll 1700$. The remaining two thirds of the test area make up zone A, where HIC must be $\ll 1000$ (30). The OEM can define to the governing certification authority zones A and B as required and zone B can be made up of several areas (Figure 66 also shows an example of where these A and B zones could be located).

Figure 67 summarises graphically the legal test compliance zones relating to PP EU2 for the Elite vehicle, as can be seen the child zone covers the majority of the bonnet surface resulting in a short extended adult zone at the base of the windscreen area (denoted by X) and towards to the rear of the front fender area where it meets the lower A pillar (denoted by Y), both areas being rigid parts of the vehicle structure.

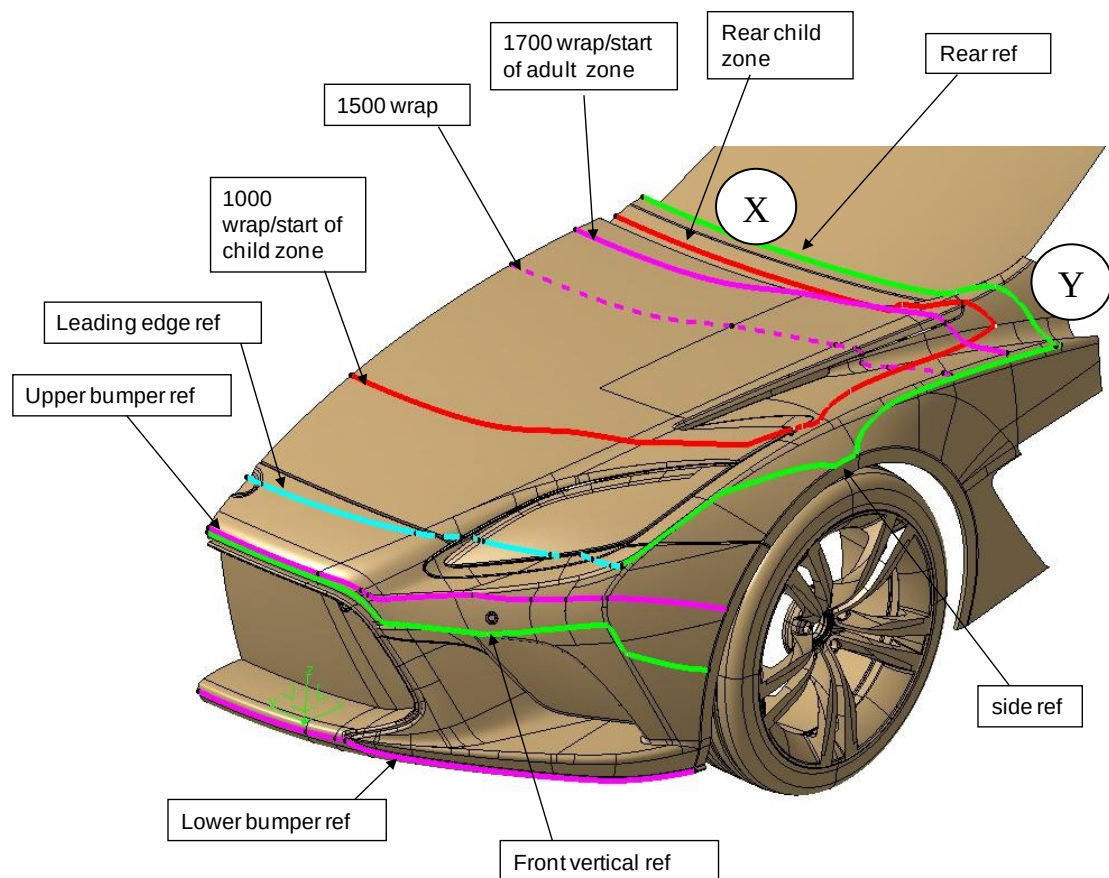


Figure 67 – Resulting legal test zones for PP EU2 for Elite concept vehicle

By plotting real world test data (as shown in Figure 38), it is possible to establish a feasible level of energy absorption efficiency for both the adult and child head test impactors. From this data target values for the maximum theoretical bonnet deformation space can be derived (shown in Figure 68).

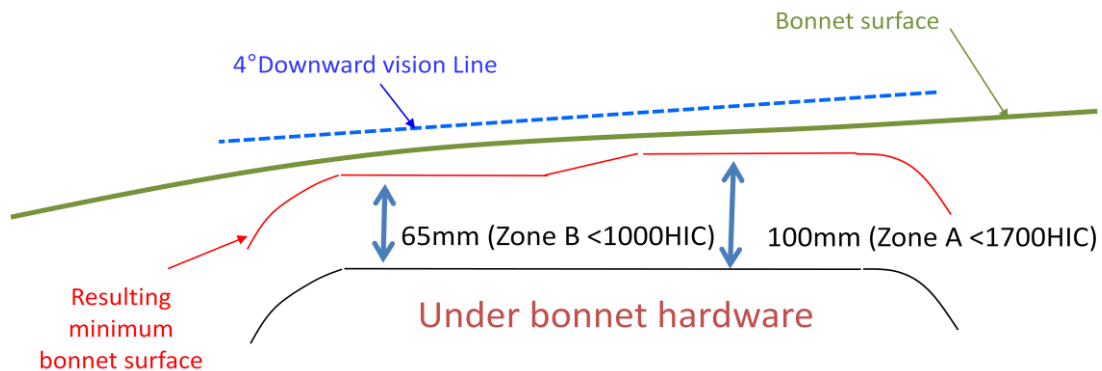


Figure 68 – Cross section of bonnet to hardware clearance Zone (33)

Table 3 shows the resultant HIC and associated under bonnet clearance targets for both A and B zones in order for a vehicle to meet PP EU2 requirements. Programme engineering target HIC values must also include a safety margin to account for test variations due to tolerances relating to impact speed, direction and location and also to consider for component geometry and material tolerances, this for the purposes of this thesis is assumed by Lotus to be 20%.

Under bonnet clearances for the child zone are the same as the adult zone (even though in theory the clearances will be less due to the reduced head-form mass).

Target	Legal Requirement	Variability allowance	Programme Engineering Target	Design clearance to Underbonnet Components (mm)
HIC Zone A	1000HIC	20%	800HIC	100
HIC Zone B	1700HIC	20%	1360HIC	65

Table 3 – Summary table of Lotus PP EU2 head impact targets

4.2 Vehicle Attribute Considerations

One of the primary objectives of this thesis is to identify how PP EU2 targets could be achieved for the Lotus Elite vehicle, it is also the aim of Lotus to design and develop a vehicle that also satisfies other attribute performance requirements and functional targets.

Lawrence et al (43) observed it is important that these load cases have to be carefully managed and balanced to ensure a compliant legal vehicle but, also that the vehicle performs in order to realise volume against its competitor set and obtain customer satisfaction (hence actual sales). These overlapping requirements are identified and discussed in the following section.

An overview of overall vehicle attributes and how they are affected by PP can be seen in Figure 69. The effect of PP is shown by a horizontal arrow indicating a positive effect, neutral or resulting in a 'trade' both being required due to a conflict being generated.

An example of target conflict is by altering the height of the bonnet surface to create additional deformation space to meet HIC requirements an increase in fuel consumption will result (due to an increase in frontal area and therefore drag coefficient).

Another further example of these conflicts is the constraint of legislative requirements, as the styled 'A' surface cannot be changed easily due to design and major tooling effects in terms of prohibitively high costs and part delivery lead-times, but mainly due to the fact that the Downward Vision Legislation (DVL) ECE R125 (25) angle is also fixed as changing the occupant position would also incur a substantial design and development cost.

Trades between attributes will be required and their resultant impact minimised in order to deliver a balanced vehicle to market to meet all customer and legislative requirements. These need to be quantified in terms of impact and qualified in terms of benefit.

As discussed PP test impact areas are defined by the outer geometry of the vehicle, countermeasures are therefore very much aesthetically-dependent and form an important part of the design definition process.

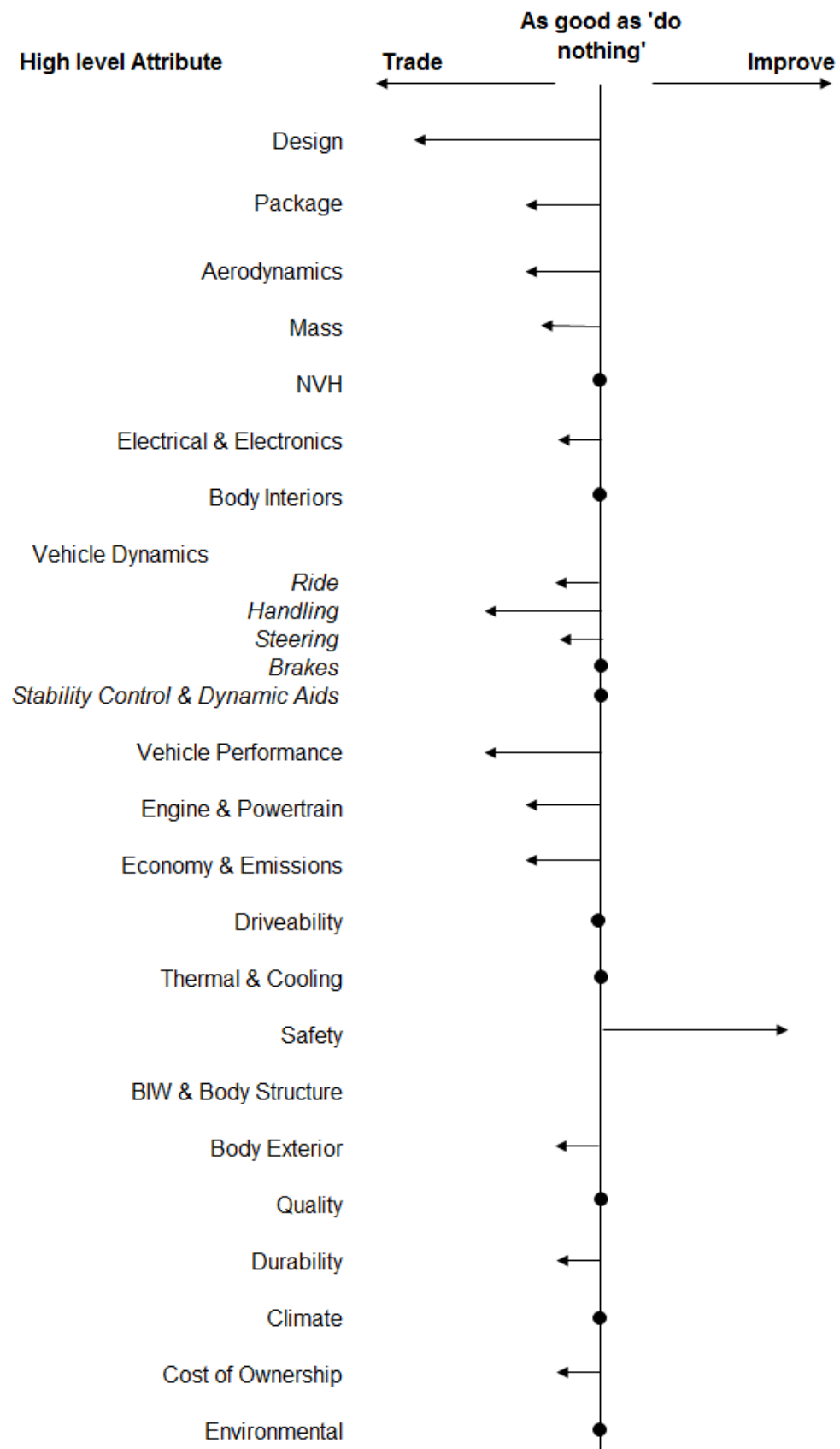


Figure 69 – Potential attribute effects of PP to core Elite programme

Further commercial examples of where attributes maybe in conflict and need further consideration and trade-off analysis and transactions made are as follows:

- **Commercial:**
 - Technical risk and delivery
 - Time to market?
 - Piece material cost
 - Tooling and development costs
 - Commonality
 - Cost of Ownership

Therefore is it important to incorporate a structured trade off process to ensure both internal and external facing attributes are prioritised and all stakeholders are engaged to maintain the compatibility of all targets.

5 Results and Findings

Having reviewed the requirements regarding head impact zone locations, under bonnet clearances and the associated PP EU2 test methods, an assessment of the current state of the Elite exterior surface and component package can now be made in order to formulate a future programme strategy to meet PP EU2 requirements.

As discussed in order to comply with the regulatory requirements for PP EU2 a certain amount of bonnet deflection is required, resulting in sufficient energy absorption and therefore reduces the potential pedestrian injury risk (i.e. a reduced HIC value). Hofinger et al (45) comments that bonnet deflection is primarily determined by vehicle geometry relating to the visible surface of the bonnet and rigid components underneath it, i.e. the physical gap needs to be sufficient to guarantee compliance.

5.1 Current State Elite

5.1.1 HI Clearances

With the target requirements for HIC and resultant clearances defined the current state of the Elite front end package and exterior surface geometry compliance to PP EU2 targets can now be derived and gaps identified. By understanding any resultant gaps in achieving these targets a strategy can be then developed based on available technology enablers to assess which ones can be best deployed and implemented to close these gaps.

As defined previously, under bonnet hard-point clearances required are 100mm in the Z plane for 1000HIC (2/3 of PP HI test area – zone A) and 65mm in Z for 1700HIC (1/3 of PP HI test area – zone B) as illustrated by Figure 70.

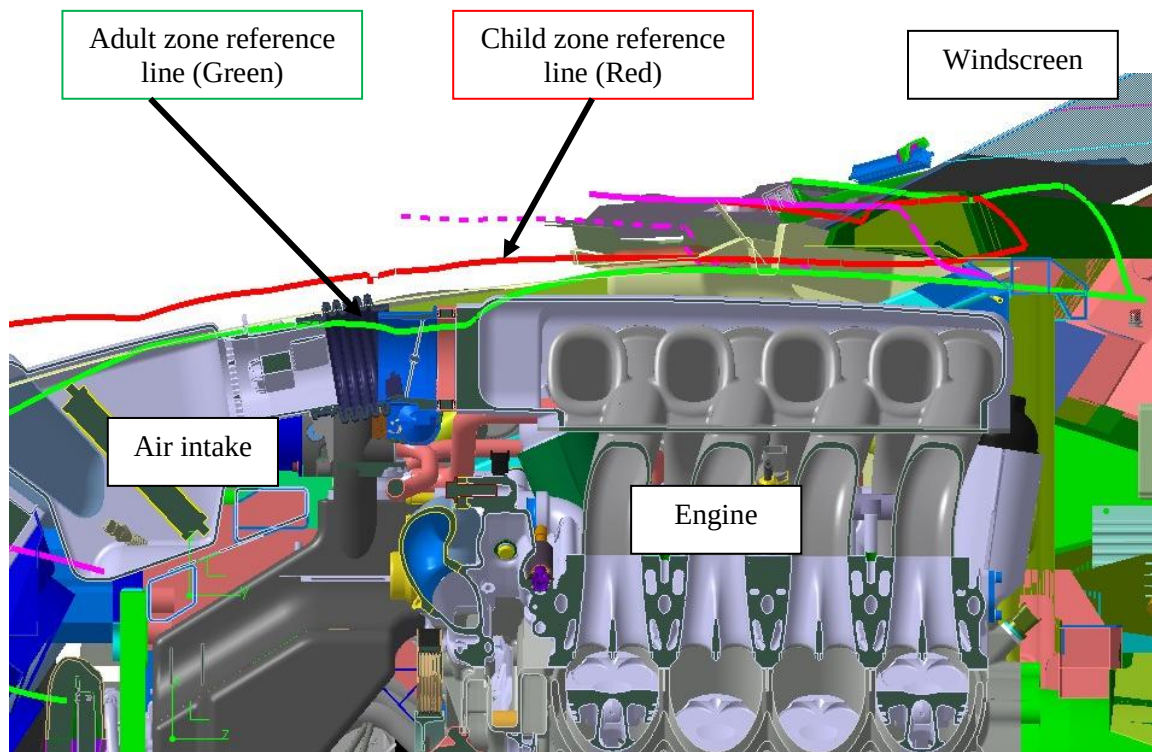


Figure 70 -Cross section of Elite bonnet PP EU2 HI target envelope

By utilising a Computer Aided Design (CAD) authoring tools such the Computer Aided Three-dimensional Interactive Application (CATIA), the Elite A-Surface can be cut to the perimeter of the required HI test zone and translated downwards in the Z plane by the required clearance requirements (in this case 100mm as the worst case, higher HIC target zone B). These new virtual surfaces enable infringements of the clearances required to meet programme HIC targets to be graphically identified.

Figure 71 shows the impact on the vehicle as a Y section view of the Elite bonnet and engine bay area and identifies clearance issues where components are shown above these virtual surface become hard-points for zone B requirements.

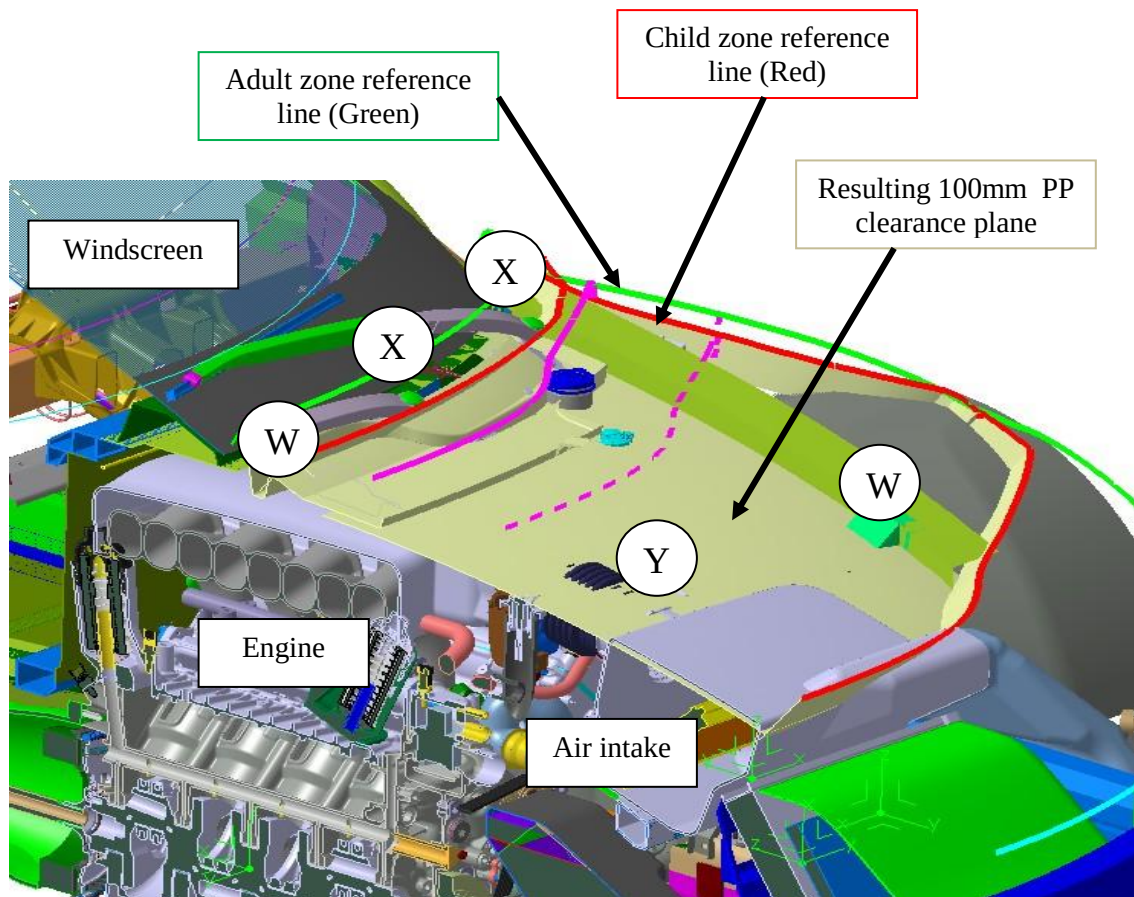


Figure 71 –100mm Z internal clearance target overlaid to Elite package and PP zones

Negative clearance issues i.e. ‘exposed’ components will therefore affect the resultant HIC values in these areas, possibly failing the test criteria. These ‘exposed’ areas are identified as structural body elements (W), the windscreen surround and wiper spindles (X) and air filter box (Y) and allow ‘hotspot’ priority components to be investigated.

Further analysis of this virtual test data showed that the areas (denoted by Z) around the lower windscreen surround, lower A pillar to fender interface and the wiper spindle (see Figure 72). These areas demonstrated significantly high intrusion levels through the 100mm zone B plane and would require specific focus to reengineer.

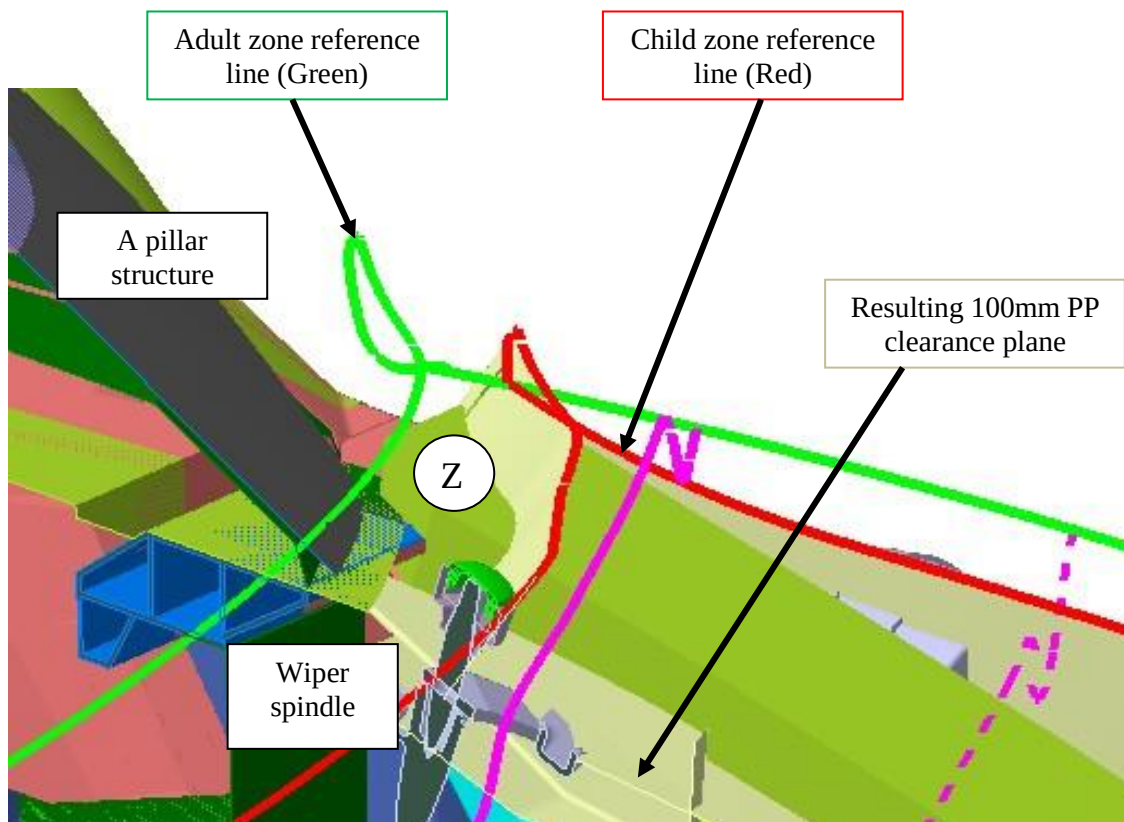


Figure 72 - Example of a high z intrusion area selected for CAE HIC analysis

5.1.2 HIC Status

The author employed historical internal data and a third party resource using a CAE derived mathematical model for the Elite CAD package to determine the virtual HIC results in the non-compliant clearance areas as indicated in Figure 71 using the PP EU2 targets defined in Table 3.

A PP EU2 CAE model of the Elite vehicle was created and a series of virtual testing was carried out. The image shown in Figure 73 shows the results of an initial report provided to the programme relating to PP EU2 HIC performance. This identified seven specific points on the bonnet that were virtually tested and where components protruded through the 100mm Z clearance plane.

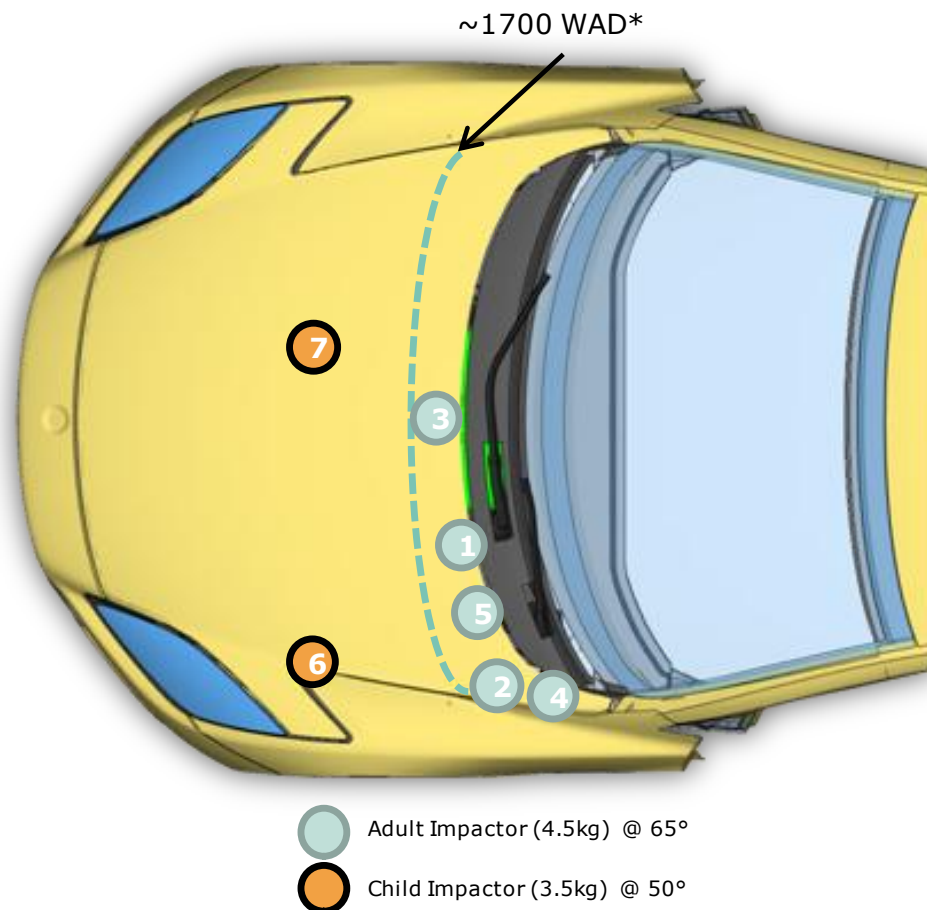


Figure 73 – Selected CAE PP HI points for Elite concept bonnet area

Table 4 shows the resultant CAE HIC results for the associated impact locations shown in Figure 73 indicating over PP EU2 target values in RED, warning values in AMBER and OK items in GREEN. As can be seen that two specific points were substantially exceeded the lower target HIC of 1000 (relating to zone A) by nearly 80%, both located in the adult test zone in the lower windscreen area of the vehicle.

	HIC
Impact Point	EPCA 0.1 Hood
1. Wiper a*	1790
2. Hinge	1115
3. Engine	368
4. A-Pillar base	1500
5. Wiper/Hinge	572
6. Wing Support	910
7. Engine	537

Table 4 – CAE derived HIC results for selected high impact points for Elite concept

This initial first pass HIC CAE analysis also indicated that the child zone captures the proposed bonnet hinge location and package, resulting in HIC close to 1000 at some points (as indicated in Figure 74 and are highlighted in Table 5).

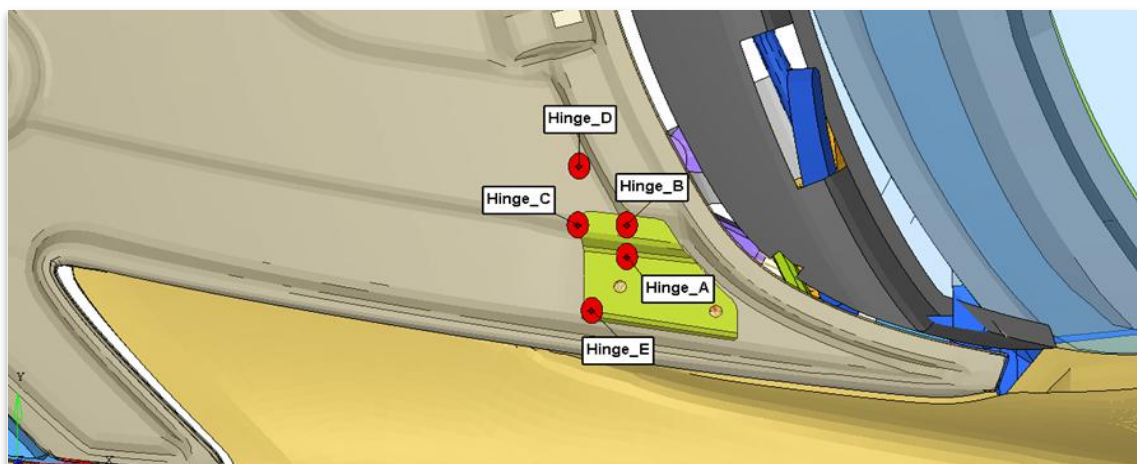


Figure 74 – CAE derived HIC results for Elite concept bonnet hinge area

	HPC
Impact Point	Hood (EPCAE 0.1)
1. Hinge A	837
1. Hinge B	812
1. Hinge C	878
1. Hinge D	654
1. Hinge E	850
2. Wing Support A	745
2. Wing Support B	917
2. Wing Support C	518

Table 5 - CAE derived HIC results for high scoring areas in the bonnet hinge area

Further observations from the initial results indicated that the child zone also starts rearward of the headlight (as shown in Figure 75) but, will still be further influenced by the head lamp stiffness and hood interaction with the head lamp so careful design consideration are required in this area..

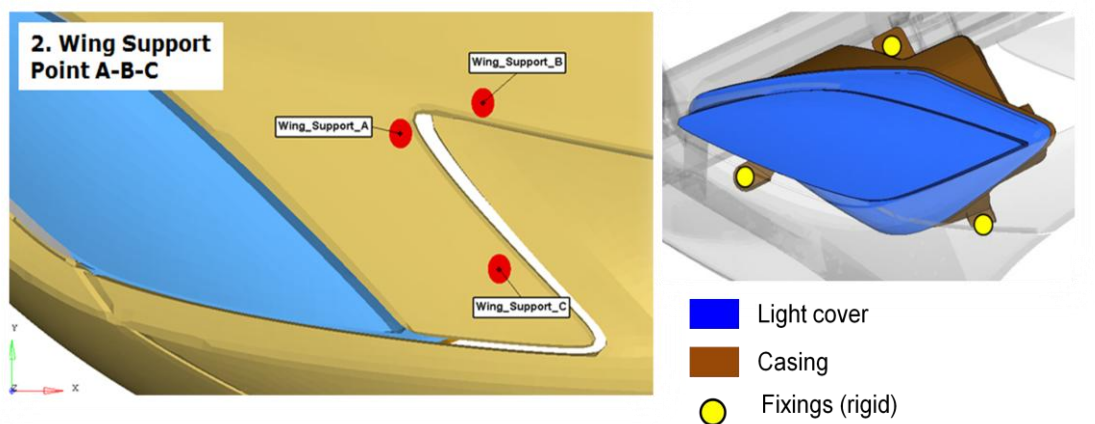


Figure 75 –CAE derived HIC results for Elite concept bonnet around headlamp area

The data set in Table 6 provides an initial landscape of the performance of the Lotus Elite showcar against PP EU2 requirements. These results are a single first step in many iterative design and test loops to further mature the engineering geometry and material characteristics to meets PP programme targets.

			Status		Requirement
			Points	%	
Child Zone	<1000 HPC	<800 HPC	9	100%	50%
	<1700 HPC	<1360 HPC	9	100%	100%
Adult Zone	<1000 HPC	<800 HPC	4	44%	NA
	<1700 HPC	<1360 HPC	8	89%	100%
Overall	<1000 HPC	<800 HPC	13	72%	66%
	<1700 HPC	<1360 HPC	17	94%	100%

Table 6 – First run CAE derived PP EU2 HIC status for Elite showcar concept

5.1.3 Current State Elite – Key Observations

These initial results create a firm foundation and waypoint marker going forward for the Elite programme. It provides a virtual HIC model landscape of the vehicle in order to identify key areas that require further analysis, repackaging, or a more fundamental physical package or material strategy change.

Key recommendation items for further consideration from these initial findings are:

- Wiper spindles need to be covered
- The rear of the bonnet needs to be stiffened to minimise intrusion.
- A pillar geometry
- Headlamp mounting strategy
- Fender to bonnet flange and relating interface shut-lines

These initial CAE results are encouraging but highlight issues that reinforce the finely balanced relationship between the frontal exterior surface and the package of under bonnet components to meet PP requirement and those of the aesthetics requirements of the customer.

From these results an assessment can be made of the alternative strategies identified with the literature review that could be deployed to mitigate these issues in achieving the required HIC engineering targets to comply with the PP EU2 legislative requirements.

6 Discussion and Future Work

As stated in the introduction after justifying the need for Lotus to develop future vehicles such as the Elite to meet PP EU2 HI requirements, a thorough review of current literature to determine a set of requirements and available technologies that deliver PP EU2 HI solutions was conducted.

It was also an objective of this thesis to assess the current status of the PP EU2 HI compliance for the Elite vehicle and identify gaps that may exist to meet the legislative targets. The validity of the existing legislative test regime was also reviewed.

The broader significance of findings and the consequences that stem from them are discussed in the form of how the legacy of this thesis can be integrated into the product (Lotus Elite), process or wider PP governance structures.

Any limitations to the thesis findings and how might these be addressed are proposed in a series of future work-streams and next steps.

6.1 Legacy Integration

6.1.1 Product - Alternative Engineering Architecture Solutions for Elite

Based on the existing and future technology enablers investigated in Chapter 5, this chapter proposes strategic design directions Elite could take to achieve PP EU2 legislation requirements and identifies benefits, risks and challenges for each proposed architecture.

6.1.1.1 Passive System Impact Assessment

In order to provide sufficient clearance to under bonnet hard-points within the PP EU2 clearance zones, major components as discussed in the literature review would need to be modified or substantially redesigned for the Elite vehicle (see Figure 76). This section details some of the proposed changes in more detail.

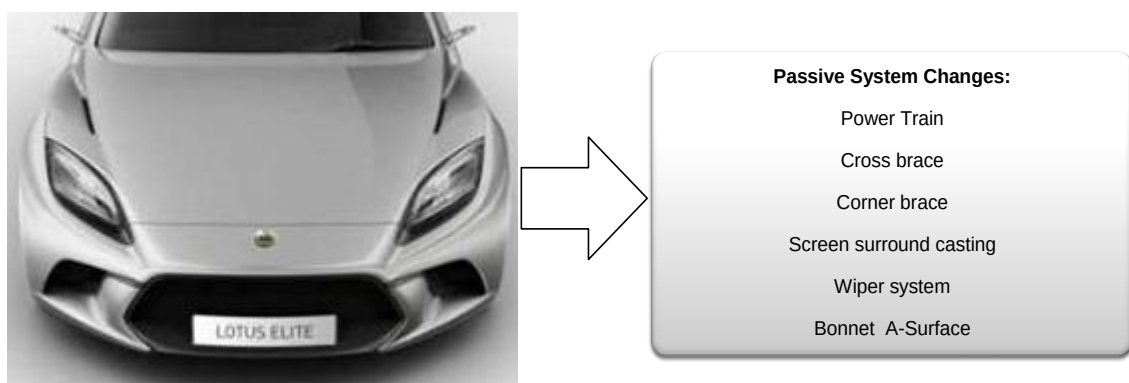


Figure 76 – Passive system changes required to concept Elite under bonnet components

6.1.1.2 Geometry changes

Incremental space must be created between HI surface of the bonnet and the associated under bonnet components to allow sufficient energy absorption. This can be carried out by the following packaging actions:

- Move the engine down in the Z axis
- Relocate parts to be outside the PP test zone and clearance requirements
- Redesign of structure components to manage energy more efficiently

6.1.1.3 Stiffness considerations:

In addition to geometric physical changes, the energy management of the bonnet and associated body in white structure needs to be optimised. By adopting design strategies such as those relating to the bonnet shock cone technology a more uniform stiffness distribution could be achieved.

Simple changes to the fender catwalk sections to reduce the local stiffness by the introduction of 'Z' type sections will contribute to create a more uniform level to reduce HIC levels at the bonnet / fender interface.

A key area to address due to the highest HIC values being demonstrated is the wiper spindle areas. Here it is not possible to move the parts due to other requirements (wiped area, engine location). By using deployable wiper spindles that break away under contact greatly lowers the levels of HIC, but careful management of this is required as to not deteriorate other attribute such as part integrity or functional performance.

6.1.1.4 Active System Impact Assessment

As discussed previously active PP systems are needed if the vehicle design or lack of under bonnet space conflicts with the requirement for a deformation zone. By lifting the bonnet promptly prior to the head impact event an active system can create the necessary space to absorb the impact energy to meet the HIC requirements.

The following sections identify the main contents of a proposed active PP system for the Lotus Elite, including the risks, challenges, constraints and the strategic objectives that the bonnet must meet. Figure 77 depicts the elements of a proposed active hinge deployable bonnet system for Elite.

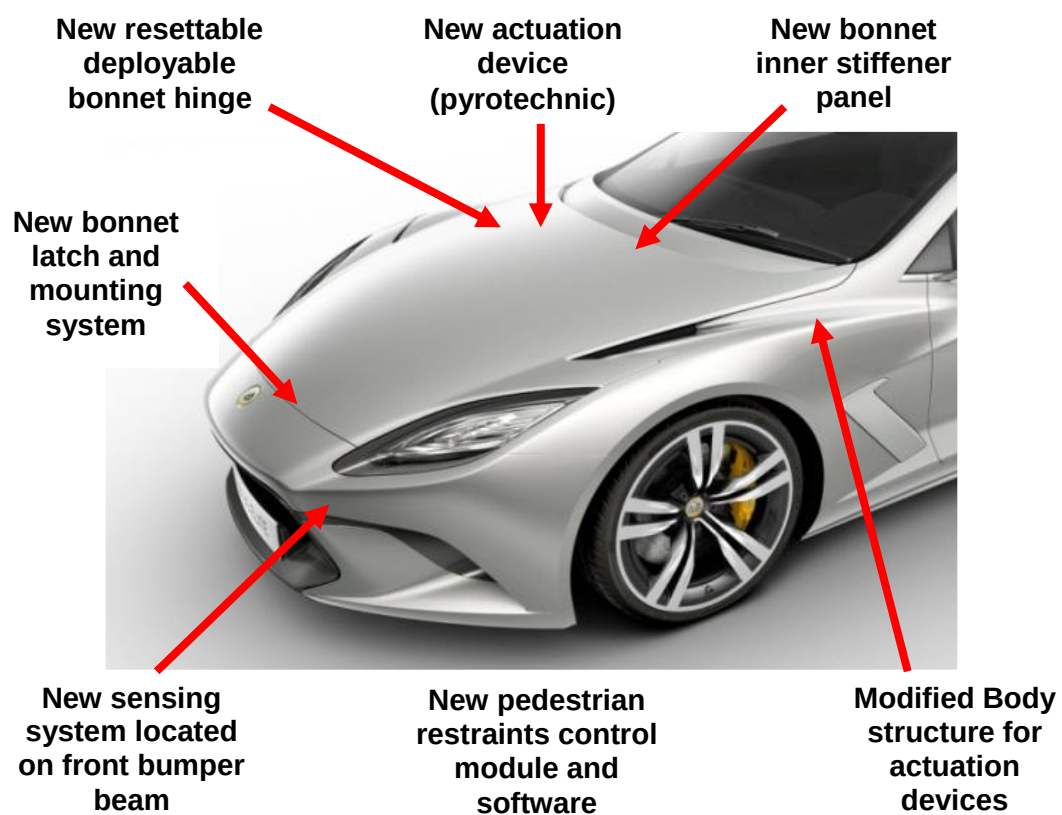


Figure 77 - Proposed active hinge deployed bonnet Elite PP system

By using a CAD authoring such as CATIA to manipulate the bonnet geometry it is possible to derive the opening angle and hence the bonnet rearward edge position in the Z axis to enable sufficient clearance to clear the under-bonnet components during a pedestrian head impact event.

From initial modelling based on existing Elite geometry this equated to 110mm of vertical Z displacement (see Figure 78). This can also be checked by rotating the A-surface clearance zone, again using CATIA and verifying that no unacceptable clearances exist in the required deployed position (not carried out).

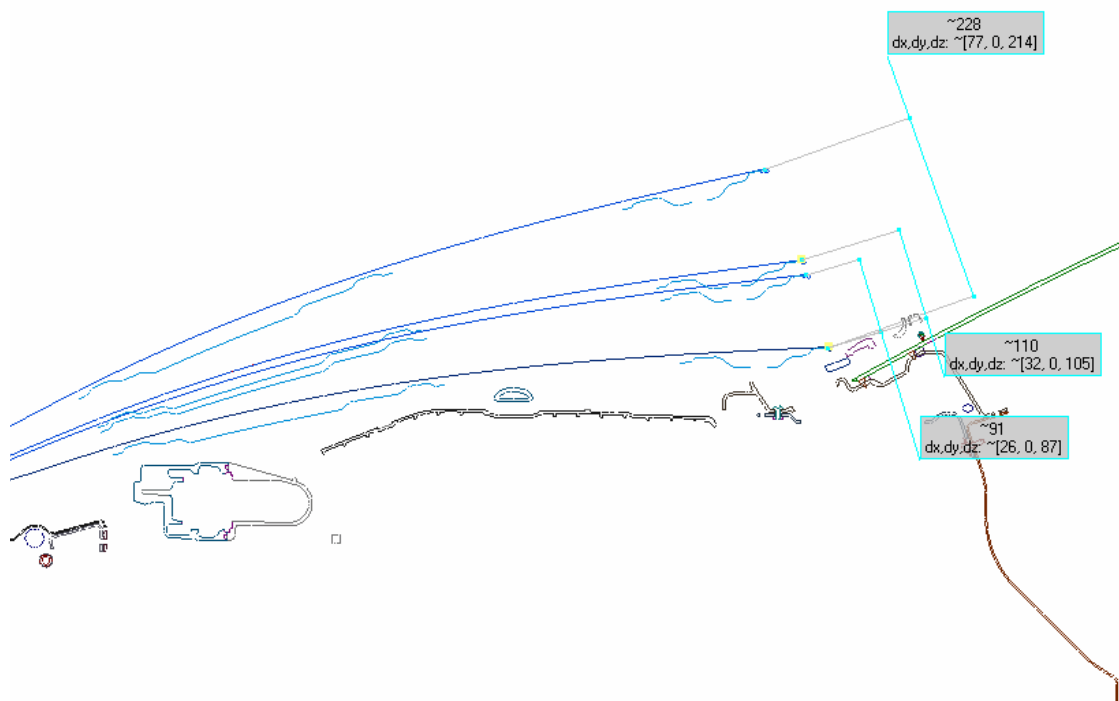


Figure 78 - Bonnet cross section showing lift requirements in Z at trailing edge

As previously discussed it is important to ensure that the maximum available clearance is achieved prior to the pedestrian impact as to reduce the injury severity. To determine how long the active bonnet will take to reach the fully deployed position, a series of MATHematical DYnamic MOdels (MADYMO)⁸ simulations were performed.

Using a range of humanoid dummies in multiple positions the minimum time between contact with vehicle front end and contact of the dummy head with the bonnet in deployed position could be determined, in this initial study 51ms (as shown in Figure 79).

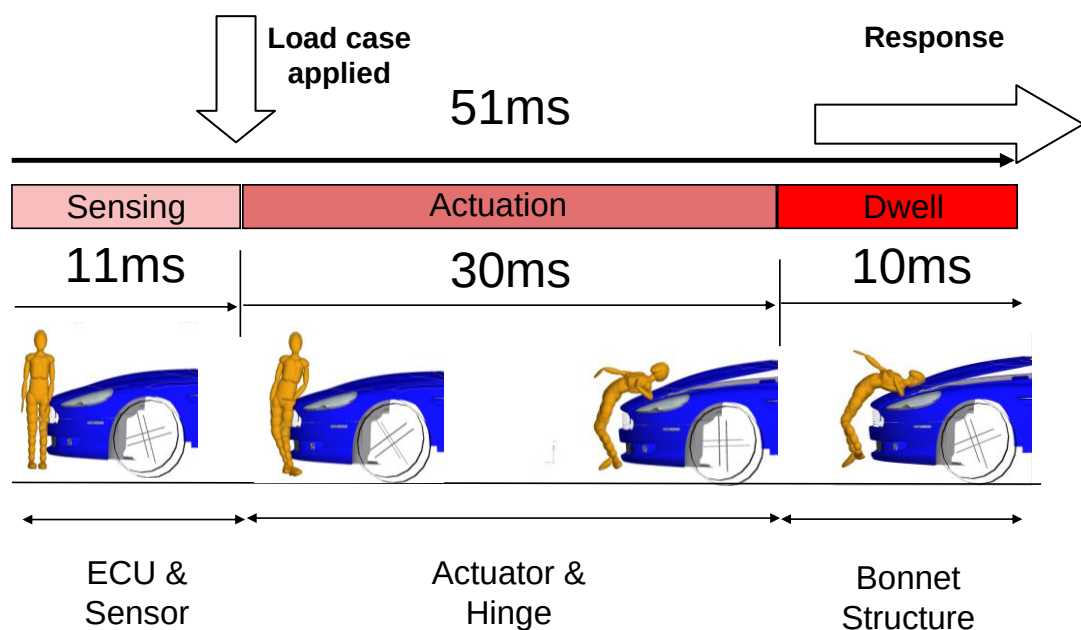


Figure 79– Timeframe for Elite hinge deployed bonnet PP countermeasure event

⁸ MADYMO is a software package developed by TASS (TNO - Automotive Safety Solutions), headquartered in the Netherlands. It is regarded as a leading design & analysis software package for occupant safety systems in the automotive industry.

6.1.2 Process

Based on the PP requirements and current state results a series of design guidelines can be created to support the design and engineering departments to meet PP target requirements more effectively.

- Integrate PP elements into the feasibility process and as part of attribute (Safety) requirements in NPI
- Create a design guidelines book and cascade to the styling and engineering packaging teams

By making PP visibility and associated targets and health status more transparent to the wider Lotus organisation, this critical part of delivering the vehicle can be managed.

The chosen method for assessing PP technologies takes elements from those described in the literature review and frames them within a relatively straightforward matrix (refer to Table 7) to evaluate and compare each technology strand against a set of attributes that are rated and ranked in priority order. These attributes cover both:

- Engineering – technical feasibility and target achievement
- Commercial feasibility and viability – business case, delivery

The technology assessment matrix in Table 7 is a simple format that consists of alternative engineering concepts along the top (left to right) and a series of requirements in the left-hand column. Information is obtained via literature, CAE or physical testing to allow all alternative solutions parameters to be collated.

Table 7 – Example of technology assessment matrix for PP active actuators

- Which ones could close gaps to targets, and by how much
- Which ones could be used
- How could they be integrated and in what timeframe
- Associated implementation effects, both negative and positive
- Indicative costs for both investment and material

110

and incorporates internal engineering areas such as Chassis, Body Structures and Electrical coupled with outward facing departments such as Service and Product Marketing. This approach allows a balanced, prioritised and complete customer viewpoint to be assessed.

Technology assessment Matrix PP active bonnet systems		Impact compared to standard static bonnet ++ / + / N / - / --	
Assessment attribute	Airbag deployed bonnet	Hinge deployed bonnet	
Coverage of Pedestrian Protection across bonnet area	++	+	
Vehicle package requirements	--	--	
Speed of deployment	+	++	
Cost effect - Piece cost	--	-	
Cost effect - Development and investment	--	-	
Delivery (time to market)	--	-	
Risk	---	-	
Reliability	-	--	

Table 8 –PP technology strategy assessment matrix for Lotus Elite

The recommendation of this thesis is for Lotus to adopt a passive PP technology strategy for the Elite programme, key factors resulting from the assessment are:

- Reduced development and material cost, lower technical risk, arguably faster delivery time
- Builds on strengths of the Lotus engineering and manufacturing organisation

6.1.3 Governance

Real world accident correlation work by Anderson et al, 2003 (46) indicated that the existing legal test procedures do not adequately provide protection to the windscreen area, where the highest percentage of fatal injuries occur. By extending the WAD distances up to 2100mm from the existing 1700mm, 60% of pedestrians (with severe head injuries from the car) are provided protection, while 2300mm would target almost 90%.

This also indicated that a countermeasure for the windscreen area extending 200mm further than current standards or ratings require would have a potential to protect approximately 50% more of the severely injured. However the larger WAD of 2100mm used by EuroNCAP in its testing may be a more reflective design parameter in order to reduce the effect of these ‘real world’ scenarios.

Therefore in relation to the existing PP EU2 legislative test regime as discussed the existing procedures may not accurately reflect ‘real word’ accident scenarios, which highlighted that injuries caused by the windscreen and ‘A’ pillar areas are not currently considered due to existing test zone construction parameters.

A review of numerous academic studies found that the correlation between injury severity rating between ‘real’ world accidents and the EuroNCAP test procedure was very good. This opens up the further question as to why the EuroNCAP test procedure is not used as the legislative requirement.

Hobbs (47) also concluded that perceptions of vehicle safety, including pedestrian safety may affect consumer choices but, it is unlikely these are less influential than perceptions on occupant safety. Hence programmes such as EuroNCAP although very informative, have to a certain extent a lesser effect on the final choice of the consumer on their vehicle purchase, particularly in the case of Lotus products where exterior style and handling performance are the overriding purchasing factors.

Even though HLS market vehicles such as the proposed Lotus Elite are not currently tested, this has huge significance as the consumer is missing potential vital information that they might use in the decision process to make a particular vehicle purchase transaction.

It is a recommendation of this thesis that agencies such as EuroNCAP should revisit their market segment test regime with a view to expanding it to include more fragmented HLS market segment lower volume vehicles manufacturers such as Porsche, Jaguar and Lotus.

Requirements arising from PP safety legislation and consumer ratings have an intense effect on existing and future vehicle development.

These requirements however create constraints and conflicts for vehicle attributes that require the strategic assessment and potential development of alternative materials and/or technology enablers to satisfy both internal customer design driven targets and external legislative requirements.

The design of a vehicle and the technology of the front end structure and package especially depend strongly on these governance measures and induce trade-off during the vehicle development process.

6.2 Future work and Next Steps

Having determined that PP EU2 HI requirements are to be met by future Lotus vehicles such as the Elite in order for Lotus to meet its business objectives and a current HI performance status derived, this section identifies future work and resulting next steps.

It was agreed within the NEP programme team and Lotus Engineering directors to progress a passive PP mitigation strategy for future Lotus vehicles. A CAE and associated physical test and validation plan was to be developed specifically to monitor and progress the passive technology work stream and integrated into the overall vehicle programme timing plan.

A further deep dive CAE analysis was to be conducted with a third party consultancy into the PP non-compliant areas of the vehicle to gain an improved resolution of the data set relating to clearances and resultant HIC values.

Benchmarking of passive PP vehicle systems is also recommended as part of this PP work stream to further understand the nature of how competitors are currently meeting the HIC requirements. This would be in the form of purchasing or renting competitor HLS market or passive PP technology vehicles, a thorough detailed engineering analysis via teardown or immersion events or physical HI testing would be conducted.

Lotus internal NPI process updates would be required to capture the process and associated deliverables (to also identify success criteria and ownership) relating to the PP work stream. This should also include a dedicated section to capture the design studio process regarding surface feasibility.

The limited view regarding legislative testing and its correlation to Sportscar HI test zone construction shows that a further body of work would be required to review this field of literature in more detail to ascertain the validity of the data. The question arises that sources of injury and its associated severity related to specific Sportcar geometry are not currently covered by legislative testing.

The performance of the Elite vehicle in relation to meeting EuroNCAP testing requirements and targets should be evaluated as reviewed literature indicates this is more correlated to ‘real-world’ accident data.

In summary it is fundamental for the development of safer vehicles that test procedures as a basis for safety rating are evaluated in a ‘real’ world environment in order to drive higher rating vehicles as a performance indicator the PP test is designed to simulate more severe crash events with a focus on long term injuries.

Lotus needs to be mindful that it is only a matter of time before its products are consumer tested within the EuroNCAP structure. A suggestion is that as in the historical case of Volvo, Lotus adds safety into its core attribute set and aims to be a visible leader in its market segment for pedestrian protection, utilising this fact in its future promotional brand material to capitalise on this potential key attribute.

7 Conclusions

The primary aim of this thesis was to conduct a strategic review of the alternative engineering concepts available to Lotus Elite to meet European Stage II PP legislative 2012 targets, specifically relating to head impact criteria utilising its proposed NEP architecture as a base. Through a review of current literature it was concluded that meeting PP EU2 guidelines is must for the Lotus Cars organisation as it enables the transformation strategy to profitability to be realised.

The thesis also reviewed the effects and mechanisms relating to injuries relating to pedestrian impacts and concluded that passenger cars and particularly the geometry and package of the front of a vehicle have a major contributing effect on the severity of these injuries.

- Data from real-world, car-to-pedestrian crashes can provide important knowledge on the fatality risks of pedestrian casualties.
- Injuries to head and neck are most frequently found in pedestrians, this can constitute to a serious threat to life or survival post hospitalisation.

A secondary aim was to review how these concepts could be evaluated from a technology implementation perspective for the Lotus Elite vehicle and how this process could be integrated into the Lotus business model to assess future technology applications.

Through CAE calculation based on existing vehicle package and geometry, test results showed that the current Elite concept proposal would not meet PP EU2 requirements,

However it was agreed within the NEP programme team and Lotus Cars Engineering directors to progress a passive PP mitigation strategy for the Lotus Elite. A CAE and associated physical test and validation plan is to be developed specifically to monitor and progress the passive technology work stream and integrated into the overall vehicle programme timing plan.

Literature reviews of technology enabling actions were researched, assessed and a series of passive based actions proposed that could potentially deliver a product design to meet these PP EU2 targets.

- Primary actions were to move components either out or below the HI defined clearance zone target areas
- Optimise shut-line management to avoid high stiffness areas.
- Investigate engine compartment mountings to enable parts to break away if impacted by a pedestrian to lower HIC levels

It was also recommended that HLS segment vehicles with package layouts and geometry such as the Elite may require further amended PP test procedures particularly in the windscreen and ‘A’ pillar area to replicate ‘real world’ sources of severe head injuries.

Lotus internal NPI process updates would be required to capture the process and associated deliverables (to also identify success criteria and ownership) relating to the PP work stream. This should also include a dedicated section to capture the design studio process regarding surface feasibility.

The limited view regarding legislative testing and its correlation to Sportscar HI test zone construction shows that a further body of work would be required to review this field of literature in more detail to ascertain the validity of the data. The question arises that sources of injury in the windscreen and 'A' pillar area to replicate 'real world' of severe head injuries and its associated severity related to the specific Sportcar geometry are not currently covered by legislative testing.

The performance of the Elite vehicle in relation to meeting EuroNCAP testing requirements and targets should be evaluated as reviewed literature indicates this is more correlated to 'real-world' accident data.

This thesis has achieved what it planned showing a structured approach to justifying the need for Lotus to adopt a PP mitigation strategy and to define what requirements and technology would need to be assessed to enable the deployment of the chosen passive strategy. Also it has highlighted that existing legislative test procedures and targets may need to be revisited to more accurately reflect 'real' world injury scenarios.

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