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In-depth Metropolitan Road Accident Database Development and Accident Analysis

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“Dovrei chiedere scusa a me stessa per aver creduto
di non essere abbastanza!”
Alda Merini

To Federica

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Preface

The research described in this manuscript is part of a doctoral track running from January 2010 to December 2014. The activity has been carried out at the Department of Industrial Engineering (DIEF) of the University of Florence, Italy.

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Abstract

It is inevitable that the members of our contemporary society must move and interact with road infrastructures and vehicles and this exposes them to the high risk of injuries and fatalities. Road safety recognizes this risk and the safety need for all road users involved in road traffic. Globally, motorcyclists, cyclists and pedestrians are the road users most vulnerable and in high-income countries these types of accidents happened principally in urban areas.

The aim of road safety is the elimination of fatal crashes and the reduction of serious injuries through the provision of a safe transport system that takes into account the possibility of human error and the vulnerability of people to serious injury.

The approach most commonly employed for this purpose is the study of real-world road accidents, and more in particular, the in-depth investigation of the accidents. Through these investigations it is possible to discover the response of the vehicles and infrastructure to the crash as well as human behaviour and the injury mechanisms.

This typology research is strongly recommended by the state-of-the-art of the road accident. The European Union recommends the development of new independent bodies as well as the use of comparable data sets. This is the leading motivation that defines the framework of the present research and the fact that there is a lack of in-depth data on road accidents coming from southern Europe compared to that of northern Europe.

Accordingly, the in-depth investigation methodology is defined and the in-depth road accident database is described. Overall, a collection of 80 road accidents which principally occurred in urban areas have been studied. The main injury mechanisms and injury causes by road user types are described. An accident causation factor analysis on pedestrian and powered two-wheel users has been carried out. Finally, the evaluation of the effectiveness of the pedestrian protection system has been performed based on real-world data and a pilot demonstration project has been completed.

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List of abbreviations

AAAM	Association for the Advancement of Automotive Medicine
ACEM	Association of European Motorcycle Manufacturers
ADAS	Advanced Driver Assistance Systems
AEB	Autonomous Emergency Braking
AIS	Abbreviated Injury Scale
ARU	Accident Research Unit
ASFA	The Federation of French Motorway and Toll Facility Companies
BASC	Birmingham Automotive Safety Centre
BASt	Federal Highway Research Institute Germany
BLE	Bonnet Leading Edge
CaDaS	Common accident Data Set
CARE	Community database of Accidents on the Roads in Europe
CCIS	Cooperative Crash Injury Study
CDC	Crash Deformation Classification
CDS	Crashworthiness Data System
CIREN	Crash Injury Research and Engineering Network
CREAM	Cognitive Reliability and Error Analysis Method
CT	Computer Tomography
CTL	Centro di Ricerca per il Trasporto e la Logistica
DaCoTA	Road safety Data Collection, Transfer and Analysis
DIEF	Department of Industrial Engineering
DREAM	Driving Reliability and Error Analysis Method
E	Effectiveness
EES	Energy Equivalent Speed
EMS	Emergency Medical System
EMTRAS	EMergency TRAuma Score
ER	Emergency Department
ERSO	European Road Safety Observatory
ETSC	European Transport Safety Council
Euro NCAP	European New car assessment Programme

FARS	Fatality Analysis Reporting System
FAT	Forschungsvereinigung Automobiltechnik e.V.
GCS	Glasgow Coma Scale
GES	General Estimates System
GIDAS	German In-Depth Accident Study
GOS	Glasgow Outcome Scale
HMI	Human Machine Interface
ICD10	International Statistical Classification of Diseases and Related Health Problems
ICU	Intensive Care Unit
IDB	European Injury Database
INRETS	The French National Institute for Transport and Safety Research
InSAFE	In-depth Study of road Accident in FlorencE
IRTAD	International Traffic Safety Data and Analysis Group
ISS	Injury Severity Score
ISTAT	Istituto Nazionale di Statistica
LAB	The Laboratory of Accidentology, Biomechanics and the Study of Human Behaviour
LOS	Length Of Stay
LRR	Long Radar Range
LTV	Light Truck Vehicles
MAIDS	Motorcycle Accident In-Depth Study
MAIS	Maximum Abbreviated Injury Scale
MHH	Medical University Hannover
MTO	Man, Technology, Organization
MV	Motor Vehicle
NASS	National Automotive Sampling System
NCSA	National Center for Statistics and Analysis
NFS	No Further Specification
NHTSA	National Highway Traffic Safety Administration
NISS	New Injury Severity Score
OD	Odds Ratio
OECD	Organisation for Economic Co-operation and Development
ONISR	Observatoire National Interministriel de la Securit Routire
OTS	On-The-Spot
PCC	Passenger Compartment Classification
PDOF	Principal Direction of Force
PENDANT	Pan-European Coordinated Accident and Injury Database
PPS	Pedestrian Protection System
PTW	Powered Two Wheeler
PV	Passenger Vehicle
RASIF	Road Accident Serious Injuries in Florence

RDMS	Relational Database Management Systems
RR	Relative Risk
SD	Standard Deviation
SETRA	Service d'etudes Techniques des Routes et Autoroutes
SNACS	SafetyNet Accident Causation System
SRR	Short Radar Range
STAIRS	Standardization of Accident and Injury Registration Systems
STRADA	Swedish Traffic Accident Data Acquisition
TBI	Traumatic Brain Injury
TDC	Truck Deformation Classification
TRL	Transport Research Laboratory Limited
TTC	Time To Collision
TTR	Tuscany Trauma Network
TUD	Technische Unversitt Dresden
VOSA	Vehicle Operations and Standards Agency
VRU	Vulnerable Road Users
VSRC	Vehicle Safety Research Centre
WAD	Whiplash Associated Disorder
WAD	Wrap Around Distance
WHO	World Health Organization

Chapter 1

Introduction

It is estimated that every year more than one million people die as a consequence of road traffic accidents. Worldwide, road traffic injuries are the eighth leading cause of death overall and the first leading cause of death for young people (15-29 years)[7]. The World Health Organization (WHO) forecasts, based on current trends, that by 2030 road deaths will become the fifth leading cause death in the world if action is not taken.

In 2012 road deaths of the EU27 experienced an average reduction of 9% (2661 casualties) compared to the previous year and produced a savings of 5 billion Euro according to ETSC estimates [8], but this is not sufficient. In 2012, 1078746 road accidents occurred that caused 1340000 injuries, of which 313000 people were seriously injured and 27700 killed.

Of the 27700 people killed, 21% were pedestrians, 7% cyclists and 18% motorcyclists. About 45% of road deaths are the so-called vulnerable road users.

In the high-income countries the urban areas represent the most dangerous environment for the vulnerable road users: almost half of all road deaths that occurred in these areas were pedestrians or cyclists. This was also confirmed by Siim Kallas, Vice-President of the EU Commission, who said[1]: ”Pedestrians and cyclists are facing the biggest risks in urban areas. And these risks are likely to increase rather than decrease with ever rising traffic volumes in our growing cities”.

Modern urban traffic is a complex, rapidly changing and dynamic system, where the task of the driver has gradually become more and more complicated.

For this reason it is crucial to obtain answers to how and why accidents occur to develop efficacious policy countermeasures and active safety systems to prevent road accidents. It is also essential to find the answers to how and why the injuries occurred, to understand the typology and severity of the injuries due to real-world accidents and to evaluate the impact of the new active and passive safety systems.

Accordingly, it is vitally important to have complete and detailed data on injuries as well as the link between police and hospital databases. While this connection is well known, it is not as satisfactorily widespread in Europe as it is in the US. Previous EU projects (STAIRS, MAIDS, SafetyNet, DaCoTA) have built the foundation for the development of a common EU methodology of gathering

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[1] Source: $http : //europa.eu/rapid/press - release_I P - 13 - 403_e n.htm$

road accident data, especially on an in-depth level.

At the end of 2010 the EU Commission established new safety targets for the decade 2011-2020. One of the objectives is to halve the number of road deaths compared to 2010. Another ambitious goal is to establish a road injury reduction target. Until now it has not been possible to set specific values due to the lack of a common definition of severe and minor injuries. For this purpose, the EU objective is to:

- establish a common definition of serious and minor injuries;
- establish a common EU-wide injury target to integrate into the 2010-2020 road safety guidelines;
- promote the exchange of best practices for emergency service response to accidents; and,
- promote a wide collection of data and an analysis of injuries.

These objectives highlight that the in-depth studies of road accidents, especially those which have caused serious injuries, are very crucial aspects for improving road safety. In detail, the understanding of which injuries are produced by specific accidents or impacts, as well as which injury mechanisms have generated those injuries and the consequent disabilities are essential components.

The seriously injured casualties provide us with a higher level of injury detail due to sophisticated examinations and diagnoses compared to those people who incur minor injuries or those who have died. In the majority of the EU countries the causes of death in road accidents are seldom investigated by means of autopsy. Rather they are commonly defined by visual examination, but this does not allow us to determine the specific cause of death.

In Europe the most popular road accident investigation groups are localized in the northern and western Europe: UK, Germany, Sweden, France, etc. While in southern Europe, Spain and Greece are the only countries who have teams that are carrying out this typology of research.

In Italy the research groups that have already conducted in-depth investigations of road accidents are the University of Pavia in the MAIDS project (1999-2000) and the CTL - La Sapienza University in the SafetyNet project (2003-2008) and in the DaCoTA project (2010-2012). But these accident collections were either concluded much before this study or they were conducted for only a short period of time.

These are the leading motivations that define the framework of the present research and the fact that there is a lack of in-depth data on road accidents coming from southern Europe compared to that of northern Europe.

The goal of the present research is to build a new in-depth investigation team and the relative database of road accidents, studying the dynamics of the events, the causation factors, the injury typologies, the severities and the disabilities. And then to start an in-depth investigation of road accidents with seriously injured people (ISS>15 or those who have suffered major trauma), focusing mainly in a specific metropolitan area.

Since 2012 this research has been co-financed by the EU commission and by the University of Florence within the RASIF[2] (Road Accident Serious Injuries in Florence) project.

In Chapters 2 and 3 the state-of-the-art for the road accident database and a review of road traffic injuries subdivided by road users are presented.

In Chapter 4 the methodology of the InSAFE research and the database are described.

Chapter 5 shows the results of the pilot analysis of 80 serious road accidents which occurred in an urban area.

Chapter 6 presents the analysis of the road accident causation of the previous sample. The DREAM method is the methodology used for this purpose.

In Chapter 7 focusing on pedestrian accidents, an evaluation of the effectiveness of the AEB Protection System based on the real-world accident scenario is presented.

Finally, the conclusion and recommendations are drawn.

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[2] Grant agreement: MOVE/C4/SUB/2011-294/SI2.625719

Chapter 2

State-of-the-art of road accident databases

2.1 Introduction

The State-of-the-art of the real world road accidents is principally made up of four different aspects. There are studies that aim to develop road accident collection strategies, the assessment of the dynamics of the main crash parameters and injury severity. There are also studies that aim to understand the accident causations and to analyze the phenomenon and its magnitudes.

Consequently, the state-of-the-art will be divided into three separate sections: in the first, national and in depth real world road accident databases will be presented; in the second, a statistical analysis overview will be described; and, in the final section the main injuries and severities for the types of road accidents will be shown.

2.2 Road accident collection systems

The real world traffic accident is the interaction between human, vehicle and traffic environment, an organizational triad. A mistaken communication between them could produce a critical event and thus a possible road accident. The study of real world accidents and their main causation factors is crucial to prevent similar events from occurring in the future.

Accident analysis is a complex analysis that permits us to improve our knowledge of the causation factors, accident frequencies, the dynamics followed in pre-crash, crash and post-crash phases and both the injury outcomes and severity. Naturally, the aim of each accident analysis is dependent upon the methodologies of data gathering in terms of number and typology of recorded accidents, parameters and accuracy of the information.

All data is collected in specific databases that can diverge from each other according to their aims. For example, some databases will be focused on the injury mechanisms, others on the crash dynamics experienced by vehicles involved or on the most general information regarding to the accident.

As a result, the real world accident databases are divided into two macro categories: *National* and *In-depth.*

2.2.1 National accident databases

The national road accident databases are the collection systems of road accident's that are occurred on the national level on a continuing basis. One of the main goals of these datasets is the evaluation of the national road safety level. The managing authorities of these databases are generally public institutions, and the information is derived from police reports.

The gathering method is usually similar among them: all road accidents with casualties or deaths that have occurred on the national roadways. Some of the principal common features of these systems are the collection of evidence that concerns the environment (e.g. localization, traffic signs, weather), vehicles (e.g. type, model, vehicle identification number) and persons involved (demographic data, alcohol usage, vehicle position, pedestrian movement).

All this information is generally collected in order to determine judicial responsibilities rather than to clarify the events and circumstances that have led to the accident. Therefore these types of databases are not adequate for the in-depth analysis of the phenomenon, although they are very important tools to provide a broader vision of road safety on the national net. This can also be easily extended to a global level: European or Worldwide.

Some of the main European datasets are the ISTAT in Italy, the STATS19 in the UK, the StBA in Germany, The National Database of Injury Traffic Accidents (Fichier National des Accidents Corporels de la Circulation Routire) in France and the STRADA in Sweden. In the U.S. the most famous national road accident database is the National Automotive Sampling System (NASS) managed by the National Highway and Traffic Safety Administration (NHTSA).

ISTAT database

ISTAT is the Italian national road accident database developed and maintained by the National Institute of Statistics. The database contains information about all traffic accidents that have occurred on the national road net, and have caused injuries or deaths (by the 30th day) and have been documented by police and/or military corps. The data gathering is based on a composite organisational model and it is realised by a group of public corporations and local organisations. ISTAT annually produces official statistics on road accidents. Provisional data becomes definitive 300 days from the start of data gathering. Data is available in aggregate form; raw data can only be requested by research institutes [9].

STATS19 database

The STATS19 is the UK national system of road accident sampling by the police and which is based on the main UK crash statistics. All road accidents are included in this database involving human death or personal injury occurring both on or off the Highway; one or more vehicles are involved; and are notified to the police within 30 days from the data of the accident. These statistics provide data about the circumstances of personal injury road accidents, including the types of vehicles involved, the consequential casualties and the main contributing factors that directly led to the impact [10].

StBA database

The Federal Statistical Office (StBA) is the German managing authority of traffic accident data collected by the police. Generally, aggregate data is available to the public and is published in annual reports by the StBA. The recording criterion is at least one tow-away vehicle as a result of the accident. In depth disaggregated data is available only to organisations that meet the strict requirements of the law on data protection [11].

French database

The "Fichier National des Accidents Corporels de la Circulation Routire" is the French national database of traffic injury accidents. The database is co-administered by SETRA (Service d'tudes Techniques des Routes et Autoroutes) and ONISR (Observatoire National Interministriel de la Scurit Routire) and is based on the data collected by the police authority and the Gendarmerie. Also in this case the data is widely used by the Transportation Ministry as well as transport safety research oriented organisations like INRETS (the French National Institute for Transport and Safety Research), ASFA (The Federation of French Motorway and Toll Facility Companies) and LAB (the Laboratory of Accidentology, Biomechanics and the Study of Human Behaviour) [12].

STRADA database

STRADA (Swedish Traffic Accident Data Acquisition) is the Swedish national collection system on injuries and accidents. STRADA is the most well structured national database combing information from the police and hospitals. The combined data make this method very different from earlier methods of registration of injuries and accidents in the road transport system. Consequently, a better image of the accident is obtained, increasing the knowledge of road traffic injuries and accidents. This combination has also decreased the number of unrecorded cases, since the police have limited knowledge of some road accidents. From 2009 the Swedish Transport Agency is the authority responsible for STRADA [13].

CARE database

The Community database of Accidents on the Roads in Europe (CARE) is the centralised European database on road accidents which result in death or injury across the EU [14] [15]. The European Community is the owner of CARE. Care database was created 1993, with the Council Decision 93/704/EC and after a five year feasibility studies'. Since 1999 the databank has harmonised allowing international comparisons and the exchange of information. It is still active today and annually releases statistical reports on road safety.

CARE's key objectives are the identification and quantification of road safety problems, the evaluation of the efficiency of road safety measures and the analyses to determine the relevance of Community actions and to facilitate the exchange of experience and data in this field. The CARE system units non-confidential data from across the EU Member States into one central database. It has developed a framework of transformation rules from an analysis of the original structure and definitions to ensure the compatibility of data variables and values. Harmonising the data contained inside the database allows international comparisons and the exchange of experiences.

A significant characteristic of CARE is the high level of disaggregation of the data, since for individual accidents detailed information is available in the national records.

NASS - National Automotive Sampling System

The National Automotive Sampling System (NASS), is managed by the National Highway and Traffic Safety Administration (NHTSA), and is part of the U.S. Department of Transportation.

NASS has detailed data on a representative random sampling of minor, serious, and fatal crashes involving passenger cars, pickup trucks, vans, large trucks, motorcycles, and pedestrian crashes.

NASS has two categories of data gathering: the Crashworthiness Data System (CDS) and the General Estimates System (GES). Both systems select cases from police accident reports at police agencies within randomly selected areas of the country. These areas are counties and major cities that represent all areas of the United States [16].

2.2.2 In-depth accident databases

In a different way from earlier collection, the in depth road accident databases are systems designed to answer more specific questions. Consequently, these kinds of databases diverge from the previous in two main aspects: the sample dimension and the detailed level of the sample investigated.

The national databases gather the totality of the road accidents that have occurred in a single state. The in depth databases focus attention on a smaller and more specific sample.

This data, also called microscopic data, is usually collected by independent research teams that gather information concerning the accident, vehicle, road user, injuries, interview information, road infrastructure and scene information, accident reconstructions and accident causation analysis, all of which is analysed by experienced investigators.

One of the most important benefits of this data source is the high level of detail known about each accident, and how this can be correlated to various types of outcome. The results of these analyses are used to evaluate and identify the real status of road safety, improve vehicle design, but also to develop and test new vehicle technology or human machine interface devices based on accident scenarios.

The data gathering is generally conducted by an independent investigation team to ensure an impartial investigation without focusing on assigning blame.

In this chapter some of the major European and U.S. accident databases or projects will be reviewed to identify the following information:

- owner of the database;
- number of accidents available;
- area of interest;
- criteria for sampling the accidents;
- competencies of the collecting team members;
- gathering methods;
- material available for each accident;
- number of analysed parameters;
- characteristics.

STAIRS project

Standardization of Accident and Injury Registration Systems (STAIRS) was the first EU project harmonizing of the European in depth road accident databases, both for road accident causation and severity crash injuries. Between 1996 and 1999, this project provided the core framework for all successive Pan-European crash injury studies [17].

The project analysed existing real-life crash studies carried out by independent groups in the UK (CCIS), France (INRETS) and Germany (MHU). The main objectives of project were to:

- produce recommendations for: specification of the core data, data collection methods and procedures, data quality assurance, validation of harmonisation protocols, confidentiality of data and ethical issues;

- identify steps for the implementation of a harmonised database.

The study concentrates on the systems and data necessary for the evaluation of injury prevention measures, not accident prevention measures. The purpose of the protocol was validated using a small number of existing cases in the UK, France and Germany.

In conclusion, for an in-depth injury database, STAIRS provides the following macro selection of data:

- a general data module;
- a vehicle data module (for each type of vehicle);
- pre- and post-crash data;
- seating data;
- restraints (a description of the action and deployment of safety systems);
- child restraints (type, position and performance);
- intrusion (description of the interior crush);
- description of the casualty (all types of road users);
- a pedestrian data module;
- description of the injuries.

PENDANT project

Pan-European Coordinated Accident and Injury Database (PENDANT) was a project co-financed by the EU and conducted in eight EU countries from 2003 to 2006. This project was successive to the STAIRS project, and was based on a protocol developed in the STAIRS programme with additional fields that take into account technological developments (e.g. accident causation events).

Some of the aims of the project were the specification of core and add-on data elements covering both active and passive safety, the study of a new approach to estimate casualty reductions applicable to both primary and secondary safety countermeasure, and the harmonization of the procedures for assessing injury severity using threat to life measures.

The project provided a database that contained in depth crash and injury data relating to over 1100 injured car occupants and pedestrians with a medium level of detail (approximately 400 fields). The in depth crash injury data collection was conducted in northern, central and southern European areas to give a range of accident conditions that was as representative as possible [18] [19]. The sample was composed mainly of vehicle passengers and pedestrians with at least 20% of the injured with AIS3+ injuries.

All the data collection team was trained on main accident investigation aspects:

- on-scene crash investigation techniques;
- retrospective crash investigation procedures and techniques;
- introduction to the Principle Direction of Force (PDOF) and the Collision Severity (Delta V);
- Collision Deformation Classification (CDC);
- injury Scaling;
- injury correlations.

CCIS

Cooperative Crash Injury Study (CCIS) is a project supported by the U.K. Department for Transport and the motor industry. It has been in operation in the cities of Birmingham and Loughborough and their rural areas since 1983.

The teams of investigators are Birmingham Automotive Safety Centre (BASC) at the University of Birmingham, Vehicle Safety Research Centre (VSRC) at Loughborough University and the Vehicle Operations and Standards Agency (VOSA) from various locations in England.

The main objectives of CCIS are to conduct in-depth accident analysis of vehicles to provide information as to how people are injured in road traffic accidents in the UK. Retrospective examinations of crashed vehicles correlated with injuries to their occupants are used to determine how people are injured. The inclusion criteria are:

- crash occurred within a predefined geographic region;
- the vehicle must be less than 7 years old;
- the vehicle must be towed from the scene; and,
- the vehicle must have at least one injured occupant.

The results of the vehicle investigations are then used to populate an anonymous electronic database, which provides a unique view of how car structures and secondary safety systems affect car occupant injuries. The database has approximately 800 variables per case collected [20] [21].

GIDAS

German In-Depth Accident Study (GIDAS) is one of the largest accident studies in Germany. Working in cooperation with the Bundesanstalt fr Straenwesen BASt (Federal Highway Research Institute Germany), Forschungsvereinigung Automobiltechnik e.V. FAT (The Research Association of Automotive Technology), Medical University Hannover (MHH) and the Technische Unversitt Dresden (TUD).

The main goal is to provide in-depth accident and injury data of traffic accidents representative for the whole of Germany. Data for the GIDAS project has been collected in Hannover and Dresden. The GIDAS project was started in July, 1999, but in 1973 BASt began an in depth investigation with the Accident Research Unit (ARU) at the MHU. The headquarters of police, rescue services and fire departments report all accidents to the GIDAS team. Based on a sample plan they decide which accidents will be collected and recorded in detail.

The on-scene investigation is done by professional and semi-professional team members. The team consists of specially trained students, supported by professional accident investigators (two technicians, a doctor and a coordinator). In total between 500 and 3000 details per accident are collected and stored in the GIDAS Database.

The main data collected are pertains to: environmental conditions; road design; accident details and cause; driving and collision speed; Delta-V and Energy Equivalent Speed (EES); vehicle deformation; impact contact points for passenger or pedestrians and information relating to the people involved (e.g., weight, height, treatments and injuries) [22] [23].

MAIDS

Motorcycle Accident In-Depth Study (MAIDS) is a database on Powered Two Wheeler (PTW) accidents created by the Association of European Motorcycle Manufacturers (ACEM), with support of the European Commission and other partners.

The study was conducted during the period 1999-2000 in five sampling areas located in France, Germany, Netherlands, Spain and Italy. During these two years data on 921 accidents with motorcycles and mopeds was collected in random samplings among those involving injured people. MAIDS also include a case-control group of 923 cases of non-accidents as a comparison to the real data.

All the accidents were investigated in detail following the common methodology for "*on-scene in-depth motorcycle accident investigations*" previously developed by the Organisation for Economic Co-operation and Development (OECD) and updated in 2008 [24].

	Cases	Controls	Total
University of Pavia (Italy)	200	200	400
TNO (Netherlands)	200	200	400
REGES (Spain)	121	123	244
ARU-MUH (Germany)	250	250	500
CEESAR (France)	150	150	300
Total	921	923	1844

Figure 2.1: MAIDS - Motorcycle Accident In-Depth Study

Figure 2.2: On-The-Spot UK investigation team

Using on-scene investigations, accident reconstructions and interviews, MAIDS recorded 1721 variables for each accident. These parameters was relative to environment, vehicle technical specifications and crash parameters, human factors, injuries and accident contributing factors [25].

OTS

The On-The-Spot (OTS) is a database created by Department for Transport and the Highway Agency in the UK. The database contains about 4524 accidents investigated from June, 2000 to October, 2009. All road users types are included.

The methodology utilized conformed to the STAIRS European accident investigation protocols. For each case more than 2000 possible variables were collected, including accident scene, path, vehicle, human and injury (severity, location and treatment).

The road accidents were collected in two different locations and by two different groups. The first group was the Vehicle Safety Research Centre (VSRC) working in the Nottinghamshire region (Midlands). The second one was Transport Research Laboratory Limited (TRL) located in the Thames Valley region (South-East England).

The teams were responsible for collecting the data at the scene of the accidents when they occurred, and post-accident liaison with emergency services, hospitals and local authorities.

The teams of experts had shifts which covered seven days of the week and 24 hours of the day. All road traffic accidents notified from the police during the periods of operation of the teams were eligible to be include in the study [26].

SafetyNet

SafetyNet was an Integrated Project funded under the Sixth Framework Research Programme. It had 21 Partners from 18 countries and had the goal of developing the framework for the European Road Safety Observatory.

The SafetyNet activities were divided across three main work areas dealing with macroscopic data, in-depth data and data application. This project produced two in depth databases: a fatal accident database with 1296 fatal accidents which occurred between 2003 and 2004; secondly, an accident causation database with 1006 accidents investigated between 2005 and 2008. All investigations were conducted using a common methodology and collected key variables pertaining to the accident vehicle, road user information, injury data, causation analysis and highway and road infrastructure features [27].

DaCoTA

The DaCoTA (Road safety Data Collection, Transfer and Analysis) research project arose from the previous main EU projects (e.g. STAIRS, PENDANT, SafetyNet). The project, co-financed by the EU, had the following leading research areas:

- developing the link between the evidence base and new road safety policies;
- establishing a Pan-European Accident Investigation Network;
- bringing a wide variety of data together for users to manipulate;
- predicting accident trends, presenting data to policy-makers;
- intelligent safety system evaluation; and,
- naturalistic driving observations.

In particular, the DaCoTA work package-2's goal was to harmonize in depth crash investigation protocols and identify and train crash investigation teams in the EU countries.

DaCoTA created a network of 22 investigating teams based in 19 European countries (not all still active) (see Figure 2.3 and Table 2.1), and also an depth database.

This database is based on web application, and is able to record approximately 1500 variables for each accident collected. Only some core-variables are mandatory, the others need not necessarily be filled in each case. These latter variables are completed depending on the accident scenario and the individual team's capabilities.

In terms of accidents collected, the project was an in-depth on-scene pilot research. In total only 77 cases were investigated and entered into the database. On these, 46 were on-scene investigations while a smaller number of cases (31) were investigated retrospectively [28] [29] [30].

FARS

Fatality Analysis Reporting System (FARS) was conceived by the National Center for Statistics and Analysis (NCSA) of the National Highway Traffic Safety

Figure 2.3: DACOTA network, EU countries and teams

Table 2.1: DACOTA network, EU countries and team

EU - Country	Investigation Team
Austria	KFV
Denmark	VD
France	IFSTTAR, LAB
Iceland	ICE
The Netherlands	SWOV
Slovenia	STSA
United Kinhdom	TSRC
Belgium	IBSR
Estonia	EST
Germany	MUH
Italy	CTL
Norway	NPRA
Spain	CIDAUT, INSIA, IDIADA
Czech Republic	CZIDIADA
Finland	VALT
Greece	CERTH
Malta	ITSD
Poland	MTI
Sweden	SAFER

Administration (NHTSA) in 1975, to identify the main traffic safety problems in the United States. FARS state employees follow specific training to extract and standardize information about fatal accidents from a series of official documents:

- police accident reports;
- state vehicle registration files;
- state driver licensing file;
- state Highway Department data;
- death certificate;
- coroner/Medical examiner report;
- hospital medical repor ts; and,
- emergency medical service reports.

For each fatal accident, the database reports a description of the accident and approximately 125 coded parameters to characterise the crash, the vehicles and the people involved [31].

The database includes all road accidents in which at least one person died on scene or within 30 days of the crash.

CIREN

CIREN is the acronym of the Crash Injury Research and Engineering Network and is sponsored by the United States National Highway Traffic and Safety Administration (NHTSA). The network was established in 1996 with grants from General Motors and seven US level one trauma centers [32] [33].

Some of the main aims of the network are to better understand crash-injury mechanisms, the design of safer vehicles and to provide data on injuries occurring in real world crashes. It is a multi-multidisciplinary research program involving physicians, engineers in academia, industry, and government.

The current model utilizes two types of centers. The first are based at level one trauma centers that admit large numbers of people injured in motor vehicle crashes. The second are engineering centers with an extensive experience in motor vehicle crashes and human injury research. Engineering teams are led by highly experienced mechanical engineers typically trained in the area of biomechanics. These teams also include trauma/emergency physicians, a crash investigator and a project coordinator. Either type of team typically includes additional physicians and/or engineers, epidemiologists, nurses and other researchers.

The CIREN database consists of multiple discrete fields of the NASS data set concerning severe motor vehicle crashes, augmented with medical and injury variables.

In addition to NASS data, some of the main variables are:

- delta-V and trajectory (both via WinSmash software [34]);
- crash type;
- vehicle make, model and body types;
- Crash Deformation Classification (CDC);
- crush profiles;
- intrusions; and,

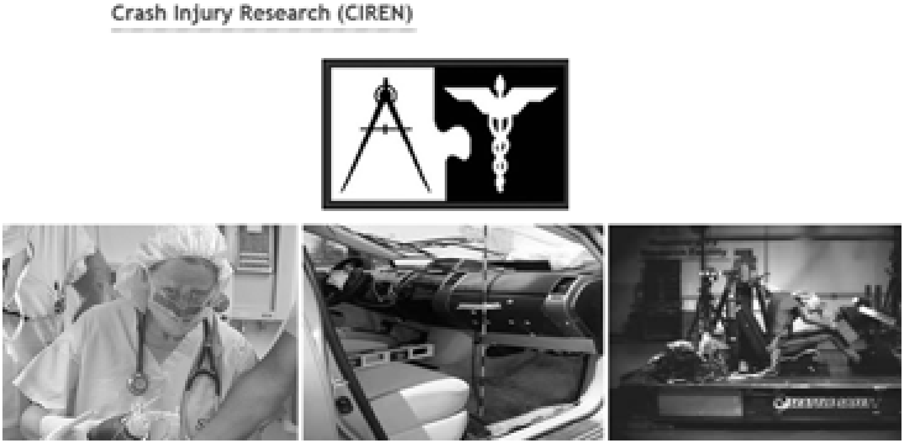


Figure 2.4: Crash Injury Research - CIREN

- occupant contacts.

While for the medical and injury data, elements include tables for

- co-morbidity;
- diagnostic procedures;
- complications;
- operative procedures;
- medical images;
- disability measurements;
- emergency medical response;
- emergency medical treatment;
- vital signs;
- physiologic measurements;
- injury location;
- ventilation periods;
- intensive care unit stays.

The principal table of the dataset is the CIRENINJURY Table, which permits the linking of injuries to their mechanisms and other medical information to vehicle data [33].

During the meeting of all the participants, the injury is linked to crash intrusions, contacts, bio-mechanical descriptors (e.g. sheer mechanism) and human drawing maps.

Labels and drawings are layered over the standard drawings to clarify positions and mechanisms. These are very useful for the bio-engineer who requires a detailed localization of an injury in order to effectively analyse the mechanics and discover new relationships. In this way the injury layers may be added together or "clustered" so that patterns over several patients may be analysed. This process enables repetitive injury patterns to be highlighted.

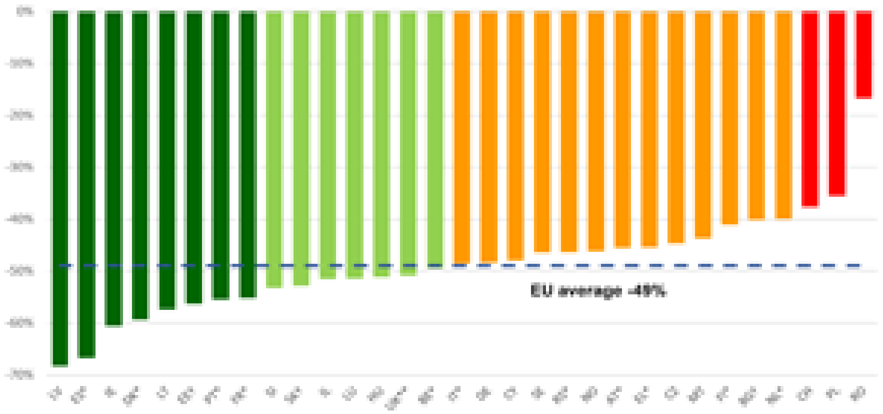


Figure 2.5: Road deaths' variations between 2001 and 2012

2.3 Road accident statistics

The World Community well understands the importance of road accident analysis for the assessment of our traffic safety level and its multiple goals. There is the necessity to identify and quantify these road safety problems as well as to evaluate the polices adopted and new strategies, and address new traffic safety research.

2.3.1 Road deaths

In the first decade of the 21st century (2001-2012) more than of 16 EU countries had reached the EU target of halving road casualties, but this is still not nearly sufficient (see Figure 2.5). In 2012 a total of 27700 people were killed in road collisions and approximately 313000 were seriously injured.

In 2012 EU27 road deaths experienced an average reduction equal to 9% (2661 casualties, see Figure 2.6) compared to previous year and had produced a savings of 5 billion Euro according to ETSC estimates [8]. This savings is most important factor in the need to monitor and continue research and development of road safety.

According to the studies conducted by the European Road Safety Observatory (ERSO) on the CARE database, since 2007 there has also been a reduction in terms of people injured.

Another relevant safety performance index for road mortality is the number of victims per billion-kilometres travelled by vehicles. This index compares the countries with a minor reduction in road deaths versus those that have the highest values of kilometres traveled per year (see Figure 2.7).

In 2010 there emerges in the CARE database source, data that in urban areas shows that approximately 44% of pedestrians involved in accidents died [35]. Clustering pedestrian and driver deaths for 4-month period, is also possible to see that the highest frequency of deaths is, respectively, on the third and second 4-month period (see Figure 2.8).

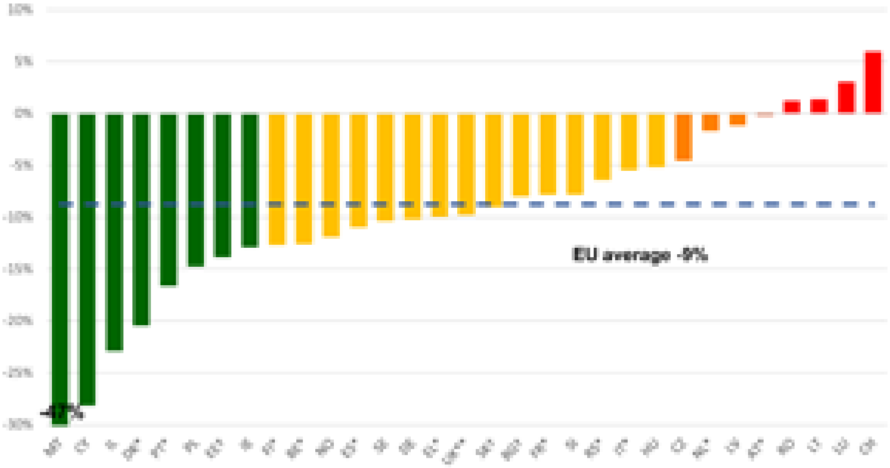


Figure 2.6: Road deaths' variations between 2011 and 2012

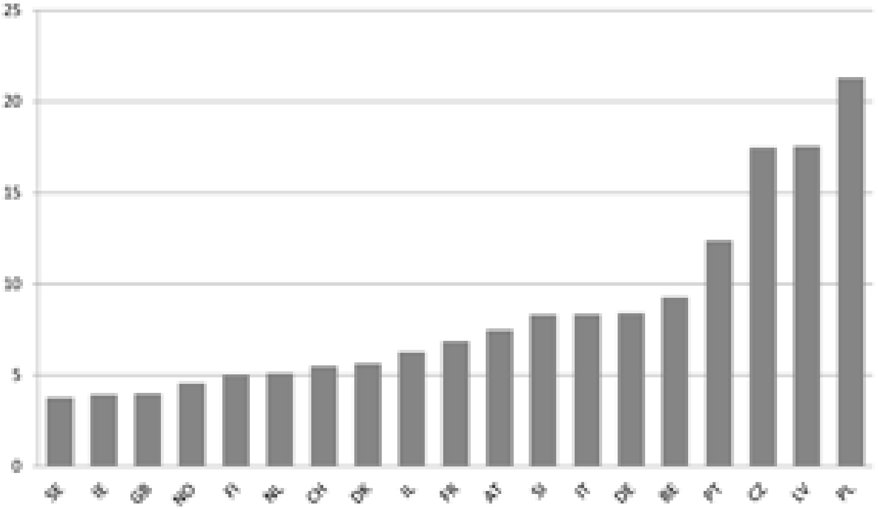


Figure 2.7: Road deaths for billion vehicle kilometres (mean value)

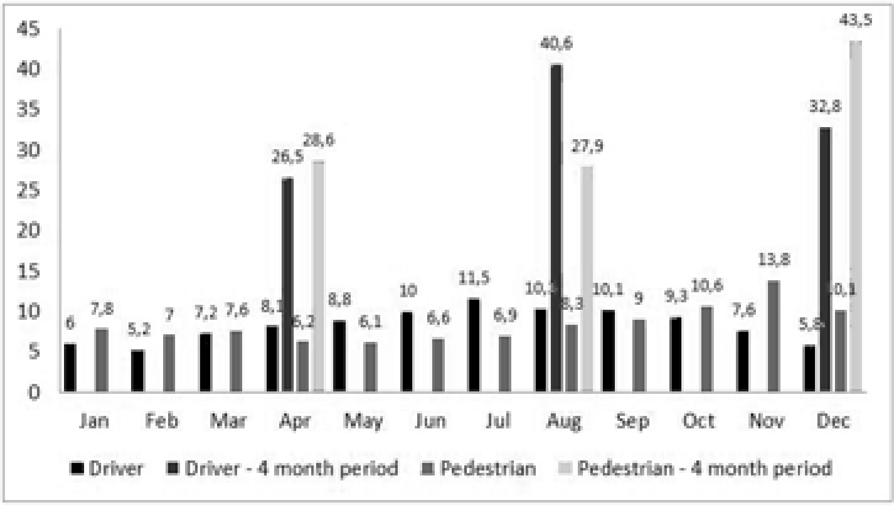


Figure 2.8: Number of fatalities IN EU-22, 2010

Regarding pedestrian deaths during the 4-month period, one of the possible causes of death could be attributed to the increased reduction of visibility for the driver to see the pedestrian during this period. While for the drivers who died, the highest percentage of deaths was in the second 4-month period, that is, the vehicles' highest usage period. According to the IRTAD Report [36] for European Countries the Vulnerable Road Users (VRU) (e.g. pedestrians, cyclists and motorcyclists) are the users most injured compared to the cars occupants. In Italy from 1990 the trend of VRUs injuries has increased relative to car occupants (Table 2.2). All these results are in line with the evolution of road infrastructure, automotive and crashworthiness research currently begin performed. Nevertheless, they confirm that it is necessary to do much more work on VRUs safety.

Another indicator that highlight the major focus on the car occupants' safety if compared to other road users is the safety improvement in extra urban areas. For example in Italy the percentage of fatalities that have occurred on rural roads or extra urban areas and highways has been reduced more than 50%. This is not true in urban areas where the fatalities have been reduced of 38% compared to 1990.

2.3.2 Some road accident health indicators

In 2007 the European Council issued a recommendation on usefulness of the common injury surveillance system (2007/C 164/01). To date the European Injury Database (UE IDB) has been used. This database contains standardized information on the cause of injuries treated in Emergency Departments (ED). The ED's involved in this database are approximately 100 hospitals in 13 member states.

The EU IDB database is composed of macro modules. In the "*Transport Module*" section the injuries suffered in the road accidents are recorded in three

Table 2.2: Fatalities by road user group, 1990-2011

	1990		2000		2010		2011		2010	2000	1990
	N	%	N	%	N	%	N	%	%	%	%
Bicylists	477	7	401	6	263	6	282	7	7,2	-29,7	-40,9
Mopeds	620	9	637	9	203	5	165	4	-19	-74,1	-73,4
Motorclycles and scooters	713	10	770	11	943	23	923	24	-2,1	19,9	29,5
Passenger car	3797	53	3850	55	1817	44	1661	43	-8,6	-56,9	-56,3
Pedestrians	1069	15	982	14	614	15	589	15	-4,1	-40	-44,9
Others	474	7	421	6	247	6	224	6	-10	-46,8	-52,7
Total	7151	100	7061	100	400	100	3844	100	-5,6	-45,3	-46

different modes [37]:

1. mode of transport;
2. role of injured person;
3. counterpart.

All these variables, even if not linked with police data, can complement the information relative to road accidents and, more specifically, injury patterns and the improvement of the assessment of injury severity. The main indicators used are:

- percentage of casualties admitted to the hospital;
- Length of Stay (LoS) in hospital;
- nature of body parts injured;
- type of body parts injured;
- potentially long-term consequences of injuries.

According to data published in the ”*IDB injury database*” [38] every year in Europe about 4000000 of people are injured due to road accidents. Of these people 700000 are admitted to the hospital and 38000 are die. Two-thirds of road accident casualties taken to the emergency rooms are VRU, and about fifty percent of these are admitted to the hospital.

Broughton [37] compared different types of road users over 4 years (2005-2008) in 9 EU countries, for a total of 71460, and showed as pedestrians, cyclists and motorcyclists were the road users with the major value of LoS. The longest value was experienced by pedestrian (LoS average 10 days) as compared to car occupants (LoS average 6 days). The body parts most frequently injured were the upper extremities (26%) followed by the head (24%) and lower extremities (22%).

In terms of body parts injured by road users, pedestrians sustained more frequent head injuries (30%) compared to the other road users, followed by cyclists (26%) and car occupants (24%). Instead, motorcyclists suffered lower (35%) and upper (32%) extremities injuries more frequently. Contusions and fractures were the most frequent types of injuries with percentage of 31% and 34% for VRU and 38% and 22% for VRU and motorized road users, respectively.

Comparing concussion injuries between VRU and motorized road users, Broughton showed the percentages are comparable, 7% and 9%. Despite greater safety devices for the motorized user, the interesting aspect of this data is the high proportion of motorized road user head injuries with respect to VRU.

2.3.3 The monetary value of the human life

The social costs of road accidents are an estimation of the monetary value loss by collective society due to road accidents events. This monetary value is not only evaluated on the basis of costs directly sustained by society, but also through the quantification of the economic burden on society itself as a consequence of road accidents.

Jost et al.[8] quantified the monetary value of the lost of human life that could be avoided by preventing just one road fatality to be 1.88 million Euros. Using these basis the total value of the reductions in road deaths in the EU27 for 2012 compared to 2011 have been estimated to be approximately 5 billion Euros. Once this shows more that the savings potential provided by road safety improvements is considerable, making it clear to policy makers that road safety policies are extremely important as well as further road accident research. In 2012 the Italian Ministry of Infrastructure and Transport published an assessment of the cost society of road accidents [39]. The categories of costs considered are broken down as follows:

- health care (medical treatment, Emergency Medical System (EMS), Emergency Department (ED), admitting, rehabilitation);
- human costs (biological and moral damage);
- loss of productive capacity (death, temporary or permanent disability); and,
- material damage (administrative and judicial).

Biological injury is damage caused to the person in term of physical or psychological well being.

The moral damage (non-pecuniary) means the unjust suffering caused by the loss to next kin due to the actions of other people.The administrative expenses are costs for car insurance and police investigations of the road accidents. Finally, the court costs are costs sustained by the judiciary.

The road accident reports of the Italian police do not differentiate between degrees of severity (the difference is made only between injured and non injured). The estimate of the average cost per road accident by degree of severity (fatal, serious, slight, and property damage-only accidents) was done following the conventional use of CARE database (i.e. hospitalised at least 24 hours for seriously injured and hospitalised less than 24 hours for slightly injured). The results are shown in Table 2.3. Assigning a monetary value for the loss of human life and disabilities can be seen as an ethical question. This shows once again that the potential savings offered by road safety improvements is considerable, making it

Table 2.3: Road accident costs per Severity

Severity	**M€/casualty**	**M€/road crash**
Fatal	1,503	1,642
Severe	0,197	0,309
Slight	0,017	0,032

clear to policy makers that road safety policies as well as further road accident research are extremely important.

In conclusion, this is the most objective way to assess the costs and benefits of road safety measures and helps make the most effective use of generally limited resources.

Chapter 3

State-of-the-art of road traffic injuries

3.1 Introduction

In Chapter 2 the state-of-the-art of road accident collection was presented in terms of main road accident databases and statistical evidence.

In this chapter, a review of the literature on the leading characteristics of road traffic injuries will be presented. The features of road injuries will be summarised in terms of road user types (i.e. car occupants, riders and pillions, pedestrians and cyclists).

For each category of road user the body parts most frequently injured by accident configurations and the severity both in terms of Abbreviated Injury Scale (AIS) and Injury Severity Score (ISS) will be evaluated. Powered Two Wheelers will be analysed respectively in head-on collisions, single vehicle accidents and approaching turn crashes.

3.2 Passenger vehicle occupants

3.2.1 Frontal crash

Pintar et al. [40], showed that the relation of frontal collisions to Motor Vehicle (MV) front width and injury severity is very interesting.

In this case the most severe crashes are those that involve less than the 40% of the MV front-end width (offset $< 40\%$). Due to the small portion of the vehicle structure involved in the crashes and the consequent low crash energy dissipation, these collisions are very severe for the near side occupant.

In Pintar's study he found that for the right front passenger the body parts most frequently injured (AIS2+ and AIS3+) were the head, thorax and extremities (lower and upper). In greater detail Pintar began with a selection from the CIREN database of 71 cases of frontal crashes with a narrow offset ($< 41cm$). The majority had an airbag deployment and in 72% of cases the occupants were belted. The distribution of AIS3+ injuries are similar to AIS2+ injuries by body regions and that the extremities, especially the lower, are the body parts most frequent injured (38%). This is followed by the chest and the pelvis (about 20%)(Figure 3.1).

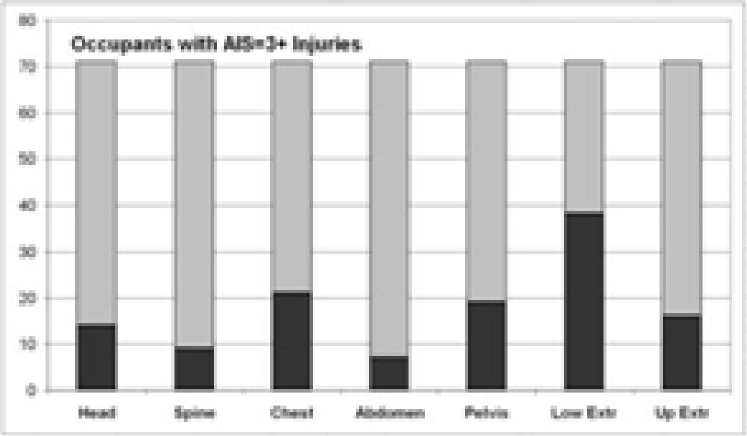


Figure 3.1: Occupants with AIS3+ injuries involved in crashes with small overlap

Focusing on occupants with AIS3+ injuries, he found that five had brain haemorrhages or hematoma, two had basilar skull fractures and two had brain steam lacerations or head crushes. Regarding the lower extremities 33 occupants had femur fractures and, if counting AIS2+ injuries, 22 occupants had tibia/fibula fractures and 24 had pelvis fractures.

Brumbelow [41], based on NASS-CDS database, led an accident analysis of vehicles produced after 2000 that had received a good rating in the IIHS frontal offset test. A least one front passenger sustained an AIS3+ or fatal injury. Figure 3.2 shows crash configurations that involved 96 occupants. Small overlap, moderate overlap and center impact configurations represent a similar number of crashes (two-thirds of the cases), followed by underride and low severity impacts. Full impacts were counted in only 6% of the samples analysed. Of the 89 people for which detailed injury data was available, underride and override impact configurations had a higher median Injury Severity Score (ISS)($\overline{ISS}$=26) compared to the other configurations. This was followed by a small overlap ($\overline{ISS}$=21) (figure 3.3).

The higher median ISS was attributed to intrusions and the chest was the most commonly injured body region in all impact combinations. This is even more true for occupants restrained or in the case of intrusions. Underride and override crashes were the most frequent crashes with AIS3+ head injuries, and the second most common in center, small overlap and moderate overlap crashes, as well as in crashes with intrusion or restraint factors. With regard to thorax and lumbar spine injuries Richards [42] analysed frontal collision crashes which occurred in the US from 1995 to 2004 (NASS database). The front occupants were restrained with three point seatbelts (9262 occupiers), compared to those that had airbag deployment (4887 occupiers). 80% of the crashes were developed with a delta-V minor of 37 km/h.

He found that 0.6% of thoracic and lumbar spine AIS2+ injuries occurred with a delta-V up to 50km/h (weighted cases). Instead, the rate increases to 10.3%

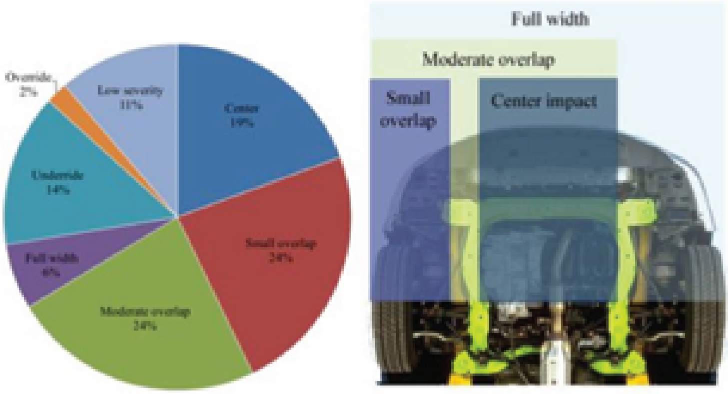


Figure 3.2: Distribution of crash configurations and width of the frontal collision

and 11.3% for three-belted occupants and three-belted occupants with deployed airbags when the delta-V is greater than 60km/h.

Abdominal injuries were investigated by Martin [43] based on the crashes of the Rhone Road Trauma Registry (1996-2006). Among belted users he found a higher risk of sustain moderate or severe abdominal injuries for the rear seat occupants with respect to front seat occupants. Among occupants with at least one serious injury, 16% of rear passengers had abdominal injuries, while 10% and 7% of front passengers and drivers experienced such injuries respectively.

Frampton [44], in his depth analyses of the UK CCIS data (1998-2010), focuses his attention on the following crash sample (4183 people):

- passenger car with driver airbag;
- single frontal impact within +30° of the vehicle's longitudinal axis (no rollover);
- belted occupant over 10 years of age;
- no injuries among all involved occupants.

All drivers had an airbag and the 90% a seatbelt pretensioner. The same proportion of front passengers had seatbelt pretensioners and 61% an airbag. None of the rear seat passengers had an airbag and only 7% had the seatbelt pretensioners.

According to Martin, Frampton identified an increment of injury severity to drivers (11%), to front passenger (13%) and rear passengers (17%). The AIS2+ abdominal injury rates for rear occupants are double relative to drivers and 1,5 times higher compared to front seat passengers. While AIS3+ abdominal injury rates were respectively 3 and 2 times higher.

In terms of age and gender, Frampton shows the rate of injury increased with the age of front passengers. While of the rear occupant, the higher injury rate was among young (< 20) and older (> 65) people. The rate of AIS3+ abdominal injuries appear similar between males and females. In the Figure 3.4 Frampton shows the frequency of people that suffered abdominal injuries by organ types. The abdominal cavity can be divided in hollow organs (intestine, colon, duodenum,

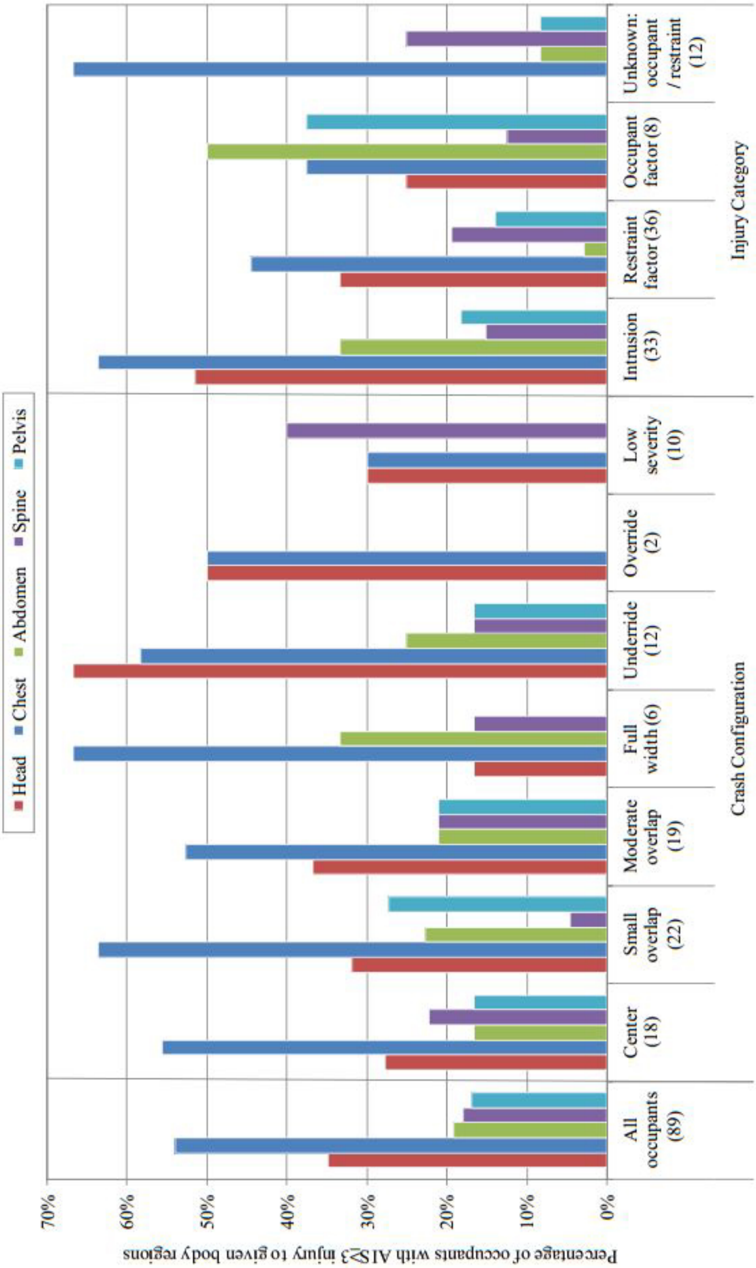
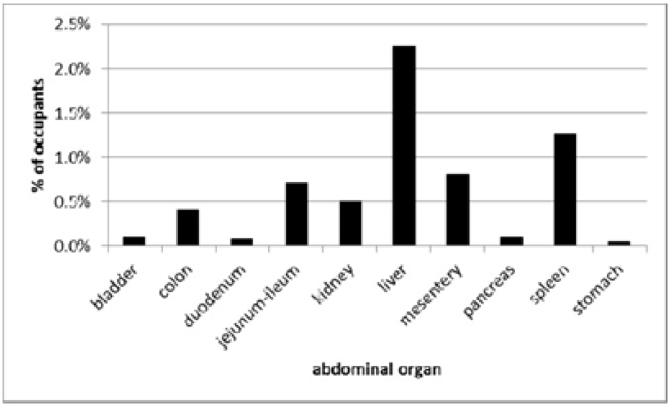
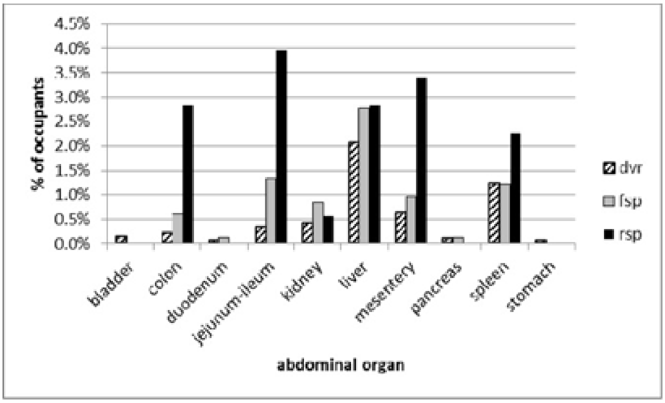


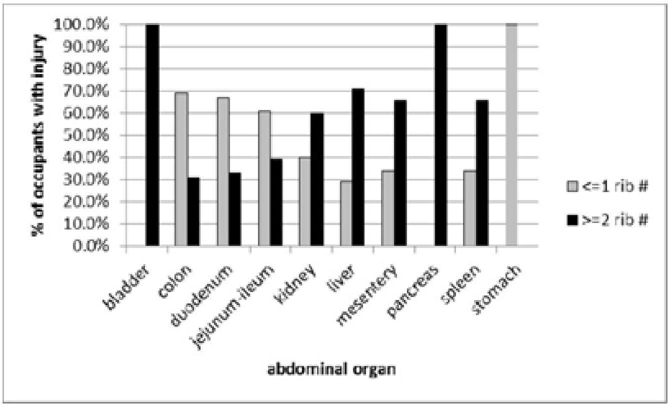
Figure 3.3: Distribution of injuries per body parts and overlap in frontal collision



(a) injury rates



(b) by Seat Position



(c) with Rib Fractures

Figure 3.4: Abdominal injuries by organs in frontal impacts

mesentery, stomach and bladder) and solid organs (liver, spleen, kidneys, and pancreas).

The liver was by far the most frequently injured abdominal organ. This was followed by the spleen and then the jejunum-ileum and mesentery. The colon and kidneys were the next most frequently injured organs. Bladder, duodenum, pancreas and stomach injuries were infrequent.

3.2.2 Side crashes

Car occupants in side crashes have a generally higher risk of injuries than in frontal crashes. This is due to the fact that there is less vehicle structure to attenuate crash forces. Moreover the occupant sitting on the struck-side of the car has little space for sideways movement before striking the car interior.

The side crashes can be divided in *near-side crash* and in *far-side crash*. Haland [45] found that the near-side crashes are 2.3 times more common than far-side crashes.

Fildes [46] found that the risk of serious or fatal injuries in near-side occupants is 2 times higher than for far-side occupants and; moreover, the risk is 2 times higher when the passenger compartment was damaged.

With regard to injury distribution in two different side crashes, Stolinsky [47] finds more injuries in the near-side (60%) than with respect to the far-side (40%).

Near-side crashes

The near-side crashes are the configuration in which the occupant is seated on the struck side of the vehicle (e.g. left car occupants with a PDOF between 8 and 10 o'clock, and right car occupants with a PDOF between 2 and 4 o'clock).

The NASS 1999-2005 data shows that 16% of the people involved in a side crash were in the near-side position compared to car point of impact. Scarboro [48] in 2007 conducted a study on the base of NASS, CIREN and SCI databases.

He analysed injuries of the near-side occupants involved in crashes with a low delta-V and found that the occupants evidenced a higher proportion of AIS3+ injuries in thorax (63%), lower extremities (42%) and head (26%) respectively. The thorax organs most frequently seriously injured (AIS3+) were: ribs (52%), lung (29%) and heart (6%). While for the lower extremities the pelvis (80%), femur (10%) and tibia (5%) were most seriously injured.

Another detailed study was conducted by Sunnevang [49]. The author extracts crashes from the NASS database (1994-2008), and finds that the incidence of AIS3+ thoracic injuries is highest at lateral delta-V in the range 20-40km/h. In this range the risk of AIS3+ thorax injuries is about four times higher for occupants over 60 years, than with respect to occupants between 10-59 years of age.

Impacts with obstacles (i.e. a pole) represent a small percentage with respect to car-to-car side impacts. But this type of crash assumes a very significant relevance due to its high severity. This is one of the most aggressive crashes for the automobile structure due to the close proximity of the occupants to the side structure [50].

Otte [51] analysed crashes from the GIDAS and CCIS databases that involved vehicles after 1998 and that had sustained one only side impact with a narrow object (tree, lamp etc.) and a belted nearside occupant had sustained injuries. Compared to other accident types, the single side to pole impact has the highest percentage of MAIS 3+ injured occupants.

In relation to the dynamic factors that characterize this type of crash, it appears that 50% of occupants receive a delta-V less than 35km/h. Moreover, for 50% of the occupants the impact speed was lower than 46km/h. Considering the body injuries reported by the occupants in the car side to pole impact, it appears that the head, thorax and extremities account for more than 80% of all injuries. The majority of slight injuries were reported to the head and extremities (about 75% of AIS1 and AIS2 injuries). Considering the AIS3+ injuries, 32% (GIDAS) and 38% (CCIS) of all severe injuries were to the thorax.

Of the seriously injured occupants (MAIS3+) 52.4% of the injured receive an impact in the vehicle's area between A and B pillar and the PDOF was perpendicular to the vehicle.

Finally Otte, by means of logistic regression, finds delta-V as the most influential factor in general MAIS and for injury severity of the thorax and abdomen.

Far-side crashes

Far-side crashes concern vehicle occupants that are located in the opposite or centre part of the struck side vehicle.

From the NASS database Gabler found that 22% of the seriously injured people were far-side occupants [52] and he showed that the far-side impact is more dangerous for cars than Light Truck Vehicles (LTV) or vans.

The main dynamic parameters that influence injury severity are total delta-V (e.g. Delta$V = 32kmh$ produced a MAIS3+), compartment intrusion (e.g. MAIS3+ were relative to CDC until to the 3 and 4 zones), PDOF (e.g. 60% of MAIS3+ were caused by PDOF 60±30 degrees) and, finally, the impact location.

The main causes of AIS2+ head injuries can be identified from the following sources: steering comb (8.8%), right B pillar (7.7%) and right interior (7.3%). While for the AIS2+ thorax injuries, the majority of causes are seat back contact (49.3%) and belt webbing or buckle contacts (24.3%).

Digges [53], using the NASS database regarding far-side belted occupant crashes without rollover, analyzes the distribution of body injuries for occupants with MAIS3+.

Among the AIS3+ injuries, 26.9% are due to contact with the far-side interior (all interior side surfaces between the floor and the roof of the vehicle), 20.8% are caused by contact with the safety belt and 12.2% impact with the roof of the vehicle.

Head and chest AIS3+ injuries were caused in 11% of the cases by contact with the right side interior, whereas a larger percentage of chest injuries (20.6%) were caused by contact with the seatbelts.

3.2.3 Rear-end crash

In rear-end road accident configurations, the most common neck injury type is the Whiplash Associated Disorder (WAD), commonly referred to as whiplash injury.

Whiplash accounts for 70% of all crash-related injuries leading to disability [54]. Fortunately, the majority of people who experienced initial neck symptoms due to a rear-end crash recover within a few weeks or months after the crash.

Many studies highlight that under similar crash conditions, females have a higher risk of whiplash injuries than males [55][56][57].

In accordance with these studies, whiplash injury risk is between 1.5 and 3 times higher for females compared to males. Comparing males and females with equivalent statures, the whiplash injury risk is about 2 times higher for females than males. Some causes of this are the differences in the head/neck physiology. Females have a lower strength and faster neck muscle reflexes than males. Females' vertebral dimensions and segment support areas are smaller than males, indicating a less stable intervertebral coupling [58] [59].

Carlsson [60], in her study based on 42 rear impact test series (male and female) at low speed (4 and 8km/h), found that females experience a higher and earlier head x-acceleration peck (32% higher and 7% earlier at 4km/h, 10% higher and 9% earlier at 8km/h), a higher T1 x-acceleration peak (18% higher and 6% earlier at 4km/h and 16% higher at 8km/h) and a shorter head-tohead restraint distance (7% at 4km/h and10% at 8km/h).

Linder [61] in her study conducted on data collected in Sweden with vehicles made between 1993 and 2007, divided the sample between driver and passenger and male and female. He found there were marginal differences between males and females in terms of some kinds of neck pain symptoms. Male and female drivers and male and female passengers showed a relatively major difference with regard to long and medium term neck pain symptoms.

It is well accepted that rear impact neck injuries result from relative motion of the head and neck, although the exact injury mechanism is not completely understood. The occupant kinematics can be described in three stages:

1. The first stage involves loading of the upper torso and shoulders from the rear through the back of the seat, and during this initial acceleration phase, the head remains stationary. The forward motion of the thorax and shoulders with respect to the stationary head results in head lag. During this phase the acceleration loading event causes the extension of the lower cervical spine, whereas the upper segments sustain flexion causing a transient non physiological curvature (S-curve) of the cervical spine;
2. In the second stage the torso continues to displace anteriorly relative to the head, the cervical spine transitions into extension and the head rotates backward to strike the head restraint. During this intermediate phase, due to acceleration loading, the lower cervical spine is subject to the extension with concomitant extension of the upper segments (C-curve);
3. The third end stage involves the rebound phase of the head-spine motion, where the head rebounds from the head restraint and cervical curvature

transitions into flexion.

The latest literature suggests some new possible injury mechanisms [62], such as tissue injury mechanism and the pain mechanism resulting from injured tissues.

3.2.4 Rollover

Rollovers are complex events which can occur with or without impact(s) and are not always the principal cause of the resulting occupant injuries.

Padmanaban [63] found in US data the abdomen, thorax, thoracic, lumbar spine and pelvic hip, were the most common body regions subject to serious injuries. In the rollover 40% of seriously injured belted occupants sustained only serious thoracic injuries, 20% sustained only serious head/face/neck injuries, and 10% sustained both serious head/face/neck that torso serious injuries. The author also found that less than one-half percent of 19.000 occupants involved in rollovers sustained AIS4+ cervical spine injuries.

Comparing US and UK data, Padmanaban shows in the UK serious torso injuries were less frequent than in the US (31%), while there was a much higher percentage (18%) of belted rollovers occupants with only serious head/face/neck injury. In addition, 26% sustained both serious head/face/neck and torso injuries. Moreover, the UK data showed a much higher proportion of serious head/face/neck compared to US (44% versus 30%); but this was mainly due to sampling design differences between the two databases.

In a more recent study conducted in the UK, Cuerden (2009) [64] found that seatbelt use and full ejection in rollovers are strongly related, with 75% of the occupants who were wearing a seatbelt were not ejected. The use of seatbelts is also important in terms of injury severity. For seat belted occupants the injuries are less severe. For belted and unbelted occupants the head was the most injured body region, followed by thorax and extremities.

With regard to front seat belted occupants, Cuerden found the injury severity also depended on the direction of the roll. The occupant seated on the opposite side to the direction of roll experienced more severe injuries.

Parenteau [65] found that rollover crash occupants had the highest frequency of AIS3+ head injury if compared to frontal, side, and rear crash modes. These studies have shown that the roof was coded as the source of injury for 65% of serious head injuries and injury patterns were similar across all vehicle types [66].

Ridella [67] shows that serious brain injuries were the most common serious injuries in rollovers and occurred 2 to 3 times more often than serious skull fractures. In serious skull fractures, fractures of the vault were 2 times more frequent than basal skull fractures. Although the majority of head injuries occurred without a spine injury, cervical spine fractures have been shown to be accompanied by head injuries in 75% of the cases, though the type of head injury was not identified in the study [68]. For Funk [69] far-side and older occupants were also more likely to sustain serious head injuries.

In the 2012 Mattos [70] confirmed that the most common serious injuries were to the thorax (40%) and spinal (36%) regions, followed by head injuries 21% (see Figure 3.5 and Figure 3.6). In terms of impact location, occupants seated on the

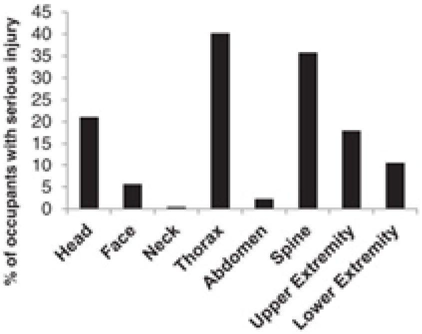


Figure 3.5: Serious injuries per body regions for restrained occupants

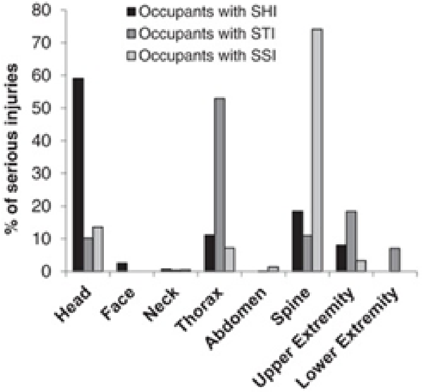


Figure 3.6: Restrained occupants with serious head, thorax and spine injuries

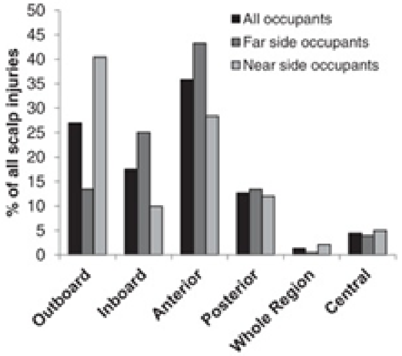


Figure 3.7: Head-face AIS 1-2 injuries in near- and far-side restrained occupants

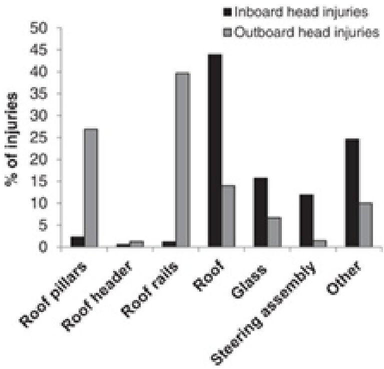


Figure 3.8: Head-face AIS 1-2 injuries distribution by injury source

far side of the vehicle during a pure trip-over rollover suffered the majority of head impacts to the inboard side and anterior aspects of the head. Occupants seated on the near side sustained impacts most frequently to the outboard side of the head.

The source of inboard head injuries was most commonly coded as the roof top. Outboard head injuries were most frequently due to impact with the roof rails and pillars (Figure 3.7 and Figure 3.8).

3.3 Motorcyclists

Powered Two Wheelers (PTWs) (e.g. mopeds, motorcycles and scooters) remain the most dangerous form of travel on today's roads.

The European Transport Safety Council shows that in 2006 the 16% of road deaths were motorcyclists [71]. At the same time in a NHTSA's report it appears that motorcyclists experience a 34-fold higher risk of death per vehicle-miles travelled than people driving other types of motor vehicles (and they are 8 times more likely to be injured) [72].

Otte [73] from 2199 motorcyclists contained in the GIDAS databases (1999-2008), found that 65% of riders experienced minor injuries while about 9% were severely injured. Moreover the percentage of MAIS4+ injuries increases with the relative speed. With a speed up to 30 km/h the percentage of MAIS4+ is equal to 0,9%, whereas with a speed up to 70 km/h the percentage increase grows to 8%. The most injured body regions were extremities, thorax and head. This was also confirmed by a previous Moskal's study based on French data [74].

PTW crashes that involved a fixed object (i.e. roadside obstacle) result in a higher risk of head, facial, chest and abdominal injuries with respect to the other types of crashes [74]. Therefore PTWs are much more vulnerable users in cases of impact with the road infrastructure and in particular with the guardrails. Different studies involving Europe and the U.S. confirm the high level of danger of guardrails.

The Motorcycle Accidents In Depth Study (MAIDS) shows that guardrails are an infrequent but real danger for PTW riders [25]: 6.5% of riders (60 out of 921) suffered injuries caused by the impact of the body with the guardrail [75]. On the basis of a detailed analysis of crashes (based on LMU COST, MAIDS, DEKRA and GIDAS databases) involving road infrastructures, it appears that PTW users who impacted obstacles such as trees/poles, guardrails and road infrastructures, experienced a significantly severe outcome in general [76].

Forman et al. [77] used hospital data from 8 European countries to examine the frequencies and patterns of injury among PTW users, their loss of functional ability and the main head injury mechanisms. The data was relative to 977557 injured patients in 2004 year. The lower extremities were the body region with the majority of injuries, (26% of the total), followed by the upper extremities (20.7%), head (18.5%) and thorax (8.2%). Cerebral concussion was the most common head injury observed (occurring in 56% of head injury cases), with most concussion cases (78%) exhibiting no other head injury. Among the AIS3+ head injuries, 48% of these were associated with a translational-impact mechanism, and 37% with a rotational mechanism.

Forman also showed that 12% of the hospitalized subjects sustained an MAIS1, 57% had an MAIS2, 21% an MAIS3, 3% had an MAIS4 and 5 and less than 1% had an MAIS6. These results were confirmed by Otte's study [73]. As a consequence of the previous MAIS values, the most frequent Injury Severity Score (ISS) ranging was 1 to 8 (69%), followed by 9 to 15 (20%). Only 11% of the casualties were classify as major trauma ($ISS > 15$).

With regard to disabilities, Forman showed that in discussing the population-level impact of functional disability, it is important to consider not only the magnitude of the individual injuries, but also the relative frequency of the injuries in the population. Head injuries are the principal cause of death for the motorcycle users [78]. Kraus [79] showed the most frequent types of injuries are concussion, haemorrhage and facial and skull fractures.

In Moskal's study [74], head injuries were reported by 11% of the helmeted riders and injuries were severe for 9% of the cases; 11.4% of the riders with head injuries sustained cranial or intracranial injuries and a high percentage (81%) of riders sustained a loss of consciousness. Richter [80] sustained that brain injuries are caused principally by the deceleration force (especially with kinetics rotation).

Spinal injuries are infrequent (ranging from 1% to 11% of all injuries) compared to others [78]. However, these type of injuries have a very high severity and often cause the death of the rider, impairment or disabilities. Kasantikul [81] said motorcycle spinal injuries are often underestimated since in some cases the cause of death is most probably associated to more evident and visible lethal injuries (e.g. to the head).

Zulkipli [82], on the basis of motorcycle crashes occurring in Malaysia between 2005-2007, found that in single vehicle crashes spinal injuries (27,3%) have a higher occurence with respect to other injuries types (15,5%). In this case the riders have a higher risk of suffering spinal injuries than those involved in multi-vehicle crashes (OR 1.74).

Finally, single vehicle crashes against fixed objects are more likely (OR 1.96) to cause spinal injuries with respect to single vehicle crashes against no fixed object.

Fixed objects on the roadside have a passenger car oriented design shape. It has been demonstrated that the guardrail causes a higher fatality risk to motorcyclists than to the person in a passenger vehicle [83].

Ooi [84] found that the risk of injuries increase (about 30%) if the motorcycle is impacted on any side different from the front. Hsieh [85] suggested that upon rear impact the spinal column does not suffer fractures but sustains torsion pattern and compression backward bending.

The injuries to the lower extremities are very common in motorcycle accidents. The proportion of riders who report injuries in this body region range between 30% and 70% [86]. Fractures are the most frequent lower extremity injuries that produce the most severe outcomes with permanent disability [87] [88].

Refaat [5] conducted an in-depth analysis on US motorcyclists who were injured or died from NASS and FARS data (1997-2006). The Maximum AIS of lower extremities for 96% is AIS 2 and AIS 3 and for the remainder is AIS 4-5. The anatomic structures with the highest percentage of injuries are the legs (28%), pelvis (18%) and knee (15%) (see Tables 3.1 and 3.2).

In particular, the tibia and fibula account for 53% and 42% respectively of injuries. Aslam [89], on a sample of 348 injured in motorcycle accidents, also found that 39% of the users presented tibia fractures. The author attributed this fracture to the fact that tibia is in a superficiality and exposed position during the motorcyclist's ride.

In the pelvis Refaat shows the more common injuries are the fracture with or without dislocation (62%) and symphysis pubis separation/fracture (15% of injuries). Among injuries to the knees, the highest proportion (36%) are the tibia fracture, plateau/Intercondyloid spine and the patella fracture (17%). In relation to thigh injuries, approximately 94% of these are femur fractures and more frequently shaft fractures (50%).

3.4 Vulnerable Road Users: pedestrians and cyclists

Pedestrians and cyclists are the most Vulnerable Road Users (VRU) who are exposure to a high risk in road traffic collisions with motor vehicles. In 2006 the EU claimed that VRUs have a fatality risk per distance travelled 7 to 9 times higher than car travellers [90]. In a vehicle-to-pedestrian accident, the pedestrian is most commonly impacted from the side by the vehicle front [91][92][93]. By means of an analysis conducted on vehicles registered after 1990, Yang et al. [94] show the head (30.9%) and lower extremities (38.3%) were the most frequently injured body parts during the accidents, followed by the thorax (12.8%) and upper extremities (7.4%) (see Table 3.3). Fredriksson [95] analysed 161 AIS3+ injured pedestrian accidents of the GIDAS databases (1999-2008) and found that 58% sustained severe injuries to the legs, 43% to the head and 37% to the thorax.

In terms of disabilities, 31% of pedestrians were estimated to have sustained at least 1% disability (lowest level), 4.6% sustained more severe disabilities level of at least 10% disability. The leg was the most frequently impaired body region (18%) for the lower disabilities level (1%) followed by arms (8.6%) and head (6.9%).

Table 3.1: Levels of leg injuries in U.S PTW crash (AIS2+) [5])(Part I)

Level	**Injury description**	**Weighted** *Frequency*	**Weighted** *Percentage*
Leg		**9784**	**27**
	Tibia, fracture	5133	52
	Fibula, fracture	4161	43
	Amputation/Massive crash	311	3
	Popliteal Artey/Vein	118	1
	Achilles tendon, laceration	55	1
	Fracture, NFS	8	¡1
Pelvis		**6504**	**18**
	Pelvis, Fracture With or Without Dislocation	4077	63
	Symphysis Pubis Separation (Fracture)	1116	17
	Sacrollium Fracture With or Without Dislocation	880	13
	Pelvis, Fracture, Substantial Deformation and displacement	430	7
Knee		**5683**	**16**
	Tibia, Fracture, Plateau /Intercondyloid Spine	2111	37
	Patella Fracture	1004	18
	Collateral or Cruciate Ligament Laceration	704	12
	Knee, Dislocation, with/without Involving Articular Cartilage	541	10
	Femur, Fracture, Condylar	486	9
	Knee, Sprain	362	6
	Knee, Laceration Into Joint	184	3
	Knee, Meniscus Tear	147	3
	Patellar Tendon Laceration	145	3
Thigh		**3863**	**11**
	Femur, Fracture, Shaft	2027	53
	Femur, Fracture, NFS	708	18
	Femur, Fracture, Open/Displaced	365	9
	Femur, Fracture, Subtrochanteric	320	8
	Femur, Fracture, Supracondylar	232	6
	Femoral Artery/Vein-Sciatic Nerve Injury	151	4
	Above Knee, Amputation Partial or Complete	60	2

Table 3.2: Levels of leg injuries in U.S PTW crash (AIS2+) [5])(Part II)

Level	**Injury description**	**Weighted** *Frequency*	**Weighted** *Percentage*
Ankle		**3560**	**10**
	Fibula, Fracture, Bimalleolar or Trimalleolar	997	28
	Fibula, Fracture, Lateral Malleolus	984	28
	Tibia, Fracture, Medial Malleolus	692	19
	Tibia, Fracture, Medial Malleolus, Open/Displaced/Comminuted	386	11
	Ankle, Dislocation, With/Without Involving Articular cartilage	362	10
	Tibia, Fracture, Posterior Malleolus	139	4
Foot		**3415**	**10**
	Metatarsal or Tarsal Fracture	1751	51
	Calcaneus Fracture	591	17
	Talus Fracture	563	17
	Foot, Fracture, NFS	475	14
	Toe, Amputation/Crush/Degloving	34	1
Hip		**1440**	**4**
	Hip, Dislocation, With/Without Involving Articular Cartilage	531	37
	Femur, Fracture, Intertrochanteric	434	30
	Femur, Fracture, Neck	356	25
	Femur, Fracture, Head	120	8
Other		**1580**	**4**
Total		**35829**	**100**

Table 3.3: VRU - Distribution of injured body regions for VRU types

Body	AIS2+ Adult	AIS2+ Children	All Injuries Adult	All Injuries Children
Head	30.9%	56.4%	25.9%	33.1%
Neck	4.3%	0.0%	5.%	1.8%
Thorax	12.8%	7.7%	12.0%	5.5%
Upper extremity	7.4%	12.8%	16.6%	20.9%
Abdomen	1.1%	0.0%	1.9%	3.0%
Pelvis	5.3%	0.0%	6.2%	8.6%
Lower extremity	38.3%	23.1%	32.4%	27.0%

For the more severe disabilities (10%) the head was the predominant body region (3.2%).

Otte [73], using GIDAS accident data collected from 1999-2008, found that cars are the most frequent striking vehicle involved in pedestrian and bicycle accidents (respectively 72.3% and 63.5%). In terms of MAIS, pedestrians suffered more severe injuries (11.2%) than motorcyclists (8.8%) or cyclists (3.5%). Pedestrians' minor injuries, except for MAIS2, were less frequent than in the others road users. Once again pedestrians and cyclists were road users with an high frequency of leg injuries as well as motorcyclists. In terms of arm injuries, the cyclists were the most injured.

Table 3.4 shows the pedestrian body region most frequently injured was the head (with 50.4% of injuries) compared to others users. This can be explained by the extensive use of helmets for riders and cyclists. The most frequent head impact was against the upper part of the hood/bonnet. However, the impact that leads to severe head injuries (AIS3+) are particularly evident in the windscreen area impact. It is important to note how the location of the impact points of the head are strongly linked to the impact speed, and for cyclists in the angle between cycle and car front and the relative speed between the vehicles.

Table 3.4: VRU - Frequencies of injured body regions for vulnerable road users

	Pedestrian (n=2035)	Bicyclist (n=3958)	Motorcyclist (n=2189)
Head	50.4%	35.6%	16.8%
Neck	4.5%	5.2%	7.3%
Thorax	19.2%	24.4%	21.7%
Upper extremity	38.2%	46.1%	44.3%
Abdomen	6.9%	6.1%	6.4%
Pelvis	14.9%	13.5%	13.8%
Lower extremity	67.4%	62.6	71.9%

Peng [96], using GIDAS data, shows that cyclists always suffer lower injury outcomes for the same accident severity. The majority of accidents with cyclists seem to occur at low speeds (up to 20 km/h), while the majority of pedestrian accidents occur between 21 km/h to 30 km/h (27,8%) followed by the 11-20 km/h range (22,8%) and the 31-40 km/h range (18.4%). The preponderance (80.5%) of cyclists were slightly injured with MAIS 1, compared to only 57.8% of pedestrians. Pedestrians have the higher frequency of MAIS 2 injuries at 29.3% of all cases than cyclists at 16.2%. Additionally, only 3% of cyclists were severely injured (MAIS 3+) in comparison to 12,5% of pedestrians. For this reason it can be concluded that pedestrian injury severity is significantly higher than for bicyclists.

In the first impact (against parts of the car) the bumper was the most frequent cause of injuries. Forty-two.seven percent (42.7%) of pedestrian and 23.4% of cyclist injuries were caused by it, followed by windscreen (30.7%-14.7%) and bonnet edge (30%-19.7%) impacts. The physical contacts with windscreen and bonnet are

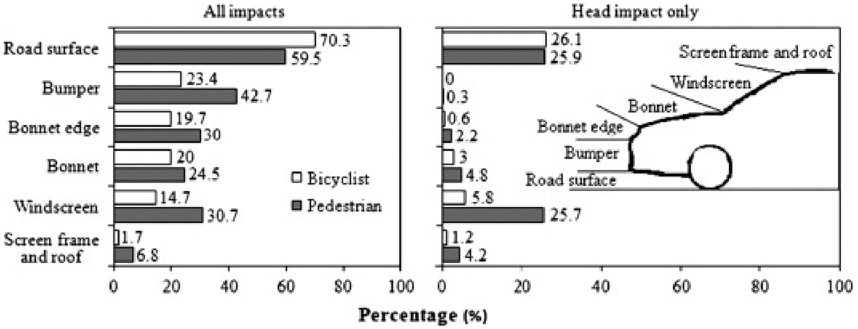


Figure 3.9: Pedestrians' causes of injuries

the main causes of head injuries for both cyclists and pedestrians. The impact on the road surface is responsible for the largest number of general injuries and head injuries (Figure 3.9).

In 2005 Roudsari et al. [97] conducted a study of US pedestrian impacts from 1994 to 1998. The vehicles involved in these accidents were all registered in the early 2000's, and a total of 3146 injuries among 386 pedestrians (313 adults and 73 children) were analysed.

The study showed that upper and lower extremities, head and face were the most commonly injured body regions both for Light Truck Vehicle (LTV) and Passenger Vehicle (PV) (Table 3.5).

Table 3.5: VRU - Pedestrian's injured body regions for vehicle type

	Children		Adults	
	PV	LTV (SUV)	PV	LTV (SUV)
Head	42%	43%	46%	54%
Face	59%	57%	42%	50%
Neck	10%	14%	24%	25%
Thorax	10%	14%	20%	37%
Abdomen	8%	14%	18%	33%
Upper extremity	56%	71%	61%	71%
Lower extremity	85%	71%	86%	84%

Focusing on PV and with-adult crashes, the windshield (63%), hood surface (11%) and A-pillar (9%) were the most common sources of head injury. Head injuries attributed to A-pillar and cowl had a higher AIS 3 than head injuries caused by other parts of the vehicle.

For thorax injuries, the hood surface (67%), windshield (14%) and cowl/scuttle (7%) were the leading causes of injuries. The likelihood of thorax injuries for LTV crashes (37%) was considerably higher than PV crashes. The thorax injuries caused by the cowl and A-pillar areas had a higher AIS (3.5 mean value).

Abdominal injuries were more likely in LTV crashes (33%) than PV crashes (18%). In the latter the hood surface (58%) and hood edge (21%) were the most common sources of injuries. The AIS mean in PV crashes was 1.6±0.8. Evaluation of the injury severity caused by different parts of the PV showed a higher AIS for injuries caused by windshield contact (2.0±1.3).

Finally, injuries to the upper extremities were more frequent in the crashes (71%) than PV crashes (61%). The AIS mean was 1.2±0.6, the hood surface (36%), windshield (27%) and ground (24%) were the major sources of injuries. For PV crashes the major sources of injuries were bumper (60%), ground (12%) and leading bonnet edge (11%).

Table 3.6: VRU - Injury severity by body regions and vehicle contacts

Source	Head		Thorax		Abdomen		Spine		Upper extremity		Lower extremity	
of Injury	Number	AIS	Number	AIS	Number	AIS	Number	AIS	Number	AIS	Number	AIS
Windshield	211 (63)	2.7 1.4	11 (14)	2.5 1.3	7 (9)	1.7 0.8	16 (19)	2 1.3	92 (27)	1.2 0.5	-	-
A pillar	29 (9)	3.0 1.3	2 (2)	3.5 0.7	-	-	-	-	-	-	-	-
Cowl	16 (5)	3.0 1.5	6 (7)	3.5 1.4	1 (1)	2.0 0.0	4 (5)	3.2 1.9	-	-	-	-
Hood surface	38 (11)	2.7 1.5	54 (67)	2.6 1.2	47 (58)	1.7 1.0	25 (30)	1.6 0.8	125 (36)	1.3 0.5	46 (11)	1.4 0.9
Hood edge	-	-	1 (1)	3.0 0.0	17 (21)	1.4 0.8	9 (11)	1.2 0.4	9 (3)	1.4 0.9	67 (11)	1.5 0.8
Front edge	-	-	-	-	-	-	-	-	-	-	-	-
Front header	13 (4)	2.7 1.7	-	-	-	-	8 (10)	3 1.6	-	-	-	
Front grill	-	-	-	-	1 (1)	1.0 0.0	-	-	-	-	21 (3)	1.3 0.5
Bumper	-	-	-	-	-	-	-	-	-	-	373 (60)	1.8 0.8
Spoiler	-	-	-	-	-	-	-	-	-	-	28 (5)	1.3 0.6
Other parts of vehicle	5 (1)	-	2 (2)	2.0 1.4	-	-	5 (6)	-	33 (10)	-	10 (2)	-
Ground	23 (7)	1.7 1.1	5 (6)	1.0 0.0	8 (10)	1.0 0.0	17 (20)	1.1 0.3	83 (24)	1.2 0.6	75 (12)	1.1 0.4
Total (%)	335 (100)	2.6 1.5	81 (100)	2.6 1.4	81 (100)	1.6 0.8	84 (100)	1.8 1.2	342 (100)	1.2 0.6	620 (100)	1.20.6

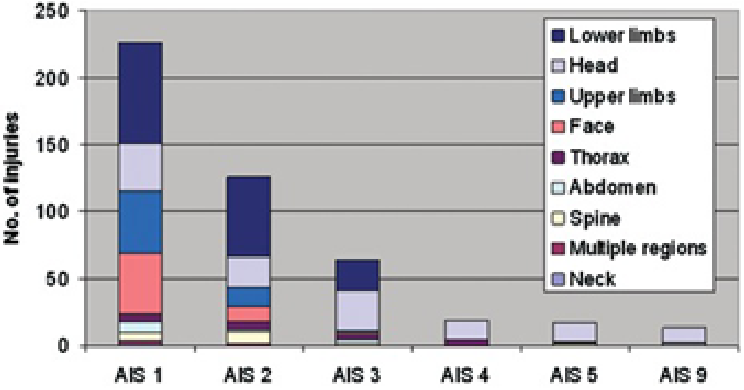


Figure 3.10: Number of injuries per body region and AIS level [1]

In the APROSYS project, conducted in four EU countries (England, Spain, Germany and Sweden) in the years 1997-2003, a sample of 70 detailed pedestrian (63) and cyclist (7) road accidents was collected.

From this study, Carter et al. [1] finds that 79% of serious accidents occurred at impact speeds of less than 40km/h, while only 31% of fatal accidents occurred at impact speeds of less than 40 km/h. The majority of MAIS 2 cases were at impact speeds between 21 and 30 km/h. Due to multiple injured body regions for VRU accidents, the relationship between the ISS score and impact speed is more in agreement with the MAIS score. In Table 3.7 Carter showed the ISS score increased with vehicle impact speed.

Table 3.7: VRU - Injury Severity Score (ISS) vs. vehicle impact speed

ISS	Mean Impact speed(km/h)
0-10 (n=24)	32.8
11-20 (n=14)	42.2
>20 (n=15)	45.3

The Figure 3.10 shows that the majority of injuries were slight (<AIS 3) and relatively few injuries had an AIS 4+. The body regions most subject to minor injuries (<AIS 3) were the upper and lower legs, the face and head. While the body regions with the most severe injuries (AIS 3+) were the head, lower legs and thorax. The most frequently injured body regions were the head and lower extremities, followed by the upper extremities, face and thorax. If the face and head are considered a single area, this is in absolute the most injured region.

In terms of major injuries (AIS4+), the head had the majority of injuries compared with lower limb injuries. Looking at AIS 2-3 injuries only, the lower extremities were the most frequently injured body region (Table 3.8).

Table 3.8: AIS body region and severity

	Slight		Serious			Unknown	
	AIS1	AIS 2	AIS 3	AIS 4	AIS 5	AIS 9	Total (%)
Head	35	22	30	14	14	11	126 (27.1)
Face	45	11	1	0	0	0	57 (12.3)
Neck	1	0	0	0	0	0	1 (0.2)
Thorax	6	6	3	5	1	1	22 (4.7)
Abdomen	9	2	4	0	1	1	17 (3.7)
Spine	5	9	1	0	1	0	16 (3.4)
Upper extremity	47	15	2	0	0	0	64 (13.8)
Lower extremity	75	60	23	0	0	0	158 (34.0)
Multiple regions	3	1	0	0	0	0	4 (0.9)
Total (%)	226 (48.6)	126 (27.1)	64 (13.8)	19 (4.1)	17 (3.7)	13 (2.8)	465 (100)

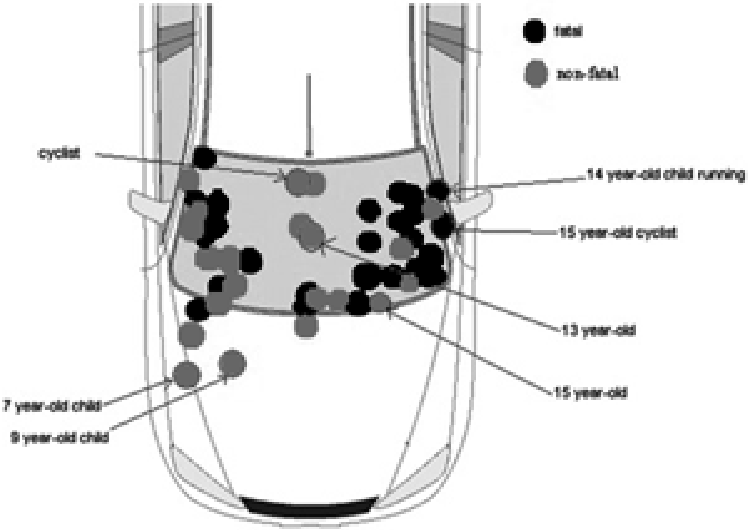


Figure 3.11: Head impact location by severity [1]

In terms of most frequently injured parts of the head, Carter [1] shows the scalp, cerebrum and skull were the most frequently injured body regions. Within the cerebrum the most frequent lesion was the subdural haematoma (25.7%), followed by cerebral contusion (22.9%) and subarachnoid haemorrhage (14.3%). The subdural haematoma is 4 times more common than the extradural haematoma and this is in agreement with Skinner.

Carter also shows the leading head impact locations were the windscreen, A-pillar and scuttle, followed by the bonnet. Only an impact occurring in the centre of the windscreen and away from the scuttle were non-fatal, while the impact on or close to the frame of windscreen and on the scuttle were frequently fatal. It is interesting to see the majority of crashes were located in the lateral extremities of the windscreen and bonnet (fender area). In a recently study conducted by Mueller [2] in a sample of 67 pedestrian collisions (US data between 2002-2006), he found that the injuries with a severity greater than MAIS3 most commonly involved the head, thorax or abdomen regions. The majority of AIS4+ head injuries were brain injuries, while the thorax injuries were rib fractures or lung contusions. Lastly, for the abdominal region the most frequent injuries were spleen or liver lacerations.

The MAIS6 spinal injury was a complete cord syndrome, and the MAIS5 pelvis injury was an open book pelvis fracture with greater than 20% blood loss. 70% of all cases had MAIS3 or greater injuries to the torso, spine, abdomen or pelvis (see Figure 3.12). The Figure 3.13 shows the injury sources associated with the most severe injury for each body region for all pedestrians in the sample. The most frequent head injuries were caused by windshield impact and ground impact.

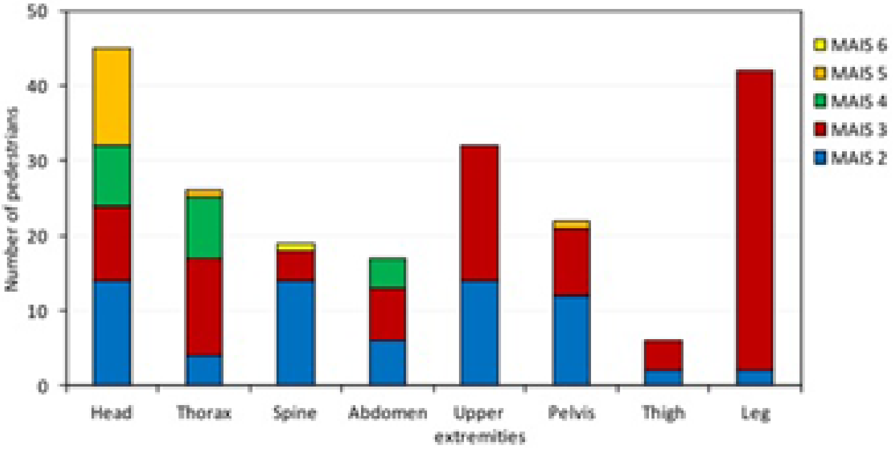


Figure 3.12: Distribution of MAIS score by pedestrian body region [2]

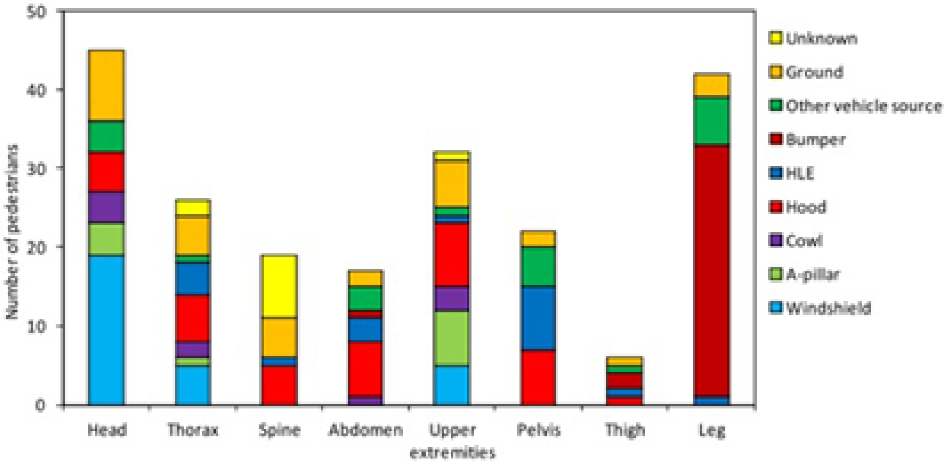


Figure 3.13: Source associated with the most severe injury by body region [2]

Chapter 4

In-depth investigation in Florence: the In-SAFE Project

4.1 Introduction

Regardless of the research on traffic accidents conducted until now, in-depth studies of the causes and behavior of vehicles involved in a crash cannot yet be considered exhaustive, and, probably never will be.

Virtually daily the environment-human-vehicle triad changes its mode of interaction with the changes in the rules, road environment, vehicles, citizen habits, etc. This means that previous discussions or research may not be the most well-representative of the real situation in which we find ourselves. Some examples are the evolution of crashworthiness and stiffness of the vehicles, as well as the car front shape or the adoption of active or passive safety devices. All this has changed considerably and quickly with the passage of time. In particular with regard to accident causes, it is extremely important to be aware of different styles and habits existing between different people's cultures.

Until today road accident research was primarily focused on the reduction of mortality. The European Union has shown, with the definition of new road safety standards for the decade 2011-2020, the goal of reducing road deaths and injuries due to road accidents. But for this latter aim it is extremely important to understand the type and severity of the injury and the mechanisms and disabilities [98].

This is why road traffic accident research, particularly related to injury awareness, is still most important for the further improvement of road safety.

4.2 The network and team structure

4.2.1 Network

A network among University of Florence, Florence Careggi Teaching Hospital, Police Forces, Emergency Medical Services (EMS) and Emergency Rooms (ER), has been created with the aim of collecting and studying data regarding serious road accidents.

The main participants of this research are the Department of Industrial Engineering (DIEF) at the University of Florence and the Intensive Care Unit (ICU) of the Emergency Department at Florence Careggi Teaching Hospital.

In 2010 a road accident investigation programme named InSAFE: In-depth Study of road Accident in FlorencE and consequently a database with the same name [99] were created.

The research programme initially obtained the ethical approval of the "*Procura della Repubblica di Firenze*" for on-scene and retrospective accident data gathering and by the *Internal Review Board* of Careggi Hospital for medical data acquisition and management. With these authorizations the investigators and researchers have had access to the following sources of information:

- police documents (e.g. reports, crash scene sketch, photographs and video, witnesses);
- injuries information;
- local/garage recovery.

This research programme is a unique activity in progress in Italy.

4.2.2 Specialists and investigation team

The *research group* is composed of the following experts:

- specialist in vehicles and accident analysis;
- specialist in emergency medicine and injury mechanisms;
- specialist in data collection systems and human factors;
- specialist in on-scene and retrospective investigations and accident causation and reconstruction;
- specialist in road design;
- specialist in injury coding and analysis;
- specialist in database development and management and data analysis;

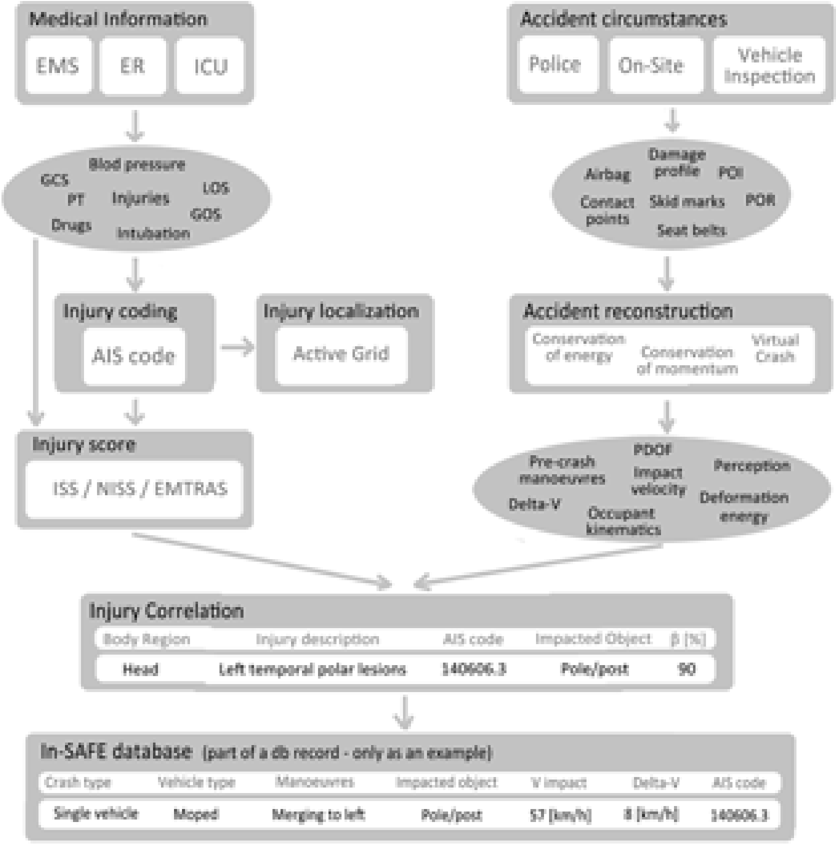
The *investigation team* is made up of 3 people: an engineer, a physician and a statistician, each properly trained in investigative techniques, accident reconstruction and causation factor analysis, injury coding, injury mechanisms and injury biomechanics, as well as data analysis techniques.

The team has collected all the information regarding accidents and victims, and successively conducted the accident reconstruction and injury analysis with the examination of its causes. All data gathered has been stored in the database. The typical work flow is shown in Figure 4.1.

4.3 Sampling plan

4.3.1 Sampling method

Since 2005 the Tuscany Trauma Network has been organized in the hub/spoke system. The Tuscany Trauma Registry (TTR) was activated in 2008. The 10 Provinces of the Tuscan region are assigned to three different ICU hubs and other



Body Region	Injury description	AIS code	Impacted Object	β [%]
Head	Left temporal polar lesions	140606.3	Pole/post	90

Crash type	Vehicle type	Manoeuvres	Impacted object	V impact	Delta-V	AIS code
Single vehicle	Moped	Merging to left	Pole/post	57 [km/h]	8 [km/h]	140606.3

Figure 4.1: InSAFE work flow showing phases and data

ICU's within the spoke function. One of the three Tuscany ICU Hubs is the "Intensive Care Unit of the Emergency Department" a partner in the study.

The principal sampling method suggested by the state-of-the-art was:

- random strategy;
- stratified strategy;
- cluster strategy; or,
- multiple strategy.

Random strategy is a basic type of sampling wherein each individual of the given population has an equal probability of being selected to participate in a study. *Stratified strategy* is the methodology used to build a stratified sample. The population is divided into different subgroups (or strata), and then the final subjects are randomly selected proportionally from the different strata. Using this method, some benefits are the smaller dimension of the sample (i.e. which can save significant time, effort and money) and the high statistical precision compared to random sampling due to the lower variability of the strata compared to the entire population.

Cluster strategy is a sampling technique where the entire population is divided in groups or clusters and a random sample of these clusters is selected. All observations in the selected clusters are included in the sample. Cluster sampling is typically used when the researcher cannot get a complete list of the members of a population they wish to study, but can get a complete list of groups or "clusters" of the population. This sampling technique may be more practical and/or economical than simple random sampling or stratified sampling [100][101][102].

The literature also suggests that *random strategy* is the best for road accident collection, as well as the most difficult to use and more expensive both in time and money. For this reason it is also possible to use random sampling where the area of sampling has been previously defined; otherwise, stratified sampling strategy is used.

The road accident study was actually carried out in a retrospective manner.

The method used in this research programme was the combination of the cluster and random techniques. The cluster was establish by:

- sampling area;
- injury severity;
- ICU admission; and,
- age.

The sampling area was created from the four Provinces, i.e. Firenze, Prato, Pistoia and Arezzo. The road accidents collected were those where there was an individual older than 16 years of age, who suffered an $ISS \geq 15$ or, more in general, had been classified as a "major trauma" and then admitted to the ICU (see Figure 4.3).

Combining the Firenze and Prato provinces, these two provinces experienced a greater number of people injured due to road accidents between the years 2009 and 2012[1] (Figure 4.2). The city of Florence and its surrounding municipalities and

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[1] ISTAT road accidents annual report

the city of Prato established a metropolitan area principally composed of urban zones and only in small part of suburban areas. This also permitted the team to conduct an in-depth study of road accidents in urban areas.

The sample was composed of random components in terms of:

- hour, weekday and month of occurrence;
- type of environment (e.g. urban, extra-urban, rural, highway);
- type of road users (e.g. vehicle, PTW, pedestrian).

In conclusion and following the previous sampling hypotheses, all the accidents with a person admitted to the ICU and that occurred in the sampling area were gathered.

In general this method leads to excluding the people either dead on-scene or with minor injuries. An exception was made for people involved in selected cases where there may have been a death or individuals not admitted to the ICU. For these people the injuries were collected by means of medical reports of the E.R. departments.

As shown in Figure 4.4, the samples gathered established a positive agreement between the major trauma cases admitted to Careggi's ICU and Tuscany's major trauma cases. Figure 4.4 shows only a minor underestimation of the cases corresponding to urban and extra urban areas.

4.3.2 Team alert system

As a consequence of the retrospective method of accident investigation, the *alert system* is based on activation from the ICU by means of a direct call or SMS.

The accident notification is carried out within the 24 hours of the occurrence of the accident. In this way the team can collected all the police information and additional road investigation data.

The team, within the successive 72 hours, localizes the vehicles involved and carries out on the inspection.

4.4 Investigation's methodology

In cooperation with the police forces, the team acquires information about the crash scene (e.g. point of impact, point of rest), environment description (roadway configuration, traffic control data, weather conditions), vehicle (type and model, engine size) and people involved in the crash (gender, age, type of licence). In Figure 4.1 the main phases of the investigation methodology are outlined.

4.4.1 On-site investigation

In particular in the metropolitan area defined in Section 4.3, and more in general when the police evaluation was not sufficiently accurate, the team collects more detailed information such as skid marks, debris, deposit of liquids, line of sight of each vehicle's driver/rider or people involved in a crash in order to substantiate the exact point of impact. Pictures are taken of the road, the trajectory

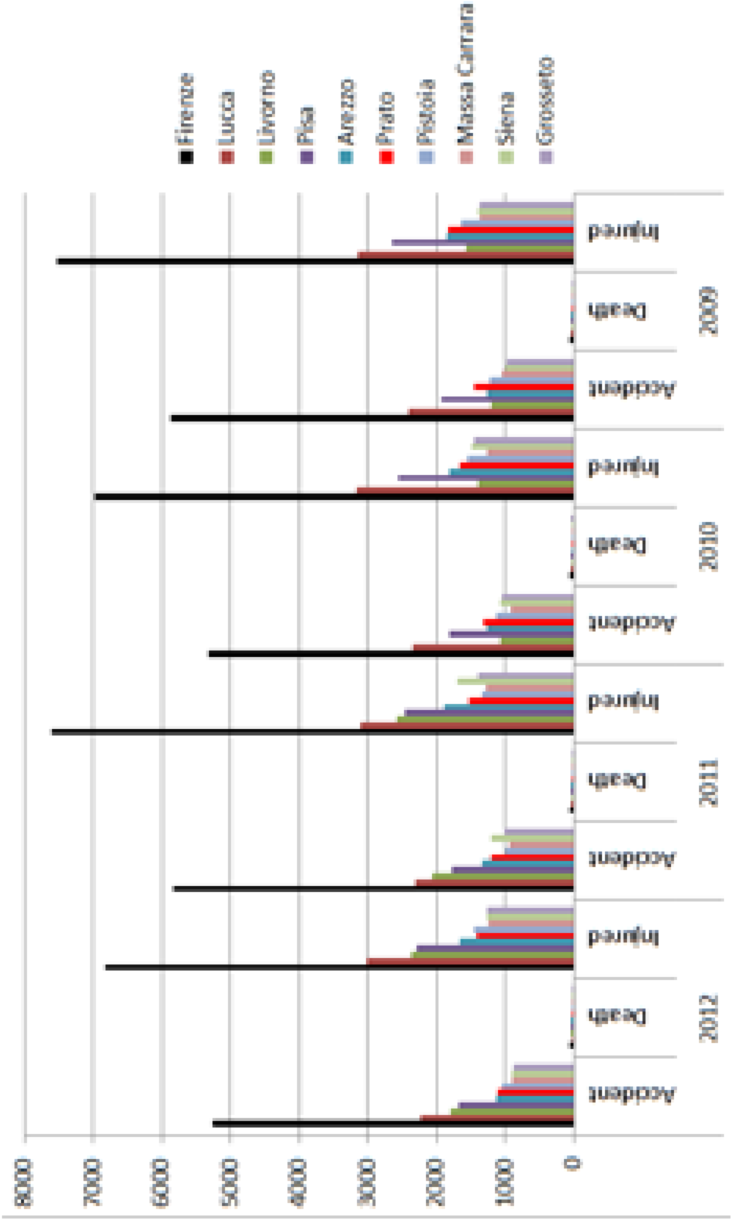


Figure 4.2: Frequency of road accidents, deaths and people injured

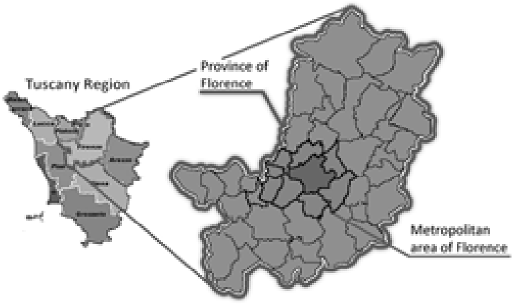


Figure 4.3: Sampling area

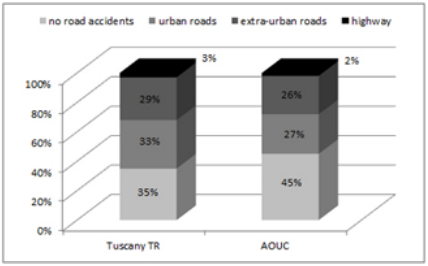


Figure 4.4: Major trauma in Tuscany and at the Careggi Hospital for 2010

followed by vehicles involved in the crash and all barriers present on the roadside are analyzed (see Figure 4.5 and 4.6).

This investigation is usually performed within 72 hours of the accident. The measurement methods used for the acquisition of additional road measurements were the triangulation method or total station instrument.

4.4.2 Vehicle investigation

When the vehicles are confiscated and brought to local recovery site, the In-SAFE team carefully examines each one involved in the accident before the vehicle is given back to the owner. Otherwise, in the circumstance where the vehicle involved is not confiscated, the inspection is done only if the owner is in agreement and with his/her written consent.

All vehicle damage and contact points are photographed both on the exterior and interior of the vehicle.

Interior parts

Vehicle interiors are thoroughly investigated to highlight possible links between injuries, contacts and for quantifying the intrusions. This data is then stored using the Passenger Compartment Classification (PCC) developed by the STAIRS

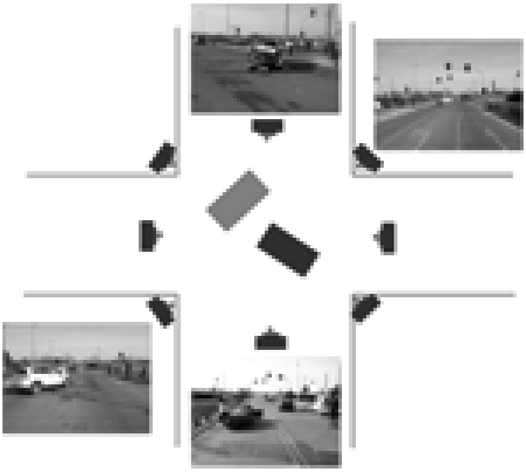
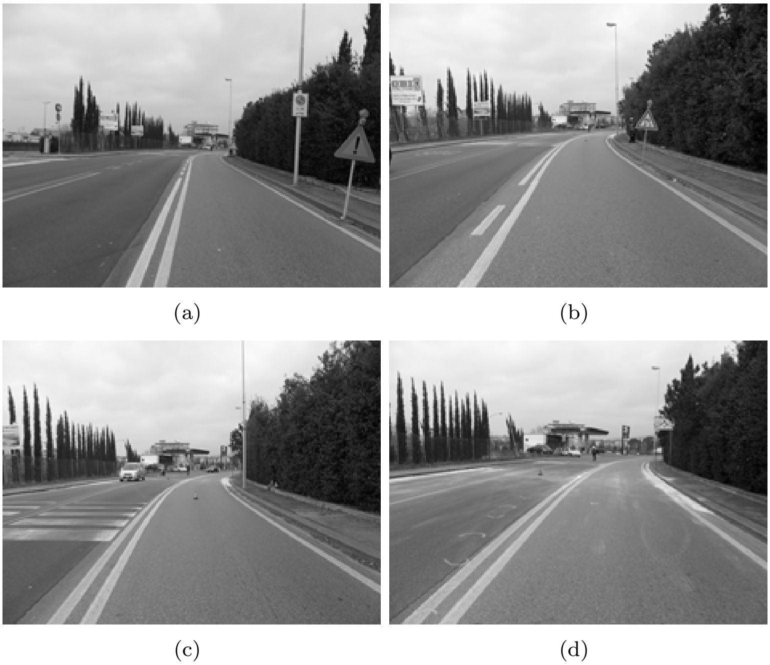


Figure 4.5: Photograph of the road accident scene



(a)

(b)

(c)

(d)

Figure 4.6: Environment and roads characteristics

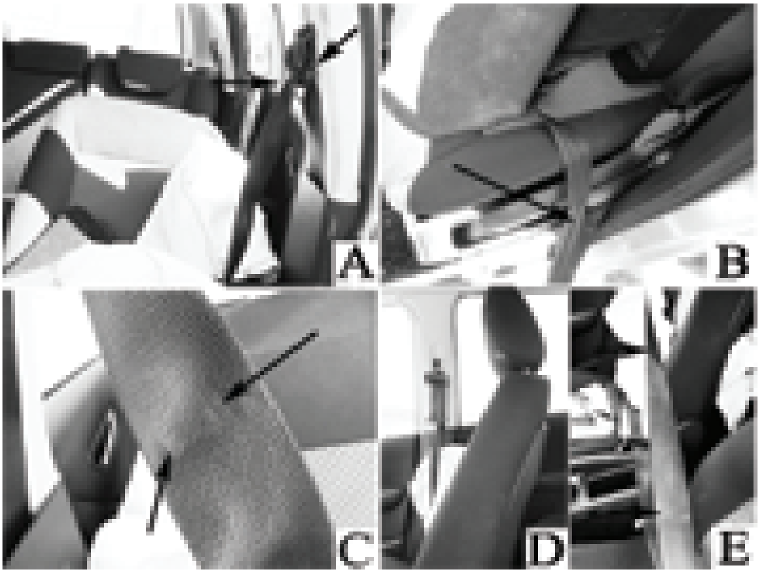


Figure 4.7: Photograph of seat belts and pretensioner status

project [17]. The principal inspections conducted by the investigator include these elements:

- seat belts and pretensioner;
- airbags;
- seat damages;
- baby restraining systems (type, model and damages);
- accelerator, brake and clutch pedals; and,
- analysis of the contact points between a person and a car's interior parts.

Special attention is given to the usage of the seat belt, activation of the pretensioner and the airbag (see Figure 4.7). The interior is also inspected to find the contacts between the occupants and the car structure. Some of the most common points of impact are the windshield (especially if the occupant is not wearing the seat belts); steering wheel; dashboard; A and B pillars and, for the rear occupants, the front seat.

Damage to seats and baby restraining systems were also analysed to understand the impact these objects had on the injuries of the people and their role during the crash. The front seat measurements acquired are those indicated in Figure 4.8.

Exterior parts

The damage profile is quantified measuring the damage width. The latter is subdivided into six parts (C1-C6), where the dimension of the damage is quantified (CRASH3 method) [103] [104].

In order to describe the nature and the location of the damage of the cars and vans, the Collision Deformation Classification (CDC)[105] is used. This code has

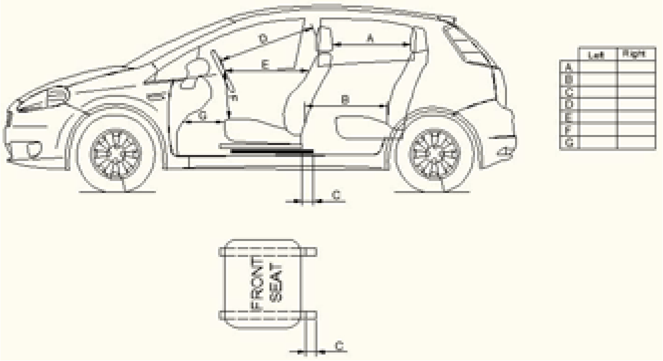


Figure 4.8: Sketch of the measurements taken of the seats

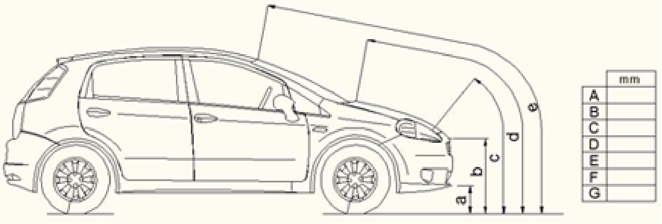


Figure 4.9: Sketch of the car front shape measurements in VRU impact

seven alphanumeric digits but, in accordance with the protocols of the STAIRS [17] and the PENDANT[106] projects, eight digits are used for a more accurate localization of the damage . The first two columns of the code describe the Principal Direction of Force (PDOF) on a clock face, the five successive columns explain the location of the damage and finally the eighth column describes the crush extent.

For accidents involving medium and heavy trucks and articulated combinations, the Truck Deformation Classification (TDC)[107] is used. To establish how a pedestrian or cyclist interacts with a vehicle during an accident, wrap-around measurements are also taken. These measurements are taken from the ground up and wrap around the vehicle Figure 4.9. Finally, for the PTW the shortening of the wheelbase is also collected.

4.5 Medical data collection

The medical data collected in the database is selected to provide a clear correlation between the dynamics of the trauma and the injury's localization and severity.

The main information for the ICU patients comes from the EMS (e.g. Glasgow Coma Scale, blood pressure, and intubation) and ER/ICU (e.g. diagnostics). The AIS, ISS and NISS scores, the EMTRAS and Computed Tomography information, are the scores and data chosen to provide the correlation between the dynamics of the accident and the injuries.

Unfortunately, for patients that are admitted to other ER's but not to the ICU, the information provided by EMS and ER medical reports is less detailed. For these cases only the AIS and ISS scores are evaluated.

4.5.1 Injury measurement and outcome scores

The principal injury measurements and outcome severity scores are the

- Abbreviated Injury Scale (AIS);
- Injury Severity Score (ISS);
- New Injury Severity Score (NISS);
- EMergency TRAuma Score (EMTRAS);
- Glasgow Coma Scale (GCS).

Abbreviated Injury Scale (AIS)

The AIS was developed by the Automotive Committee On Medical Aspects of Automotive Safety in 1971 [108].

It is a universal scoring system in the field of trauma applicable in clinical and research settings. In engineering it is commonly used as a classification system for vehicle safety. The AIS can therefore be considered as an international, interdisciplinary and universal code of injury severity. The new AIS was released with an update by the AAAM (Association for the Advancement of Automotive Medicine) in 2008.

Since different AIS versions are not always compatible, injury severity scoring tools using the new AIS should be compared to those using previous versions in terms of score and predictive performance [109]: Carroll et al. show a reduction in traumatic brain injury (TBI) AIS score when recorded using the 2005 revision versus the 1998 score [110]. For this reason the In-SAFE database includes the AIS 2005 and AIS 1998 codifications in order to assess differences in trauma severity classifications, and to allow the comparison with other databases using both revisions of the AIS. The score is an anatomically-based, consensus-derived global severity scoring system that classifies each injury by body region according to its relative importance on a 6-point ordinal scale (1=minor and 6=maximal).

Injury Severity Score (ISS) and New Injury Severity Score (NISS)

The ISS was introduced by Baker in 1974 to classify the severity of traumas involving lesions in more than one of the AIS regions. The score is calculated using the sum of the square of the three highest AIS values of three different body regions.

$$ISS = A^2 + B^2 + C^2 \tag{4.1}$$

A, B and C are the highest AIS values from the three different body regions. If a lesion is graded as AIS6, the ISS is automatically calculated as 75. No more than one AIS can be taken from a single region [109][110]. This choice puts greater emphasis on the multiplicity of trauma injury but, at the same time, it can overlook multiple lesions suffered by the same parts of the body. Another criticism is that the score assigns the same weights across different body regions. For this reason in 1997 Osler et al., developed the NISS which is calculated using the sum of the square of the 3 highest AIS's, without regard to the body region [111] [112]. The authors affirm the superiority of the NISS over the ISS to predict the outcome of the trauma patient, and this conclusion is supported by Lavoie et al. [113].

EMergency TRAuma Score (EMTRAS)

In addition to previous scores for research purposes, the EMTRAS score has also been added to the InSAFE database. EMTRAS is a new trauma score developed in Germany in 2009 that is calculated by combining four parameters from the emergency room: the age of the patient, on-scene Glasgow Coma Scale (GCS), base excess (mmol/L) and the prothrombin time at the ER (percentage value) [114].

Mangini et al. [115] show preliminary results that confirm that EMTRAS has a good correlation with mortality risk. All four parameters of the score are available in a small amount of time, allowing physicians to quickly estimate trauma patients' severity before other examinations like the CT scan are performed.

4.5.2 Other medical information

In addition to the previous medical data collected in the ICU, other information is also gathered:

- EMS rescue and physiological parameters and therapies;
- ER and ICU therapies, procedures and diagnostics;
- comorbidities.

On the accident scene, with the support of the *Emergency Medical System*, some of the principal information collected is the pulse and respiratory rate, blood pressure, use of immobilizer systems and finally the therapies provided to the casualties.

From the *Emergency Room and Intensive Care Unit* other information gathered is the main casualty treatments (e.g., intubation, therapeutic irrigation, thoracocentesis, thorax drain, etc.) and diagnostic procedures (e.g., computer tomography, total body computer tomography, RX, etc.).

Finally, the comorbidities were also collected for all patients admitted to the ICU in accordance with the International Statistical Classification of Diseases and Related Health Problems (ICD10).

4.5.3 Injury and physiological derangement evaluation

The impact of road accident dynamics and lesions on the outcome are studied by recording Length Of Stay (LOS) both in the ICU and in the hospital, if mortality occurs within 30 days or 6 months, and the follow-up program at 6 months conducted on the basis of an ICU internal program. As an indicator of the quality of life recovered at 6 months after the event (follow-up at 6 months) the Glasgow

Outcome Scale (GOS) [116] is used, as well as the questionnaire EuroQol5 EQ5-D with scale EQ5-D-VAS [117] which includes a medical examination. In case a patient does not visit a doctor, the ICU program includes a telephone interview.

4.5.4 Injury localization

All of those patients admitted to the ICU were subject to a full body CT scan.

During the meeting between the engineers and physicians to correlate each injury to its cause, as a result of the high injury detail and to help the engineers in their localization and to protect the anonymity of the people involved in the study, it is essential to have a detailed and anonymous localization of an injury.

The InSAFE system is equipped with a three-dimensional injury localization tool. The tool uses a discrete 50th percentile human body model based on a set of Computer Tomography (CT) slices. Each slice is a transverse section of the human body (X, Y plane). The three-dimensionality is due to the numbers of the slice chosen in the sagittal direction (Z axis) (Figure 4.10). On each slice it is thus possible to identify a specific injury and its extension by means of a grid drawing placed over it. All CT scans are slices of the human body not affected by specific pathologies (healthy subject).

This tool can be considered as an active system. By selecting a cell of the grid, the system stores its coordinates and the relative slice in the database. This allows us of reread the coordinates and examine the injury in a three-dimensional space.

The body regions head-face, neck, thorax and abdomen were divided, respectively, into 33, 3, 15 and 13 slices. The head and face are the body regions with the highest grid resolution: the grid dimension is equal to 5mm per side and 5mm between two adjacent slices. For the facial bones, vertebrae, rib cage, pelvis and limbs, the grid is built on anatomical atlas figures instead of CT scans.

These discrete elements (coordinates and slices) have two different advantages. The first is the possibility of an easy examination/localization of the specific injury. The second advantage is the possibility of raw data analysis. The latter seems to be more interesting since the data can be analysed both from the point of view of a specific injury, such as the incidence of the damage for specific body area, and for one specific dynamic/condition.

For example,it would be interesting to evaluate the damage distribution in terms of frequency of event, of the injuries at cerebrum and cerebellum for real pedestrian subjects, to a WRAP trajectory due to impact with a SUV. And then compared to the results with those obtained from finite element model simulations.

In conclusion, the positive aspect of this tool is not related to helping to diagnose or correlate specific injuries, but to furnish another mode of analysis of the data.

4.6 Accident reconstruction methodology

The methodology followed is the approach commonly used in the forensic field based on the evidence gathered during the investigation process in order to calculate vehicle impact speeds and to evaluate the sequence of events. The principal

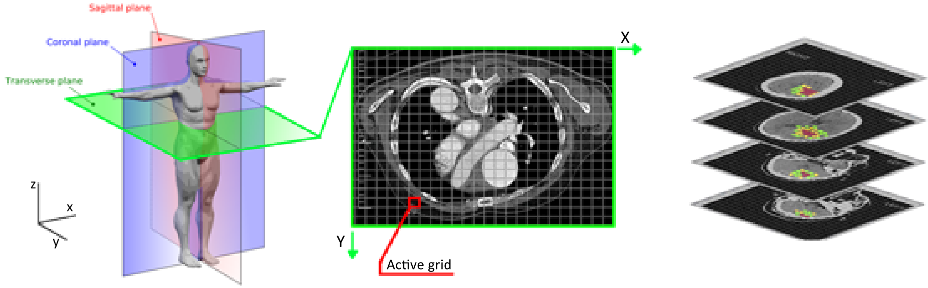


Figure 4.10: Head injury localization grid

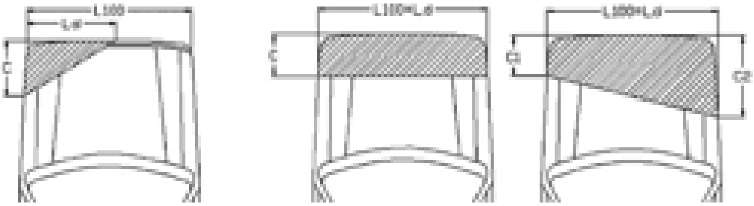


Figure 4.11: Triangle method: approximating damage on cars

techniques used are the following:

- principle of linear momentum;
- principle of conservation of angular momentum;
- crash3, EES and triangle method.

The post-crash velocity of each vehicle involved in a crash is evaluated by means of the analysis of the post-crash motion and estimation of the friction coefficient. The deformation energy and the relative speed (Vr) are estimated through the crash3 method [118], Triangle method [119][120][121] and by means of the EES comparison for cars.

The Triangle Method for car-to-car collisions combines the simplicity of the method based on EES with the flexibility of measuring the residual crush method (Crash3). This method linearizes the force versus deformation curve by approximating the damaged area with triangular, rectangular or trapezoidal geometries (see Figure 4.11). This approximation makes it possible to predetermine the analytical expression of the energy loss based on only two parameters which characterise the shape of the damage: the depth C and the width L_d. The method is based on the Campbell hypothesis when the vehicles impact against rigid barriers.

The energy absorbed by the vehicle during the compression phase can be obtained by integrating the work done by the compression force along the whole damaged profile. Using Campbell's coefficients b_0 and b_1, the correction coefficient proposed by Fonda [122] for the direction of the PDOF and with the assumption that elastic restitution is negligible, the energy of deformation can be expressed as follows:

$$E_d = \frac{M}{L \cdot \cos(PDOF)} \int_0^l \left(\frac{b_0^2}{2} + b_0 \cdot b_1 \cdot C + \frac{b_1^2 \cdot C^2}{2} \right) dl \tag{4.2}$$

and with the energy equivalent speed (EES) as

$$E_d = \frac{1}{2} \cdot m \cdot EES^2 \tag{4.3}$$

In the Triangle Method the equation of EES is obtained by reducing the damaged shape to the most basic geometry: triangular, rectangular or trapezoidal; as a function of the damage geometrical parameters C (depth) and L_d (damage width) and as a ratio to the total vehicle width L_t (total width).

$$EES\sqrt{\cos(PDOF)} = \sqrt{b_0^2 + 2b_0b_1C + b_1^2C^2} \tag{4.4}$$

$$EES\sqrt{\frac{L_t}{L_d}\cos(PDOF)} = \sqrt{b_0^2 + b_0b_1C + \frac{b_1^2C^2}{3}} \tag{4.5}$$

$$EES = \sqrt{b_0^2 + b_0b_1(C_1 + C_2) + \frac{b_1^2(C_1^2 + C_1C_2 + C_2^2)}{3}} \tag{4.6}$$

$$EES = \sqrt{0.6b_0^2 + b_0b_1C + \frac{1.4b_1^2C^2}{3}} \tag{4.7}$$

The previous equations are a linear expression of the EES as a function of C. They can be rewritten as following:

$$EES \cdot \gamma = b_0 + b_1(K \cdot C) \tag{4.8}$$

Where K is a shape parameter calculated to allow the difference in slope and intercept of the previous equations, and γ is equal to:

$$\gamma_T = \frac{L_t}{L_d}\cos(PDOF) \tag{4.9}$$

$$\gamma_R = \sqrt{\cos(PDOF)} \tag{4.10}$$

$$\gamma_O = 1 \tag{4.11}$$

The parameter K is calculated by minimising the difference between EES values obtained from the Equation 4.8 and either 4.5 or 4.7 with the least square method, and as a function of b_1.

Nullifying the derivative of the sum of the square deviations as a function of K, it is possible to obtain K = 1 for rectangular damage, K = 0.564 for triangular damage and K = 0.653 for 40% overlap crash.

The b_0 is the speed under which no permanent deformation is obtained after the crash, and in the first approximation it can be considered equal to 2 m/s.

The parameter b_1 can be calculated using a reference vehicle for which the damage and the EES parameter are known:

$$b_1 = \frac{EES\gamma - b_0}{KC} \tag{4.12}$$

Finally, by equalizing the equation 4.8, for the reference vehicle and the vehicle object of the study, it is possible to calculate the EES parameter for this latter vehicle.

$$EES_0 = \frac{1}{\gamma_0}\left[b_0 + \left(\frac{EES_r\gamma_r - b_0}{K_rCr}\right)K_oC_o\right] \tag{4.13}$$

The energy deformation for the object vehicle is:

$$E_d = \frac{1}{2}\cdot m_o \cdot ESS_o^2 \tag{4.14}$$

The energy deformation for the other vehicle involved in the crash can be calculated as:

$$E_{d_B} = E_{d_A}\frac{(KC+\delta)_B}{(KC+\delta)_A} \tag{4.15}$$

Where $\delta = A/B$ and A and B are the stiffness coefficients of the vehicle according to Campbell's theory, the parameter δ is substantially constant for all the vehicles. Vangi finds three different values for δ as a function of the damage location (see Table 4.1).

Table 4.1: Values for the δ parameter

Damage location	(m)
Front	0,071
Side	0,036
Rear	0,08

The deformation energy absorbed by PTW vehicles is estimated by the use of the empirical equation based on the wheelbase's reduction by Vangi [123] and Wood [124].

Combining literature and experimental data, Vangi finds a direct relation between EES and wheelbase's reduction (ΔP) as shown in Equation 4.16.

$$EES = b_0 + b_1\Delta P \tag{4.16}$$

Where b_0 is equal to 2.91 and b_1 is equal to 37.19.

The energy absorbed by the PTW is equal to:

$$E_d = \frac{1}{2}m_M EES^2 = \frac{1}{2}m_M\left(b_0 + b_1\Delta P\right)^2 \tag{4.17}$$

This method is applicable only when the wheelbase's shortening is less than 0.45m, i.e. until the front structure of the PTW breaks down.

Wood [124] found a similar method in the estimation of the energy absorbed by the PTW. In this case the equation proposed is the following:

$$E_d = M_m\left[641.7\left(\Delta P + 0.1\right)^{1.89}\right] \tag{4.18}$$

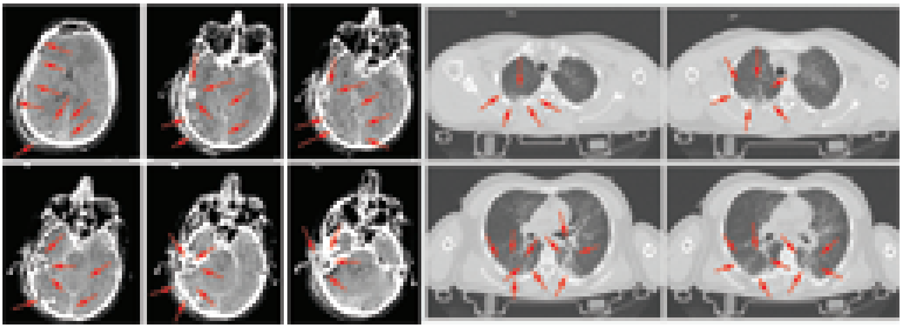


Figure 4.12: Correlation of head and thorax injuries

The impact velocity of each vehicle can be assessed by applying both the principles of conservation of energy and the conservation of momentum. The principles of conservation of energy is preferred to the conservation of momentum due to less sensitivity to the input parameters variation.

By the use of the multibody accident reconstruction software (PC-Crash and Virtual CRASH), all the above data has been verified and validated, especially when PTW vehicles are involved.

4.7 Injury to cause correlation

The core of the work done is the injury-to-cause linkage process, since it is possible to connect two or more different types of data: on one hand physics data (i.e. contact, impact velocity, etc.), and on the other hand injury data (i.e. type, location and severity).

The kinematics and dynamics of vehicles and people and their injuries, are evaluated at the same time in order to identify the possible mechanisms of injury. Based on all previous data and bibliography data, this process is accomplished by a meeting between ICU physicians and engineers.

In the end a confidence level on the process was assigned for each association, see Figure 4.12 and Table 4.2. This confidence level highlights the quality of the connection. The connection's reliability is defined on three levels:

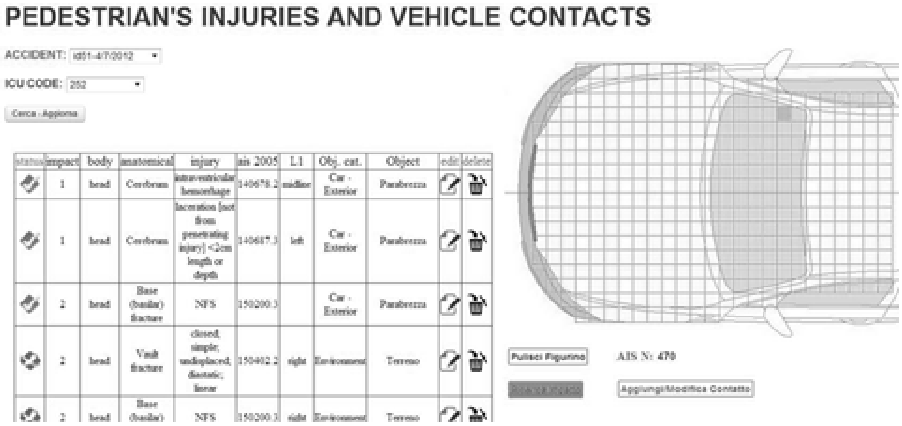
- confident
- probable
- possible

The correlation which assigns a confidence level of *possible*, requires a more in-depth biomechanic study for a better evaluation of injury mechanisms (e.g. crash tests and/or computer simulation).

In the case of a road accident with the involvement of pedestrians and cyclists (VRU), an additional method for linking a VRU's injury and vehicle contact is shown in Figure 4.13. Therefore, by using this unified representation, it is then possible to analyse the injury severity, injury type, etc. with different cars' impact points.

Table 4.2: Summary of the correlation results between injuries and causes

Body region	Injury description	AIS code	Impacted object	Confidence level
Head	Left temporal polar lesions	140606.3	Pole/post	Confident
Head	Millimetric left frontal parietal subdural hemorrhage	140651.3	Pole/post	Confident
Head	Widespread cerebral oedema	140670.3	Asphalt	Confident
Head	Right temporal parietal occipital depressed fracture	150404.3	Asphalt	Confident
Head	Right temporal styloid process fracture	150402.2	Asphalt	Confident
Head	Lacerated and contused right temporal parietal (2,5cm) lesions	140616.4	Asphalt	Confident
Head	Pneumocephalus bubbles	140682.3	Asphalt	Confident
Head	Peri mesencephalic subarachnoid haemorrhage, with relative encephalic pons and mesencephalic hypodensity	140695.3	Asphalt	Probable
External	Contused and lacerated wounds to the face, hematoma lateral	910400.1	Asphalt	Possible
Thorax	Contusion of the right upper lobe Right paravertebral inferior lobe and left paravertebral inferior lobe contusion	441412.4	Asphalt	Confident



PEDESTRIAN'S INJURIES AND VEHICLE CONTACTS

ACCIDENT: id51-4/7/2012

ICU CODE: 252

status	impact	body	anatomical	injury	ais 2005	L1	Obj. cat.	Object	edit	delete
	1	head	Cerebrum	intraventricular hemorrhage	140678.2	midline	Car - Exterior	Parabrezza		
	1	head	Cerebrum	laceration [not from penetrating injury] <2cm length or depth	140687.3	left	Car - Exterior	Parabrezza		
	2	head	Base (basilar) fracture	NFS	150200.3		Car - Exterior	Parabrezza		
	2	head	Vault fracture	closed; simple; undisplaced; diastatic; linear	150402.2	right	Environment	Terreno		
	2	head	Base (basilar)	NFS	150200.3	right	Environment	Terreno		

AIS N: 470

Figure 4.13: Connection between VRU injuries and vehicle contacts

4.8 The InSAFE database

In this section the methodology followed to store all the previous information will be explained. The Relational Database Management Systems (RDMS) was used to accomplish this.

This technology, defining appropriate relationships, allows the linkage of different data previous organized in tables. In this way, by defining appropriate querying procedures, it is possible to extract the data into the desired sequence/structure.

This procedure makes the road accident data usable in either the combined or single mode.

4.8.1 Technologies, structures and interfaces

The most advantageous database structure for the management of the insertion, modification and deletion of the accident data is based on a 3-Tier Web Architecture. The tiers are summarized on the following layers:

- presentation;
- logic;
- data.

Presentation is a static or dynamically generated content rendered by the browser (front-end).

The logic layer is a dynamic content processing and generation level application server (e.g. Java EE, ASP.NET, PHP). The third layer is a database comprising both data sets and the database management system or RDBMS software that manages and provides access to the data (back-end). The information flowing between users and database occur on the Local Area Network (LAN) of the Department of Industrial Engineering (DIEF), and the access is defended by double protection: LAN and web browser authentication.

The core system is an open source web-server solution that hosts the database, configured with a Linux distribution and a software package LAMP (acronym of Linux, Apache, MySQL and PHP), for the use and sharing of the database on the web. Linux is the operating system for the database machine; Apache is a web server application that permits the page viewing and the dynamic management of the database; MySQL is a computer language used both to store and retrieve data; finally, PHP is a general-purpose scripting language used for the web access page (front-end). The latter was also developed using the Content Management System (CMS), HTML and JavaScript. With this framework, the InSAFE users through their own web browsers, communicate with the database (PC client). The InSAFE database is a dynamic system that continually upgrades the data stored in it.

4.8.2 Clustering and typology of data stored

InSAFE is an in-depth database made up of around 1500 variables. Each of these elements are clustered into three macro entities:

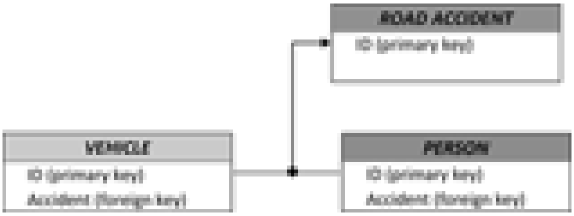


Figure 4.14: Main macro cluster of InSAFE's database data

- road accident;
- vehicle;
- person.

Road accident is the principal entity which is connected to all the others ones. These macro entities are then divided into the smallest cluster (i.e. tables). Each table is then connected to the others by means of primary and foreign keys, respecting the relations among the tables (see Figure 4.14). The *vehicle* entity includes all types of vehicles: bicycles, PTWs (scooter, moped and motorcycle), cars, trucks and buses. All people involved in the crash are entered in the macro entity *person.*

Road accident

The *road accident* entity is divided into the following data subclasses:

- date of accident;
- type of accident;
- standard codification;
- police;
- scene localization;
- description of road;
- weather conditions;
- brief description of the accident; and,
- documents produced.

The element *type of accident* includes the following road accident crashes: vehicle-to-vehicle, single vehicle, vehicle-to-cyclist and vehicle-to-pedestrian. Cars, trucks, buses and PTWs have been included in the vehicle element.

Each accident has been codified with the CaDaS, GDV and VALT systems. CaDaS system is the codification used in the CARE database, GDV is used in the *German Insurance Industry* and VALT code is used in the *Finnish Motor Insurers' Centre* (Finland). All the previous codes have also been included in the DaCoTA database.

In the *description of the road* section the road entities are described in detail. For each road the principal information recorded concerns: technical identification, carriageway's subdivision, roadway conditions, roadway alignment, roadside barriers and the traffic conditions.

Vehicle

All the information regarding the vehicles involved in the crash are included in this cluster. The principal vehicle's variables were:

- vehicle's feature;
- damages information;
- pre-crash information;
- crash information;
- post-crash information.

The primary input of the first item was the vehicle's make and model, registration year, engine size, number of seats and their disposition, active and passive protection devices (e.g. ABS, ESP, AEB, airbags, etc.).

The data gathered in *pre-crash info* includes what the driver or rider were doing before and after the precipitating event as, e.g., moving in a straight line with constant speed, passing on the left, changing lane to left, evasive manoeuvre, collision avoidance actions, steering action before the crash.

The variables for the *crash information* set are collected from the crash reconstruction phase and include collision speed, delta-V, post impact velocity, PDOF, EES, deformation energy and deformation's measurements.

Person

The person macro entity includes information regarding the people involved in the crash. These are principally related to:

- demographic data;
- equipment;
- medical information and injuries;
- pre-crash information;
- post-crash information;
- accident causation.

Information on the usage of protection devices includes seat belts, baby restraining systems, helmet (type, model and damage) and specific clothing for motorcyclists are included in equipment. The *pre-crash* and *crash info* sections are comprised of variables regarding the psychophysical conditions and human factors which could have produced the accident, possibility of a line of vision blocked by means of mobile or fixed obstacles, pedestrian's movement, pedestrian's trajectory followed (e.g. wrap, forward, fender vault), rest position, etc. While in the *medical information and injuries* section are collected all the information regarding type of injuries, injury outcome, etc. as shown in the Section 4.5.

Finally, in *accident causation*, the variables regarding the causation mechanisms of the crash based on the Driving Reliability and Error Analysis Method (DREAM) are included. The causation mechanisms analysis can easily lead to a specific sub cluster of data (see Chapter 6).

Chapter 5

Accident analysis of the InSAFE database

5.1 Accident configuration

Between 2009 and 2013 (2010 was omitted because the collection was suspended to allow for the database's release) the ICU has transmitted to the InSAFE team 363 serious road accidents, which have occurred in the sampling area. The investigation team has been able to gather information on 207 (57%), of the road accidents. The percentage of road accidents not retrieved is equal to 43% (see Table 5.1).

The principal causes of this loss of data is due to an inadequate participation of some police districts (especially those which are for farther from Florence), a deficit of accident data and/or the inability to locate the police district that provided the accident's relief. Of these 207 road accidents gathered, 80 cases occurred mainly in urban areas have been studied.

Among the 80 accidents, a total of 124 different vehicles were involved. Of these, the majority are cars (56.5%) and PTWs (32.3%) (see Table 5.2). Within the sample, the most frequent serious road accidents are the *vehicle-to-vehicle* (44.3%) and *vehicle-to-pedestrian* (41,2%) crashes (Table 5.3). In the *vehicle-to-vehicle* class (Table 5.4) the most frequent are *car-to-ptw* crashes (62%), while in the *single-vehicle* class the highest percentage is that of ptw's users (50%). Looking at the VRUs, these make up about 50% of the total sample studied, the majority are *car-to-pedestrian* impacts. In the urban area the principal acci-

Table 5.1: Number of road accidents transmitted and retrieved by the team

Years	ICU Transmitted	InSAFE Retrieved	
2009	106	40	37,7%
2011	97	59	60,8%
2012	85	45	52,9%
2013	75	63	84,0%
Total	363	207	57,0%

Table 5.2: Types of vehicles involved in the accident sample analyzed

	N	%
Cars	70	56,5%
PTWs	40	32,3%
Buses	4	3,5%
Trucks	2	1,6%
Bicycles	8	7,0%
Total	124	100,0%

Table 5.3: Types of crashes

	N	%
Vehicle to Vehicle	33	41,3%
Single Vehicle	8	10,0%
Vehicle to Bicycle	6	7,5%
Vehicle to Pedestrian	33	41,3%
Total	80	100

Table 5.4: Vehicle-to-vehicle crash types

	N	%
car to car	7	18%
car to ptw	24	62%
car to bicycle	4	10%
truck to ptw	2	5%
ptw to bicycle	2	5%
Total	39	

Table 5.5: Single vehicle crash types

	N	%
single car	3	38%
single ptw	4	50%
single bicycle	1	13%
Total	8	

Table 5.6: Pedestrian crash types

	N	%
car to pedestrian	22	67%
ptw to pedestrian	7	21%
bus to pedestrian	3	9%
bicycle to pedestrian	1	3%
Total	33	

dent configuration in the *vehicle-to-vehicle* class is the *head-on side crash* (67% of total) followed by the *head-on crash* (23%) collisions, both for the subclass *car-to-car* and for *car-to-ptw* and *car-to-bicycle* subclasses (see Table 5.7). The 80 road accidents studied principally came from the province of Firenze (84%) and in particular from the metropolitan area of Firenze (56%), Prato (12.5%) and the surrounding municipalities (10%).For these reasons the accidents occurred principally in the urban scenario (89%), in corresponding residential areas (69%), and on roads without intersections or roundabouts see Figure 5.1(a) and Figure 5.1(b)). In general the weather conditions during which the road accidents occurred were essentially clear/sunny (80%) and, in only 12.5% of cases was the weather raining or cloudy (7.5%). It was daylight in 60% of the cases and in only 32% of the accidents occurred at night with public illumination. Also for the VRUs the previous considerations can be reiterated, with the addition that the VRU impacts generally occurred with good visibility conditions: without clouds (36%) or very few (28%).

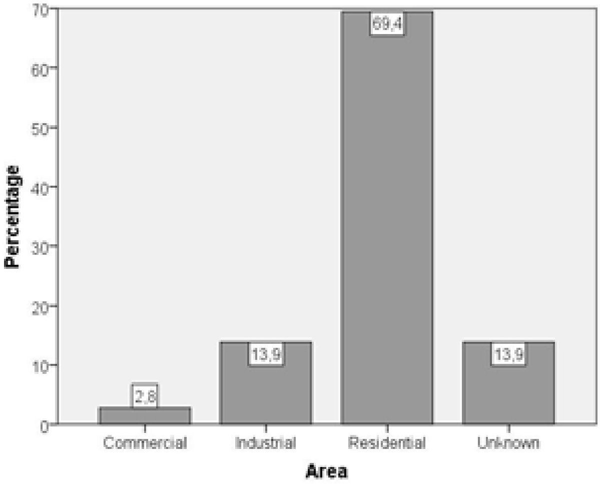
Table 5.7: Vehicle-to-vehicle accident configurations

		N	%
car-to-car	head-on crash	2	28,6%
	head-on side crash	4	57,1%
	nose to tail crash	1	14,3%
	Total	7	100,0%
car-to-ptw	head-on crash	6	25,0%
	head-on side crash	16	66,7%
	nose to tail crash	1	4,2%
	side crash	1	4,2%
	Total	24	100,0%
car-to-bicycle	head-on side crash	4	100%
	Total	4	100,0%
truck-to-ptw	head-on crash	1	50,0%
	nose to tail crash	1	50,0%
	Total	2	100,0%
ptw-to-bicycle	head-on side crash	2	100%
	Total	2	100,0%

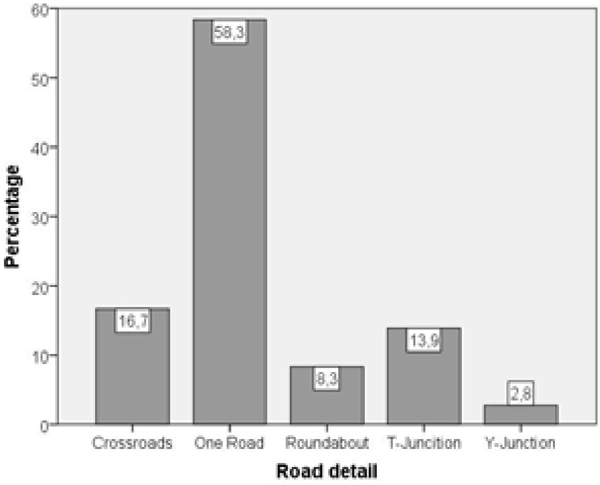
Of the 80 serious road accidents, the majority occurred mainly on one carriageway roads (90%) with two-way traffic flow conditions (73.2%) and one lane in each direction (60%).

In terms of roadway configurations closest to the point of impact (in total 97 streets), dividing it into *horizontal alignment* (e.g. straight road or curved) and *vertical alignment* (e.g. level, up or down). Both before, at the point of or after the crash, the prevailing configuration is a flat and straight road (about 80%). There were no other interesting road details in terms of curves and slope (see Figure 5.2 and Figure 5.3).

Give the limited dimension of the sample, the successive analysis will be focused only on the VRUs (cyclists and pedestrians) and PTWs users' groups, composed

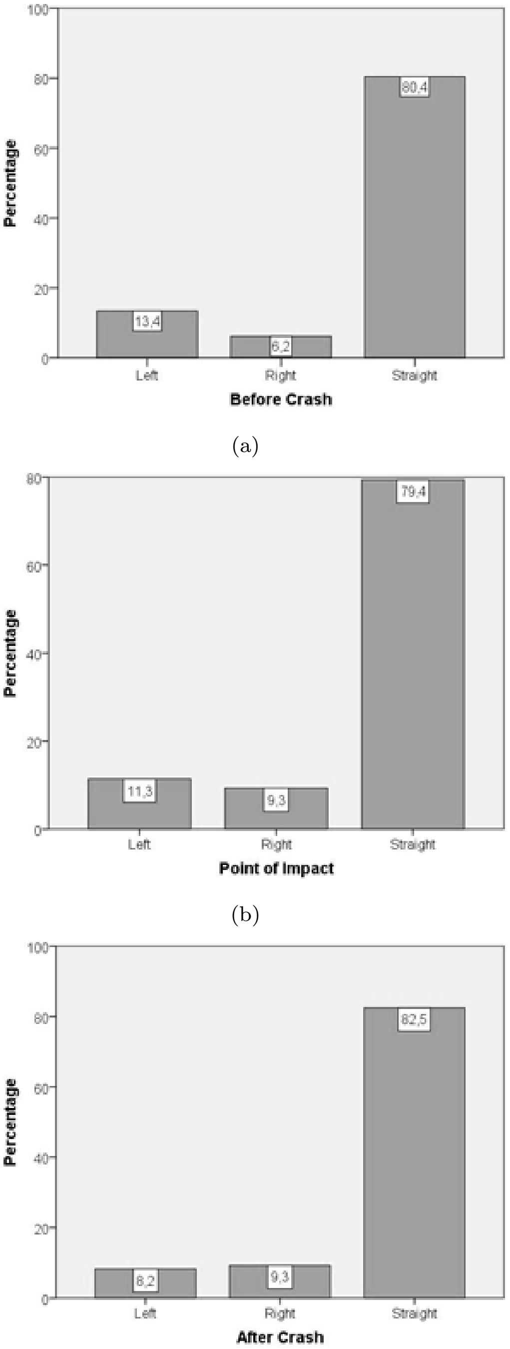


(a)



(b)

Figure 5.1: Environment and road characteristics (80 cases)



(a)

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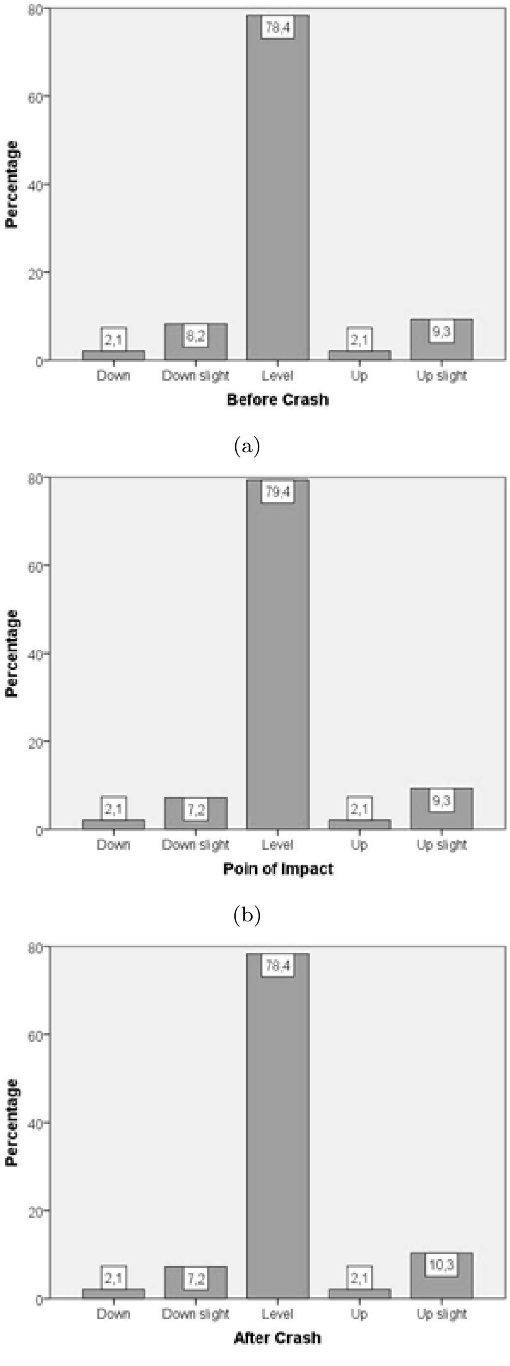
Figure 5.2: Roadway's horizontal alignment (97 cases)



(a)

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Figure 5.3: Roadway's vertical alignment (97 total)

of 33 and 26 accidents respectively.

5.1.1 Powered Two-Wheeler users

In the sample analysed (32 cases) and according to VALT coding, the most dangerous urban scenarios for PTW users are the intersections where both vehicles want to go straight (26.9%) (code 40), followed by the crossroad scenario where one of the two vehicles turns left and the other is moving in the same direction (code 30). In third position are head-on collisions (codes 20 and 21) that together compose 15.5% (see Figure 5.4), with the majority occurring at a curve (11.5% compared to 3.8%). In approximately 75% of the frequencies, two-way urban roads are those most subject to serious accidents involving PTW users.

In 80% of the cases the rider's is accident occurs on a straight road. PTW accidents in isolated curves arise only in 14.4% of the total PTW vehicles involved.

The PTWs that are in a left curve before the crash have a higher frequency (12.2%) than the PTWs that are in a right curve before the crash.

The majority of these types of accidents take place on asphalt roads (98%), dry (85%) and in day-light (53%) conditions. In terms of traffic conditions the most frequency modalities are moderate and light (both at 42%).

Finally, in 95% of the accidents with VRU the road was asphalted and in 85% of the cases it was dry. The traffic was generally moderate (55%) and in only 15% of the accidents was heavily congested (see Figure 5.5).

5.1.2 Vulnerable Road Users

The most dangerous urban scenarios for the VRUs are crosswalks on roads without junctions (73%) followed by 18% of the cases where the accident happened at intersections (see Figure 5.6) (39 total cases).

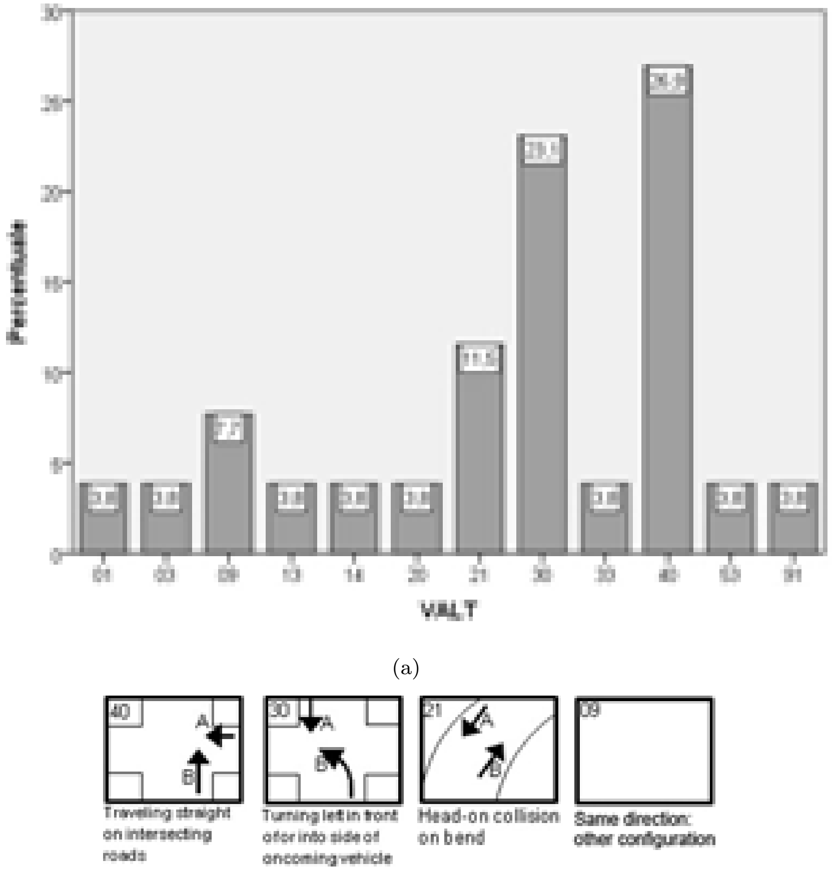
The VALT codification shows that accidents where the VRUs are hit in a crosswalk evidences clear visibility for driver or rider (code 64: pedestrian on crossing outside area of road intersection) (28.1%). And, at the same frequency, the pedestrians are hit while crossing the road outside of the crosswalk (code 71).

Finally, another typical situation for urban traffic is the VALT 65 code, where the vehicle overtakes another vehicle that had stopped to allow the pedestrian to proceed (12.5%). Two-way roads are the most dangerous with a frequency of 64%, while the remaining VRU accidents occur on one-way roads. In 80% of the cases the VRU impacts are on straight roads and 16% occur on isolated curves.

In terms of the roadway's configuration (in total 40 streets), it has been surmised that the combination of straight and flat roads is the most critical scenario for VRUs. This is probably due to fact that in these conditions less attention is paid to driving.

Another interesting aspect is the road's shape before the crash. An pedestrian impact is two times more likely to occur on the left curve (7.1%) than the right curve (3.6%). While there are no differences between a pedestrian accident occurring on either the right curve or on the left curve.

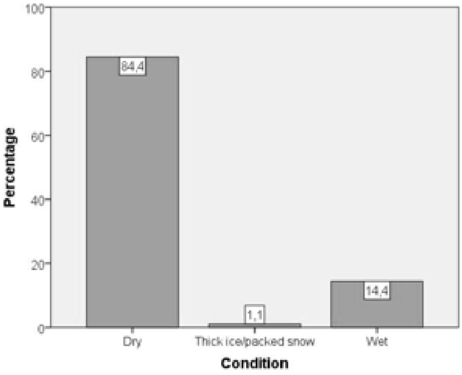
Examining the roadside barriers which a pedestrian could hit, the most frequent are:



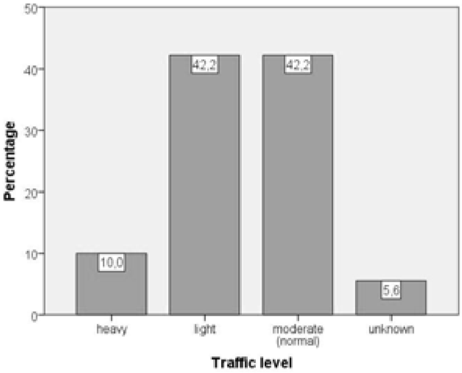
(a)

(b)

Figure 5.4: Urban crash scenarios for PTW users: VALT code (32 cases)



(a)



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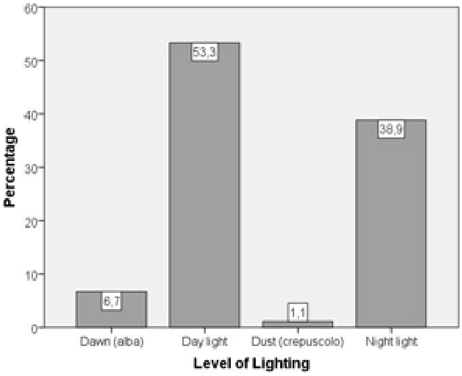
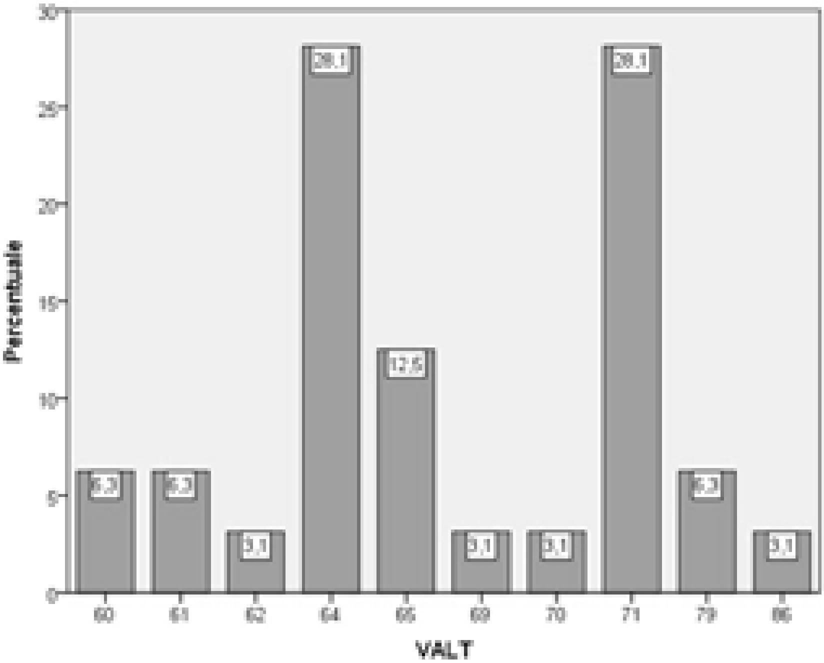
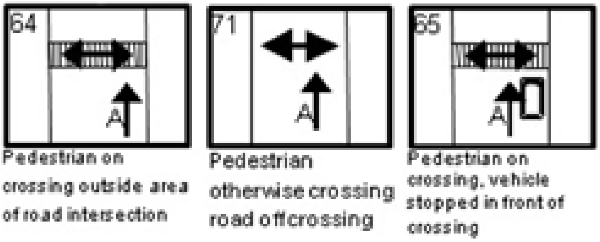


(c)

Figure 5.5: Road, traffic and light conditions in road accidents with PTW



(a)



(b)

Figure 5.6: Urban crash scenarios for VRUs: VALT code (39 cases)

- from the right side of the road, the barriers nearest to the vehicle lane are parked vehicles (25%), hedge/shoulder (10%) and guard rail (7.5%). The other barriers immediately adjacent to the previous (outwards) are sidewalk (37.5%) and bulding/structures (12.5%). While,
- from the left side of the road, the barriers nearest to the vehicle lane are sidewalk (27.5%), parked vehicle (17.5%) and hedge/shoulder (15%). The other barriers immediately adjacent to the previous (outwards) are sidewalk (30%) and bulding/structures (15%).

Finally, in 95% of the VRU impacts the road was asphalted and in 85% of the cases it was dry. The traffic was generally moderate (55%) and in only 15% of the accidents was heavily congested.

5.2 Vehicle characteristics

As shown in Table 5.2, the prevailing vehicles implicated in urban/metropolitan crashes which have produced major traumas are cars (56.5%) and PTWs (32.5%).

The majority of the cars were registered after 2000 and also in this case, due to retrospective investigative activity, the level of unknown information is significant (17%). One cause of this loss of data arises from the inability to track all the vehicles involved, but it is also because of the incomplete collection of data by the police.

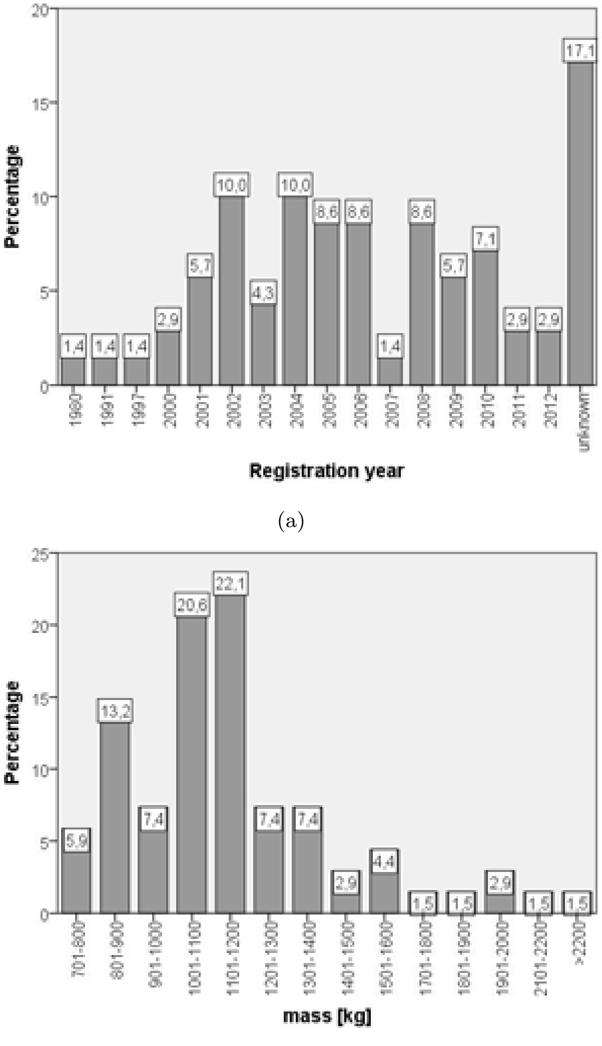
The most frequently type of car involved in these crashes is the economy/small car with a mass less than 1200 kg (about 70% of the total). In more detail the automobiles with a mass between 1000-1200 kg are the most prevalent (42.7%) (Figure 5.7).

The PTW vehicles are been divided in five classes. In the *conventional street* class are included all motorcycles naked or, in general, with medium dimensions (Yamaha FZ6, Honda Hornet, etc.), the *sport* class include all the motorcycles with a typical motorcycles that derive from the sporting competitions (Yamaha R1, Honda CBR, etc.), the *touring* class include big motorcycles with a setting of comfortable driving (Kawasaki GTR, Yamaha FJR, BMW F-800st, etc.), in the scooter are included all types of scooters and, in conclusion, the *enduro* class include motocross, supermotard and, more in general, dual-sports types.

Among the PTW vehicles, scooters are the most frequent type (72.5%). Of these 40% are small engine scooters (i.e. 50cc), while approximately 37% are in the range of 125-150cc (see Figure 5.8). In conclusion, about 70% of the scooters had a rear box and/or high windshield. With regard to motorcycles, the most common are the sports type (10%), and in terms of engine capacity the most prevalent is that within the range of 600-750cc (60%), see Figure 5.9(a)).

5.2.1 Vehicle's behaviour in VRU's accident

In the sample analysed (39 cases), the prevailingly pre-crash action taken by the drivers and riders involved in VRU impacts are driving in a straight line at a constant speed (71%) or accelerating (7.9%), followed by entering, driving around or leaving a roundabout (5.3%).



(a)

(b)

Figure 5.7: Car's registration year and mass (total cases 70)

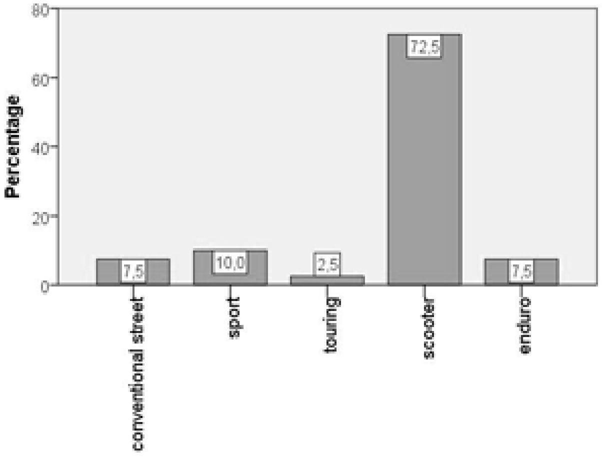


Figure 5.8: Powered Two Wheeler types (total cases 40)

Following the precipitating event (i.e. after the driver becomes aware of the VRU) and based on evidence and reconstruction analysis, in 63% of the cases gathered the driver brakes or swerves (11%), and in 26% does not take any action.

In pedestrian accidents where the operator has swerved, in 21% of the cases it is more likely that the action/decision was deemed to be correct and useful for the purpose of avoiding the impact.

The traveling speed of the vehicle before the driver becomes aware of the VRU is summarized in Table 5.8. For the sample, the mean value of the velocity is about 49 km/h.

Table 5.8: Traveling speed for VRU's impact

Min	Max	Mean		Std. Deviation
km/h	km/h	km/h	Std Error	km/h
12	70	49,1	2,444	15,1

In terms of impact speed, 85% of the accidents occurred at a velocity under 50 km/h and the majority take place in the range of 25 and 45 km/h. The mean value of the impact velocity is 38.4 km/h and the result of the sample values are essentially scattered around that number (Figure 5.10).

5.2.2 Vehicle's behaviour in PTW-to-OV crashes

In 27 PTW-to-OV[1] crashes, the principal manoeuvres that the riders followed before the precipitating event were *driving in a straight line at a constant speed* (57%) followed by the same condition but *accelerating* (14%). While for drivers,

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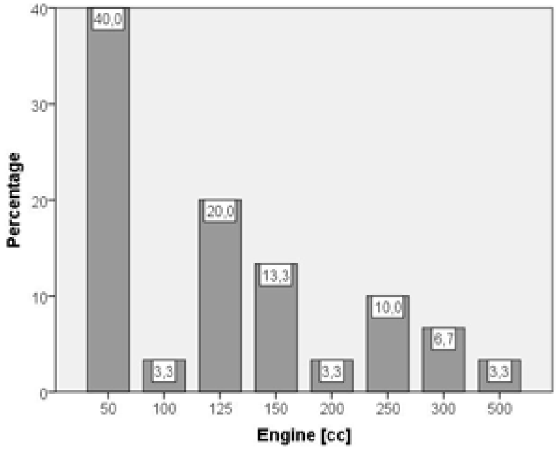
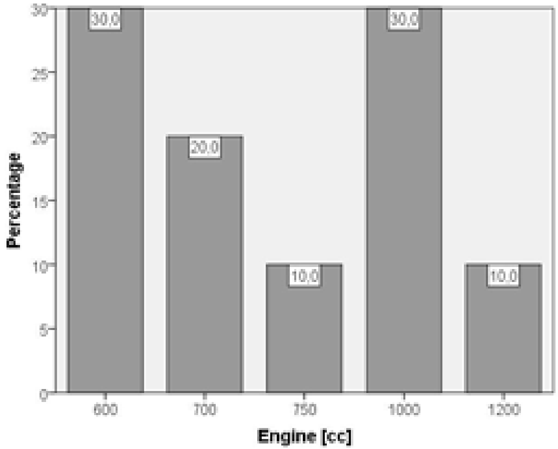
[1] OV = Other Vehicle

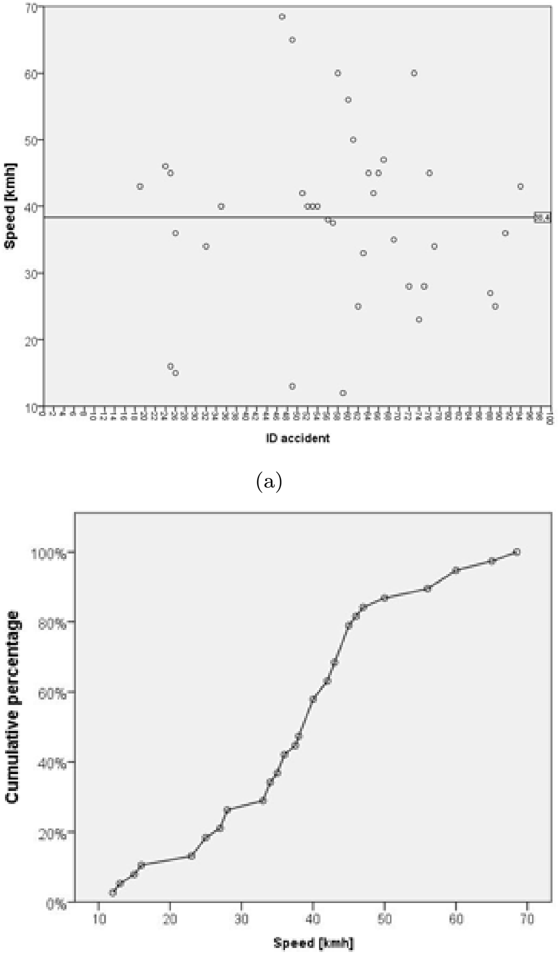


(a) Scooter



(b) Motorcycle

Figure 5.9: PTW's engine size (total cases 40)



(a)

(b)

Figure 5.10: Impact speed distribution and cumulative percentage (39 cases)

driving in a *straight line at a constant speed* was the most prevalent (32%), followed by *turning to the left and then accelerating* (12%) and entering road traffic from the right shoulder or stopped in traffic or at the side of the road (8%) (see Figure 5.11 and Figure 5.12).

After the precipitating event (PE) riders and drivers continue the previous manoeuvre (*the driving condition before the precipitating event for PTW and cars*), 28.6% and 20% respectively. In 21.4% of the PTWs, the rider is driving in a straight line but then brakes, while the drivers go on with the left turn (16%). In terms of *avoidance actions* taken by riders and drivers after the precipitating event, the data gathered highlights that riders brake more frequently than drivers (67% versus 33%), while the majority of drivers do not take any action (64% versus 36%).

A swerve action is taken in the same percentage by riders and drivers. And in both cases it emerges that this is the correct decision, but not sufficient to avoid the crash (see Table 5.9). In 14% of the cases do the PTW users lose control of the motorcycle due to blocking of the wheels.

Table 5.9: Avoidance action by drivers and riders

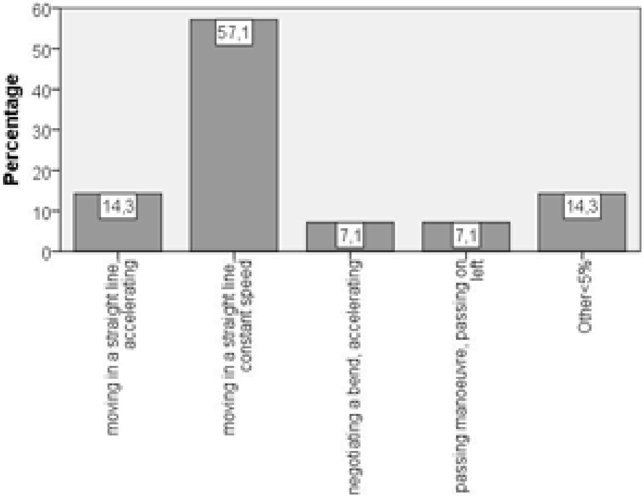
		Avoidance action				Total
		braking	none	swerve	unknown	
ptw	Count	12	8	3	5	28
	% in type	43%	29%	11%	18%	100%
	% in avoidance action	67%	36%	50%	71%	53%
car	Count	6	14	3	2	25
	% in type	24%	56%	12%	8%	100%
	% in avoidance action	33%	64%	50%	29%	47%
Total	Count	18	22	6	7	53
	% in type	34%	42%	11%	13%	100%
	% in avoidance action	100%	100%	100%	100%	100%

For PTW vehicles the mean value of the impact speed is 47.4 km/h, while the mean value of the variation speed is 41 km/h (see Table 5.10). As shown in Figure 5.13, 80% of the road accidents gathered occurred at a PTW impact speed less than 60 km/h and the most common velocity range was 40-50 km/h.

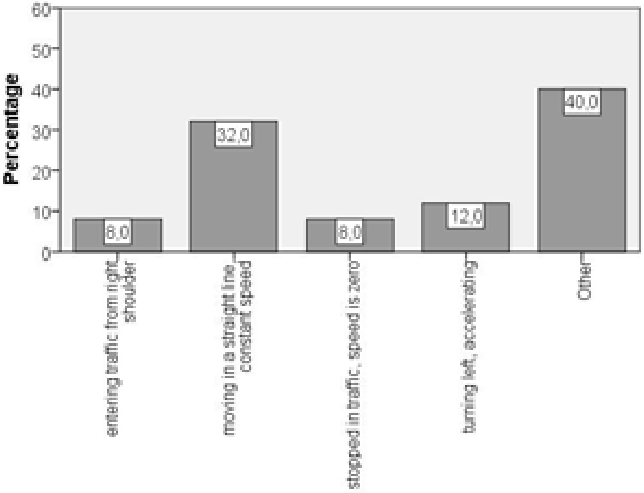
The most frequent PTW PDOF is at 12 o'clock in 46.2% of the cases, followed by 11 and 1 o'clock (see Figure 5.14(a)). The PDOF values are in agreement in the majority of PTW frontal impacts present in the sample.

Table 5.10: Impact and variation speed for PTW and car vehicles

		Min	Max	Mean	Std. Deviation
ptw	Impact speed [km/h]	20	88	47,4	16,5
	Delta V [km/h]	1	128	41,0	27,6
car	Impact speed [km/h]	8	75	33,0	18,4
	Delta V [km/h]	0,5	31,2	5,0	5,9

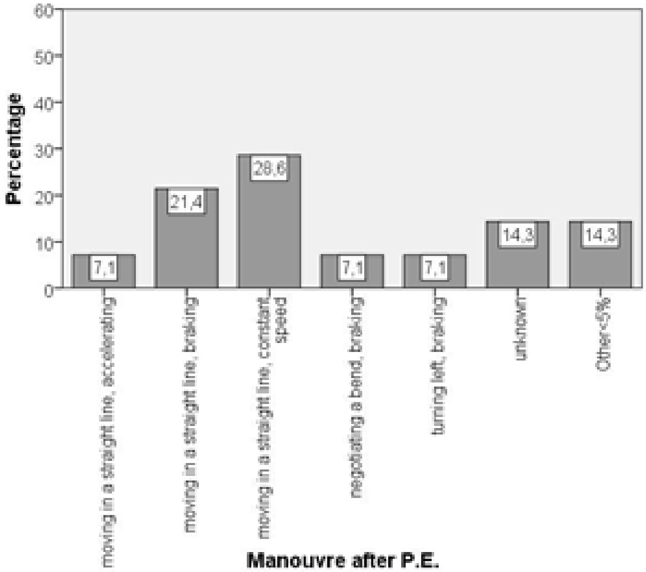


(a)

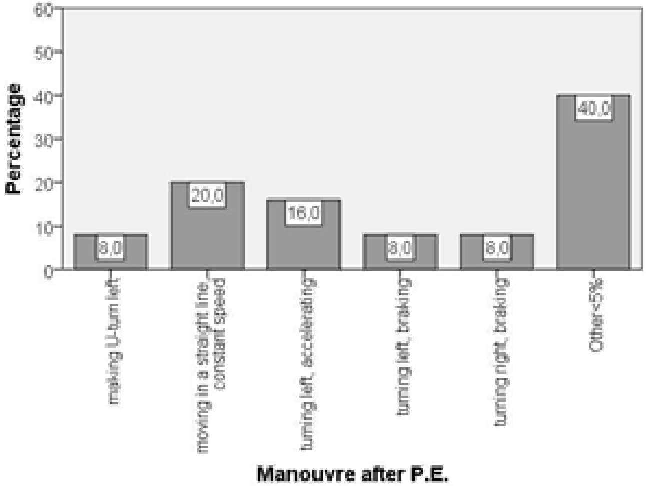


(b)

Figure 5.11: Driving conditions before the PE for PTW and OV (27 cases)

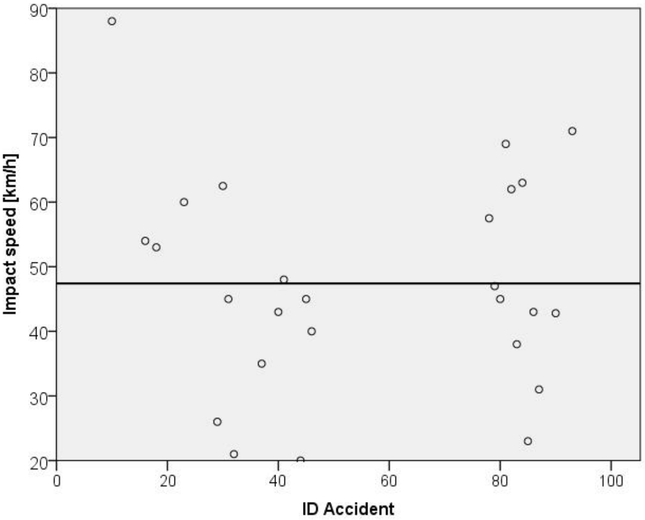


(a)

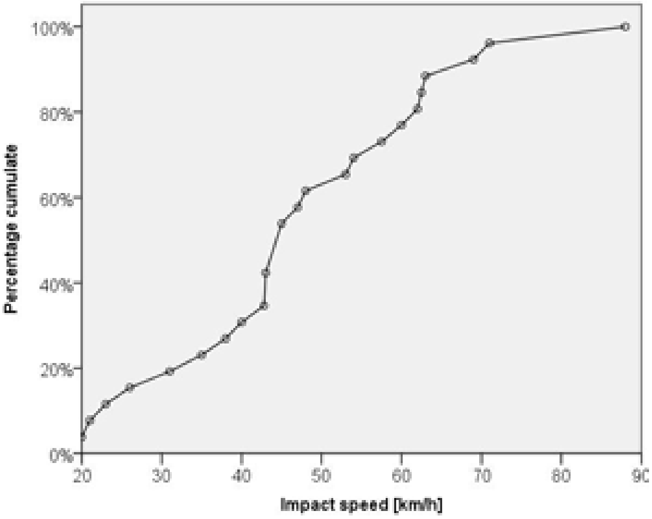


(b)

Figure 5.12: Driving conditions after the PE for PTW and OV (27 cases)

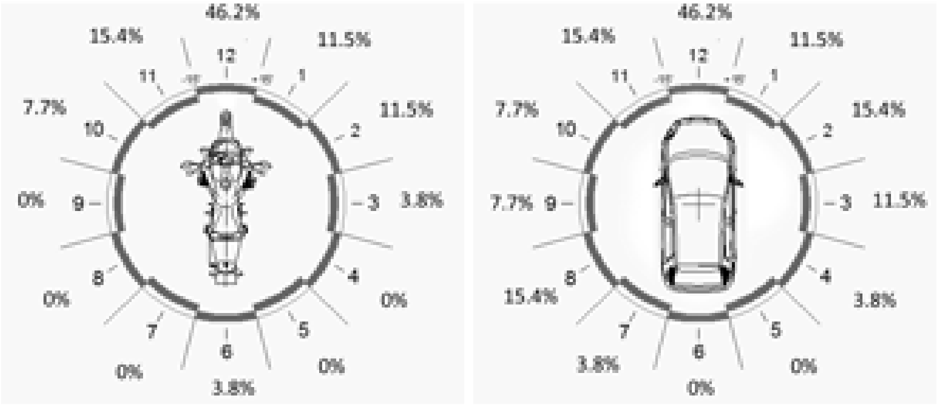


(a)



(b)

Figure 5.13: PTW's impact speed distribution and cumulative percentage



(a) (b)

Figure 5.14: PTW and car PDOF distribution

The mean impact speed value for cars is 33 km/h while the variation speed is 5 km/h (see Table 5.10). The most frequent PDOF is at 12 o'clock in 46.2% of the cars involved in this subset (see Figure 5.14(b)). In the case of the involvement of the car's front, the most common area bumped is the front left (-FL- code according to CDC classification) in 50% of the cases. For left side impacts the center zone (-RP-) is the most bumped (47%), while for right side impacts it is the front area (62.5%) (-LF-).

5.3 People characteristics

Included in the sample analysed are 204 people involved in serious road accidents. Of these, 66% are males and 33% are females. The mean age is 40.5 years (SD 19.8), while the most frequent age is 23 years with a median of 37 years.

The road users that are most frequently involved in this type of accident are drivers with 37.3%, followed by riders and car passengers at 19.6% and pedestrians at 18.6%, as shown in Table 5.11.

As previously noted, due to the small sample size and the preponderance of VRUs and motorcyclists, car driver and occupant will be briefly discussed.

5.3.1 Car driver and passenger

The car drivers of the sample are mainly males (54%) with a mean age of 41 years (SD 16.7). Since they are principally involved in VRUs crashes, the majority of them are not injured (79%) and only 7% are seriously injured.

There were 76 people driving cars. Of these in only 5% of the cases the alcohol test was performed by police or hospital. While in only 31.5% of the drivers it was possible to confirm the use of seat belts. Unfortunately, for the other people the information is not available due to the retrospective method of working. In 46%

Table 5.11: Road users involved in the sample studied

	N	%
driver	76	37,3
car passenger	39	19,6
rider	40	19,6
pillion	3	1,5
pedestrian	38	18,6
cyclist	8	3,9
Total	204	100,0

of the cases the alcohol test was done by police and in 10% of the cases it was done by the hospital.

Thirty-nine car passengers are included in the sample. The majority are females (59%) and the mean age is 35.4 years (SD 24.5). Of these 28.2% are slight injured, 10.3% are seriously injured and 5% are died. Comparing the use of seat belts between drivers and car passengers, Table 5.12 shows that the front passengers wear seat belts more frequently than rear passengers. Unfortunately, this variable has a high level of "unknown" modality.

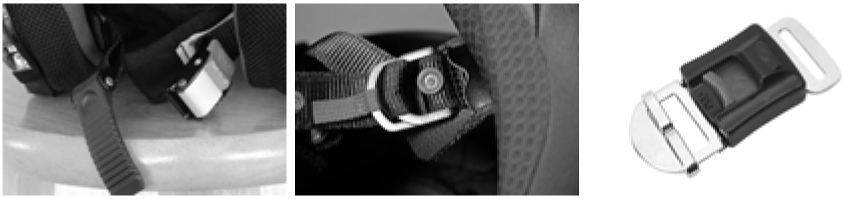
Table 5.12: Car occupants: usage of the seat belts for seat's position

	yes		no		unknown		Total	
	N	%	N	%	N	%	N	%
Front left	39	51,3%	8	10,5%	29	38,2%	76	100%
Front right	9	56,3%	3	18,8%	4	25,0%	16	100%
Rear left	1	20,0%	2	40,0%	2	40,0%	5	100%
Rear center	0	0,0%	3	100,0%	0	0,0%	3	100%
Rear right	0	0,0%	1	100,0%	0	0,0%	1	100%
Unknown	5	38,5%	4	30,8%	4	30,8%	13	100%
Total	54	47,4%	21	18,4%	39	34,2%	114	

5.3.2 Powered Two-Wheeler users

The PTW group is composed of 43 people with a mean age of 34 years (SD 14.4). The majority of these are riders (93%) and males (91%). The alcohol test was done only on 28% of the riders involved in the crashes, with a positive result in 28% of the cases. According to the injury outcome of this users' group, the alcohol test was principally done by the hospital.

In fifty-six percent of the group it was possible to identify the typology (e.g. full face, open face, etc.) either through direct examination (25% of the cases) or by photographic documentation released by the police. Forty-two percent (42%) of these were *jet/open face helmet* typology, 9% *full face* and 5% *modular* typology (see Table 5.13). The most common helmet retention system used is the "*chin*



(a) Chin strap micro-lock ratchet (b) D-shaped rings lock system (c) Chin Strap Quick Release

Figure 5.15: Helmet retention system typologies

strap quick release” (19%) followed by the ”*micro-lock ratchet lock*” (14%). Sixty percent (60%) of the retention systems are unknown.

Table 5.13: Motorcyclist’s helmet typology

	N	%
Full face	4	9,3
Modular	2	4,7
Open Face / Jet	18	41,9
Unknown	19	44,2
Total	43	100

During the crashes all 43 people wore helmets, and after having analysed the event, it can be stated that 23% of these people were wearing it correctly. Unfortunately in 72% of cases, it is not possible to establish if the helmet was worn correctly. This is due to the procedures used and insufficient information from police or EMS. As a result of the investigation’s work and the documentation available, it is possible to assert how in 23% of the cases the helmet was retained on head until the end of accident event. The helmet’s region most frequently hit by motorcyclists is the left side with 35.6% of damages. On the right side the percentage is equal to 27% as shown in the Figure 5.17.

Table 5.14: Helmet movement during the crash

	N	%
helmet retained on head	10	23,3
ejected after collision	2	4,7
ejected during crash	7	16,3
unknown	24	55,8
Total	43	100

As a consequence of the area of sampling, the motorcyclists involved in the crashes analysed were not wearing specific clothing for motorcyclists.

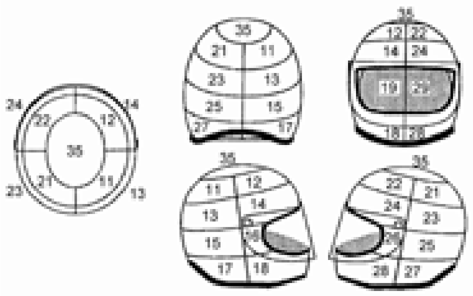


Figure 5.16: Helmet regions [3]

5.3.3 Vulnerable road users: pedestrians and cyclists

As shown in Table 5.11, 39 road accidents which involved VRUs have caused the injuries of 46 people.

The VRU group is composed of 38 pedestrians and 8 cyclists. The percentage of males (56.5%) is slightly higher than females (43.5%). The group's mean age increases if compared to other road users (49.9% SD 21.3).

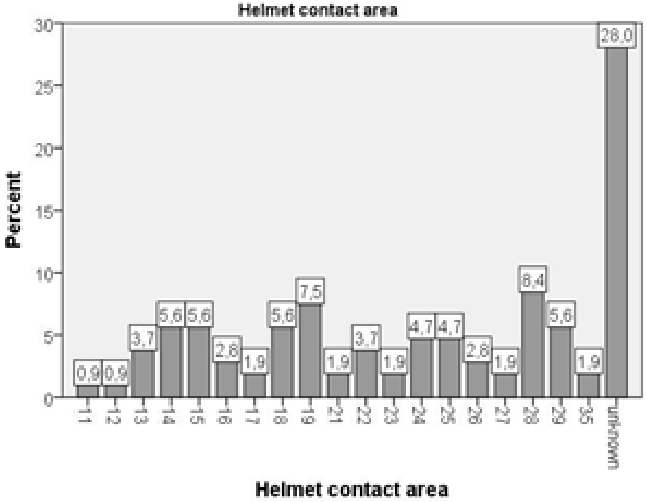
As shown in Table 5.6, the majority of the VRU impacts are due to cars (67%) followed by PTW vehicles (21%). The cars are also the vehicles that cyclists hit most frequently.

Regarding the aggressiveness of the car's front shape, the height of the Bonnet Leading Edge (BLE) of the sample analysed varies between 0.66m and 0.92m, with a mean value of 0.76m (SD 0.072) and a median of 0.73m.

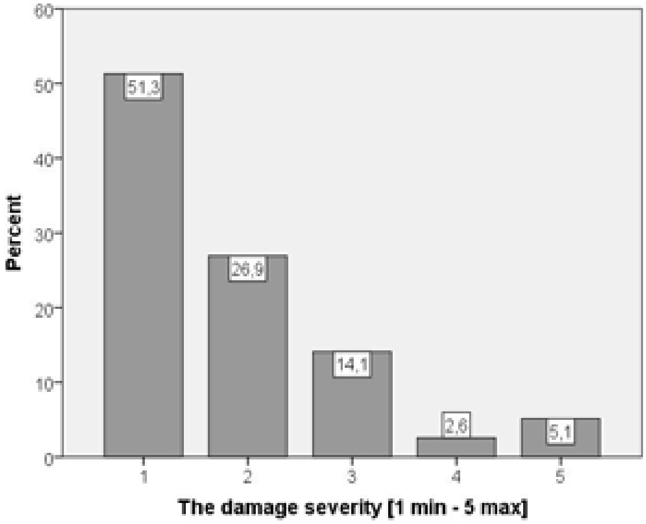
In the majority of the cases the VRU was walking in a perpendicular direction to the striking vehicle, while the main trajectories following impact were the *fender vault* (40%) and *wrap* (32%) trajectories. The prevailing pedestrian's side struck is the left at 52%. The fender vault trajectory can be seen as a special case of wrap trajectory (see Figure 5.18). It is a classification where the pedestrian is struck by only (or near) a front corner of the vehicle and subsequently falls to the side off and generally behind the vehicle. First contact is usually made at the legs, with the torso pivoting towards the hood. Due to the position of the pedestrian (near the vehicle's edge) he falls off the edge and does not impact the hood, striking the roadway. The pedestrian's head may or may not impact the vehicle.

Table 5.15: Pedestrian trajectory

Trajectory	N	%
Fender vault	10	40
Wrap	8	32
Forward	3	12
Somersault	1	4
Unknown	3	12
Total	25	100



(a) Helmet contact regions



(b) Helmet type of damages

Figure 5.17: Helmet contact regions and damages

Figure 5.18: Fender vault trajectory

The principally conditions that produce this type of trajectory are:

- braking or non-breaking vehicles;
- point of rest is either behind or to the side of the striking vehicle;
- pedestrians will land on the side of the vehicle they were struck by.

When the vehicle is braking, the pedestrians are struck by the front corner of the vehicle that wraps over the fender. The pedestrian will contact the windshield or A-pillar and roll off the decelerating vehicle.

5.4 Injuries, injury outcomes and mechanisms

In terms of injury severity of the road users involved in these crashes, Table 5.16 illustrates that 37% of the people are uninjured while 41% are severely injured, and the on-scene deaths are 1%. The latter are fatalities occurred in *car-to-car* collisions. As shown in Section 5.3, approximately 61% of the 204 people involved in the road accidents studied were admitted to hospitals for treatments. Seventy percent (70%) of these people were hospitalized for more than 24 hours, while 24% were treated in the ER and then discharged (Table 5.17).

Table 5.16: Outcome of the road users involved in serious crashes

		Dead	**Not injured**	**Serious**	**Slight**	**Unknown**	**Total**
driver	N	0	53	7	15	1	76
	%	0%	70%	9%	32%	100%	37%
car passenger	N	2	22	4	11	0	39
	%	100%	29%	5%	23%	0%	19%
rider	N	0	1	28	11	0	40
	%	0%	1%	36%	23%	0%	20%
pillion	N	0	0	3	0	0	3
	%	0%	0%	4%	0%	0%	1%
pedestrian	N	0	0	29	9	0	38
	%	0%	0%	37%	19%	0%	19%
cyclist	N	0	0	7	1	0	8
	%	0%	0%	9%	2%	0%	4%
Total	N	2	76	78	47	1	204
	%	100%	100%	100%	100%	100%	100%

Injury information is known for 93 people. Of these, the majority are males (72%). Among the 83 people seriously injured, 81 (97.5%) were admitted to the ICU. The remaining seriously injured people were admitted to other ICU's which are not partners in this research programme.

According to the UE definition for road accident deaths, for the sample of 81 people, the fatality percentage within the first month of the accident's occurrence is nearly 15%. Of these half died between the 2nd and 7th days following the accident, while no one died on the first day. The mean value of the ICU Length of Stay (ICU-LoS) is 8.23 (SD 7.189) days and the mode is 2 days. In terms of road user types, the most recurrent are VRUs and motorcyclists, as shown in Table 5.19.

Table 5.17: Frequency of the people treated in the ER and hospitalized

	N	%
Hospitalized	88	70,4
Treated and discharged	30	24
Unknown	7	5,6
Total	125	100

Table 5.18: Deaths within 30 days from the road accident

	N	%
0 - 24 h	0	0,0%
2 - 7 days	6	7,4%
8- 30 days	6	7,4%
no deaths	69	85,2%
Total	81	100,0%

Table 5.19: Types of road users where the injuries are known

	N	%
cyclist	7	7,5
driver	10	10,8
passenger	5	5,4
pedestrian	34	36,6
rider	37	39,8
Total	93	100

Comparing the frequency of injuries between *car occupants*, *cyclists*, *motorcyclists* and *pedestrians* groups (see Figure 5.19), it is possible to see how the motorcyclists are the road users most subject to injuries in all body regions. The pedestrians are the second users in overall injuries and who uniquely suffered neck injures.

For PTW users, the *torso* (i.e. thorax, abdomen, spine and upper extremities) is the region less protected in urban traffic, as well as the face due to the high frequency of jet helmets.

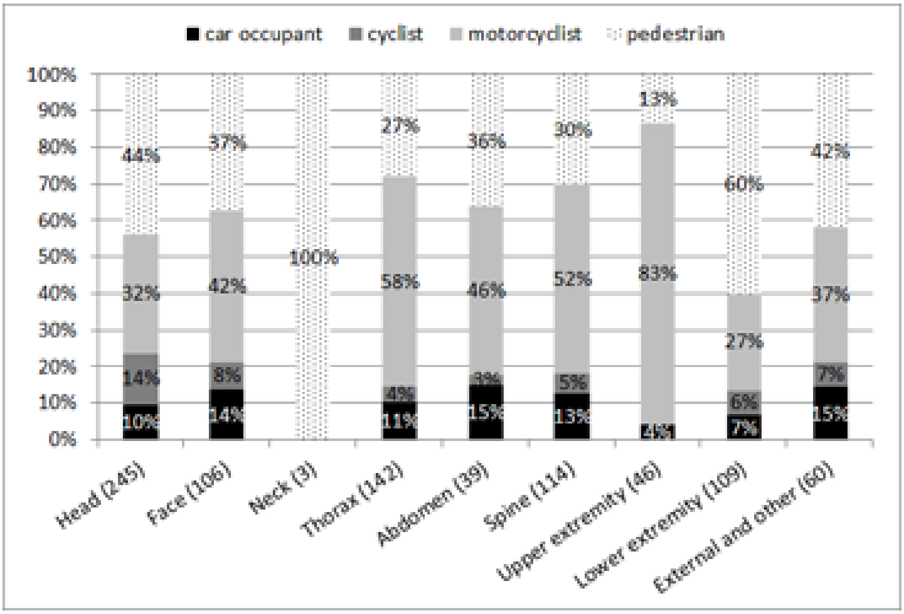


Figure 5.19: Percentage of injuries per body regions and road user type

The pedestrian's injury distribution is in line with the literature. The greatest number of injuries are to the *head-face* and *lower extremities*. Cyclists highlight a prevalence of head-face injuries compared to the other body regions. Looking at the injury severities in terms of AIS3+, the body sections most seriously injured are the head, thorax, abdomen, spine and lower extremities (Figure 5.20). Furthermore, pedestrians and PTW users are most subject to serious head and abdominal injuries, followed by the lower extremities.

Grouping the serious injuries by means of the 6 body regions used in the ISS calculation (MAIS3+, see Figure 5.21), it can be seen that the urban road users most subject to the polytrauma [125] are pedestrians and motorcyclists. Overall, the body regions that are most subject to severe injuries (MAIS4+) are the head-neck, thorax, abdomen and extremities. The most frequent MAIS level is MAIS3 with 44% of recurrences, followed by MAIS4 with 30% (see Figure 5.22(a)). The mean value of the MAIS is 3.25 (SD 0.963), while the maximum value is 5. The most frequent value of the score is $ISS = 17$ with 12.9% of recurrences. While the NISS score (due to its definition), increases to 27 (18.3%). The ISS mean value is 19.65 (SD 9.9), while the mean value for the NISS score is 26.49 (SD 13.0). The maximum values are 43 and 66, respectively.

Finally, in terms of distribution, both the ISS and the NISS are normally distributed (Shapiro-Wilk[2] p-value 0.143 and 0.072), while, vice versa, the MAIS is not (see Table 5.20).

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[2] p-value major than 0.05

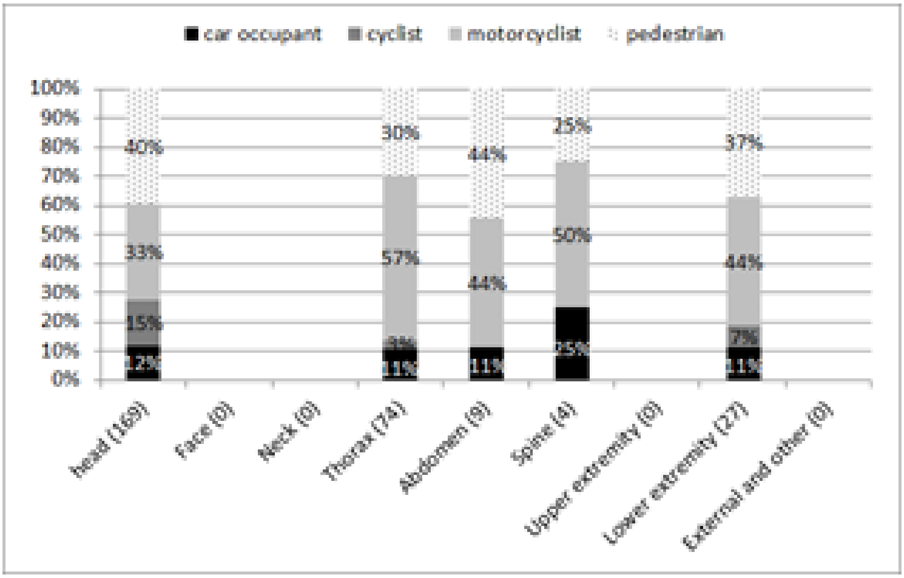


Figure 5.20: Percentage of AIS3+ injuries per body regions and road user type

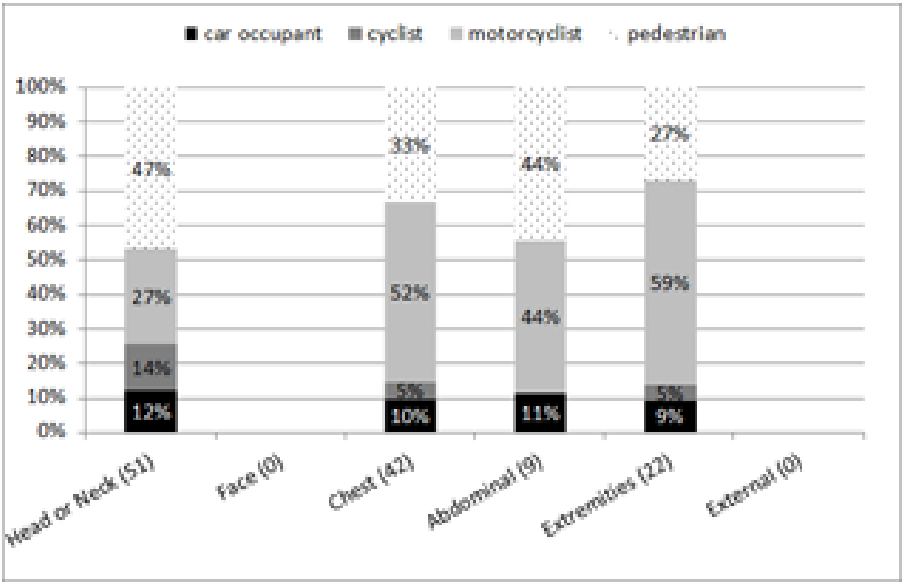
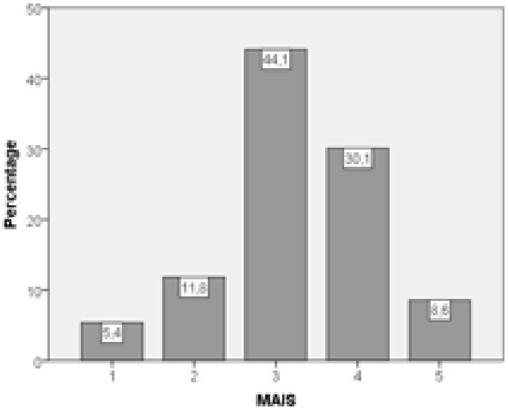
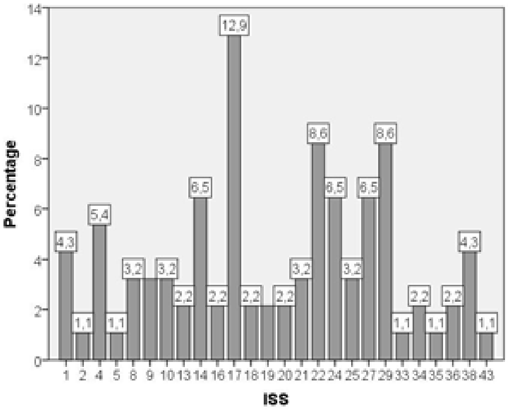


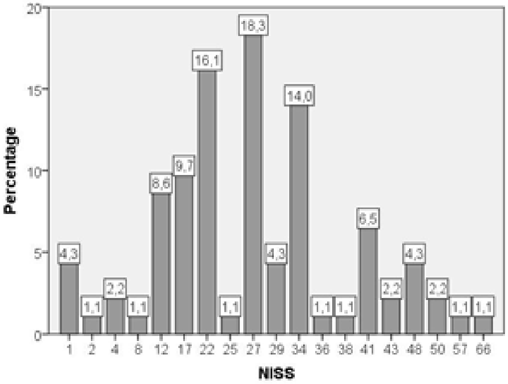
Figure 5.21: Percentage of MAIS3+ per body regions and road user type



(a) MAIS



(b) ISS



(c) NISS

Figure 5.22: Outcome score within the sample (93 cases)

Table 5.20: MAIS, ISS and NISS normality test

	Shapiro-Wilk		
	Statistic	df	p-value
MAIS	0,892	93	0
ISS	0,979	93	0,143
NISS	0,975	93	0,072

The Glasgow Coma Scale (GCS) score, gathered at three different time intervals (on scene, entrance to ER and exit from ER), shows a disagreement between the scoring evaluated on scene and those evaluated on entrance to the ER. This is particularly true both for the less serious GCS' values (14 and 15), and for the most severe GCS' values (≤ 8)[3]. This is possibly due to different physician evaluations and, according to the golden hour principle, also to a worsening of the clinical condition of the patient. However, Spearman's correlation between MAIS in the head-neck region and the GCS is statistically significant at all three time intervals with a correlation coefficient increasing and negative.

Table 5.21: GCS and MAIS head-neck - Spearman's correlation

		MAIS head-neck	GCS on-scene
MAIS head-neck	Correlation coefficient	1	-0,269
	Sig. (2-tailed)		0,016
	N	80	80
GCS on-scene	Correlation coefficient	-0,269	1
	Sig. (2-tailed)	0,016	
	N	80	80

Comparing the percentage of injuries per body regions within the 3 subsets of road users (i.e. car occupants, motorcyclists and VRUs), it is possible to highlight that in all three groups the head is the region most subject to injuries, with 24.7%, 21% and 35% respectively (see Figure 5.24). In *car occupants* the thorax, face and spine are the regions most injured (18.6%, 16.5%, 15.5%). In the motorcyclists' group the thorax (22%) and spine (15.8%) are the regions with the most injuries, followed by the face and upper extremities. The high percentage of face injuries is due to the high presence of *open face* helmets. Finally, the VRUs are the group with the highest number of *lower extremity* injuries (18.5%).

In all 3 subsets abdominal injuries are quite low, while some neck injuries are shown only in VRUs. If the VRUs are most subject to lower extremity injuries, contrarily the motorcyclists are most subject to upper extremity injuries (pedestrians: 18.5% and 1.5% versus motorcyclists: 8% and 10.2%).

Comparing the results with the state-of-the-art (Chapter 3) for the PTW group, it is possible to see how the data differs. The state-of-the-art data shows

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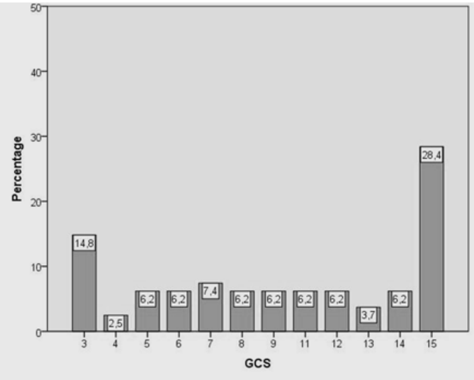
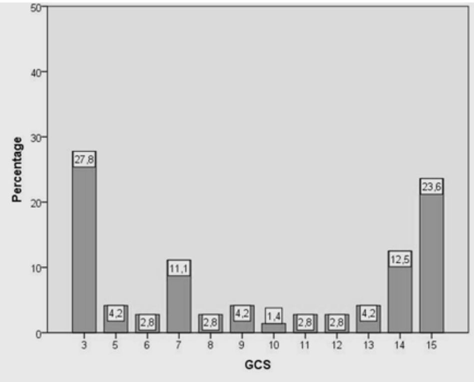
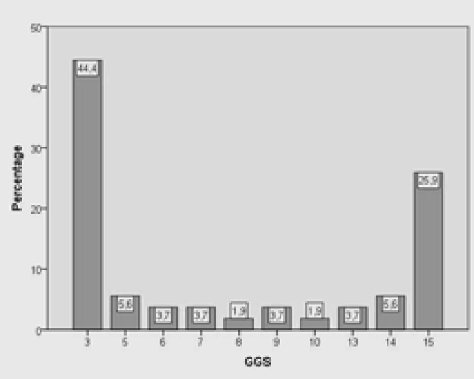
[3] Serious with GCS≤ 8, moderate with GCS 9-13 and minor with GCS≥ 14



(a) On-scene (81 cases)



(b) In-ER (72 cases)



(c) Out-ER (54 cases)

Figure 5.23: GCS score distribution at on-scene, entrance to ER, exit of ER

the majority of the injuries are located in the extremities, lower and upper respectively, followed by head and thorax. This is most probably due to the sample analysed that is more severe with respect to the samples of accidents considered the state-of-the-art (the majority had an $ISS < 15$). Similar conclusions can be made for the VRUs group. For the state-of-the-art the lower extremities are the region most subject to injuries. Instead in the sample analysed, the extremities are the body regions less injured compared to the others.

This is principally due to the type of sample gathered in which the severity is generally high. The polytrauma's condition more frequently necessitates admittance to the ICU. Those people with prevailing lower extremity injuries are usually admitted to other hospital wards. Therefore, in this sample this type of injury is under represented with respect to the state-of-the-art literature. Due to the prevailing number of VRUs and PTWs users currently present in the sample studied, the analysis will proceed focusing on these two road user groups.

5.4.1 Vulnerable Road Users: pedestrians and cyclists

As shown in Figure 5.24(c), the head is the VRU body region most subject to injuries (35%), followed by lower extremities (18.5%), thorax, face and spine. With regard to the *anatomical structures*, in Figure 5.25, it is possible to observe how the skeleton is the most frequently injured (approximately 50% of all injuries) followed by internal organs (24.4%). Within the category "level of injury", *cerebrum* (20.7%), *fracture with or without dislocation but no cord involvement* (9.9%), *base fracture* (5.4%) and the *pelvic ring fracture* (5.2%) are the most frequent.

Among the 171 skeletal injuries, the majority are fractures at the cranial base, vault and orbits of the head, and to the pelvis. The main typologies are codified as *NFS*[4] *fracture* (16.4%) and the *close and simple* fractures (11.7%).

For the cerebrum (84 injuries out of a total of 142 head injuries), as shown in Figure 5.27, the most common injuries are subarachnoid hemorrhage (10.7%), pneumocephalus, lacerations and hematoma (7.1%).

The majority of the injuries of the *lower extremities* are to skeletal level (see Table 5.22) with 85% frequency. Of these, pelvic ring fractures are prevalent, as well as injuries codified as NFS (Figure 5.28).

Table 5.22: VRU lower extremity injuries by anatomical structure

	N	%
joints	3	4
muscles, tendons, ligaments	3	4
skeletal	64	85,3
vessels	4	5,3
whole area	1	1,3
Total	75	100

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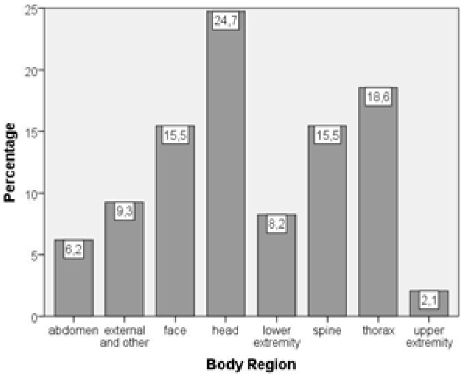
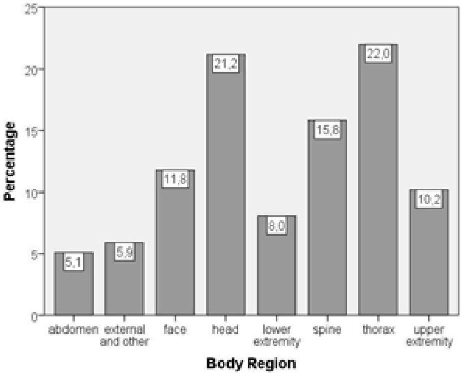
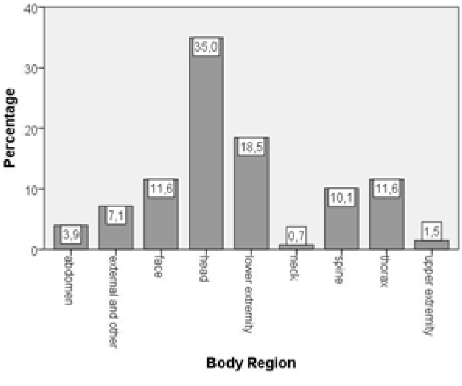
[4] NFS, No Further Specification



(a) car occupants, 97 injuries



(b) PTW users, 373 injuries



(c) VRUs, 406 injuries

Figure 5.24: Distribution of the injuries per body region and road user type

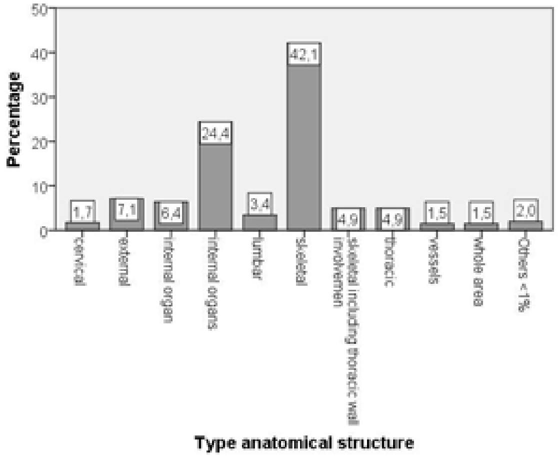


Figure 5.25: VRUs' injuries per type of anatomical structure (406 injuries)

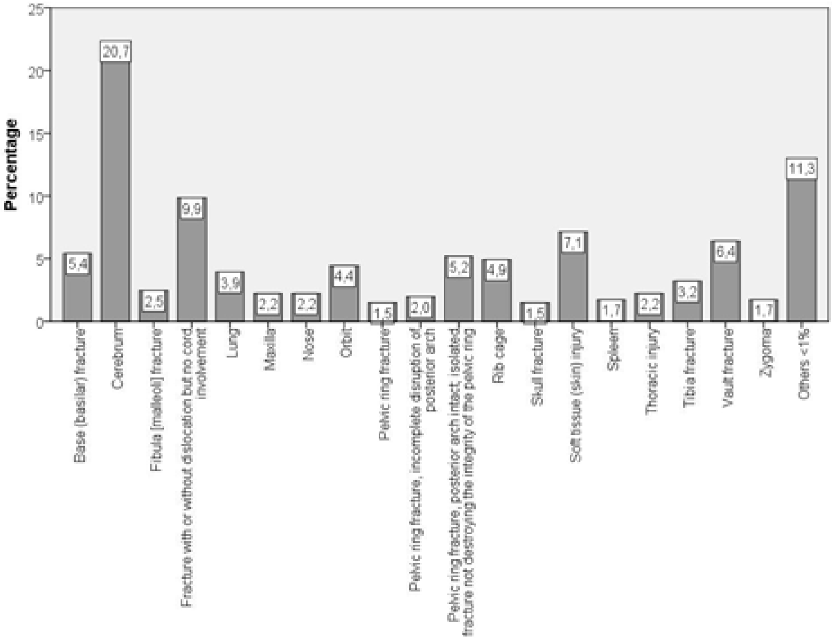


Figure 5.26: VRUs' injuries per specific anatomical structure (406 injuries

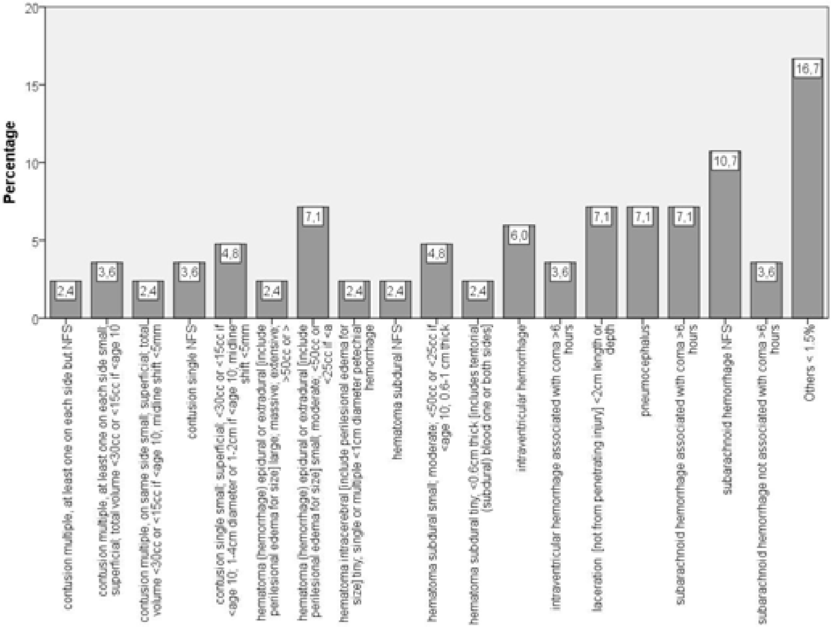


Figure 5.27: VRU - Detail of cerebrum head injuries (84 injuries

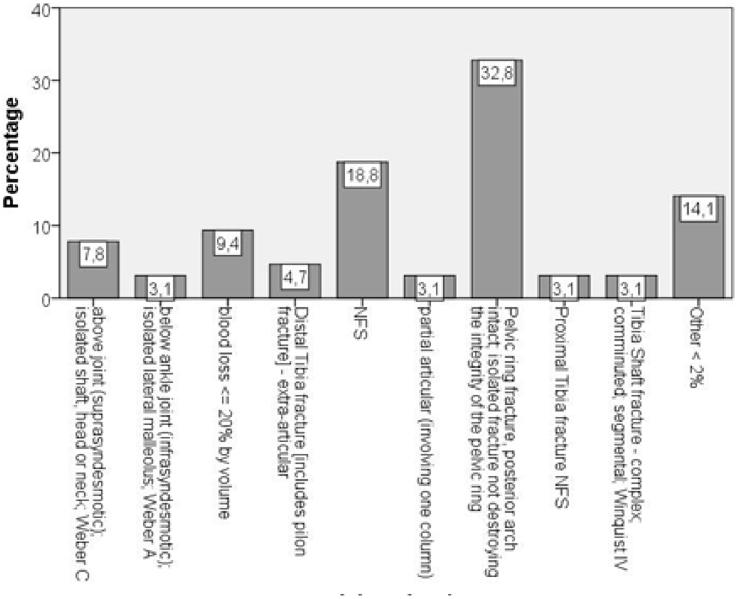


Figure 5.28: VRU - Detail of lower extremity skeletal injuries

Figure 5.29, shows a comparison between the injuries caused by a car, PTWs hit and by ground contact. In terms of body regions, the clustered bar chart shows the first impact against a car, is more dangerous than against PTW vehicle. In the second crash the majority of the injuries are located in the lower extremities and thorax regions.

It is again necessary to highlight how an impact against the ground produces a very high level of injuries, especially to the head. By grouping the head injuries caused by the impact with the car and the ground (in terms of AIS4+), it appears the second impact is more dangerous for pedestrians (26.2%) (see Table 5.23), and this is confirmed by Pearson's Chi squared that is 4.117 with an exact significance to 0.068. This could be due to at large number of recent cars that use laminated windscreens.

Table 5.23: AIS4+ per type of impact

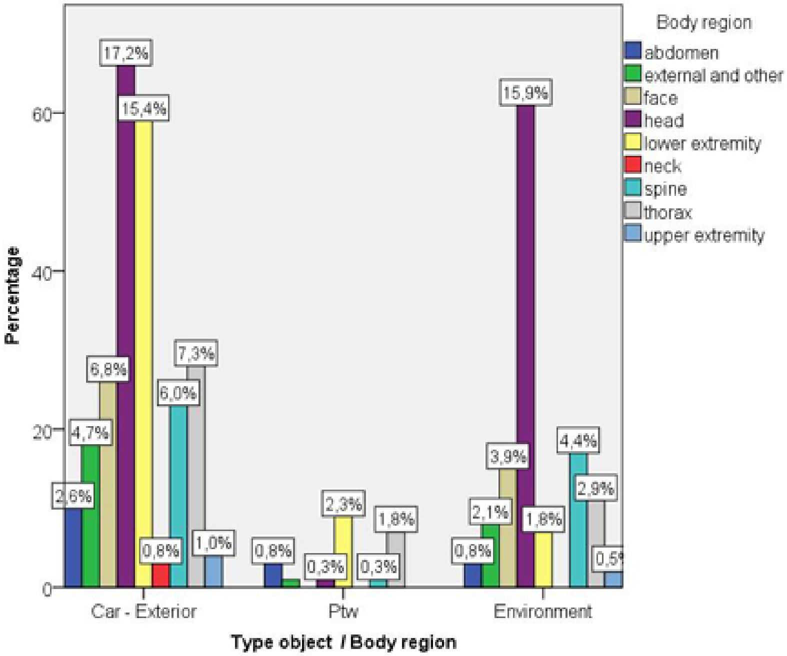
		$AIS \leq 3$	AIS4+	Total
Car	N	58	8	66
	%	88%	12%	100%
Ground	N	45	16	61
	%	74%	26%	1
	N	103	24	127
Total	%	81%	19%	100%

Regarding the VRU impact by cars and vans, in the Figure 5.30 are shown the principal car's part and the relative injuries caused. For pedestrians and cyclist the ground or roadside obstacle are the first cause of injuries (37,5% and 24.6%), followed by the windscreen (17.4%) for pedestrians and the bonnet (21%) for cyclists.

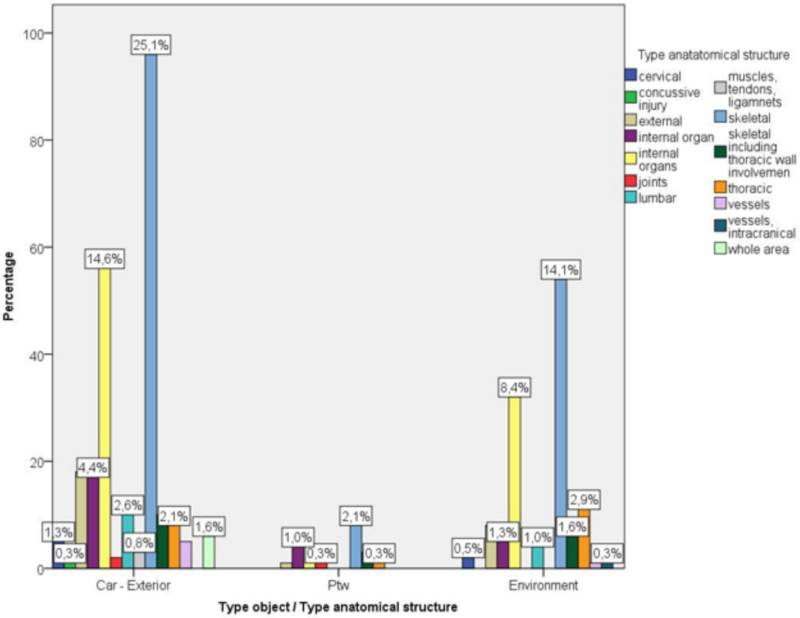
In contrast to the state-of-art, there are windscreen's areas that have caused injuries. The most frequent is the header rail (12.3%), followed by the central area of the windscreen. On the other hand, both for pedestrians and cyclists the bonnet leading edge is accountable for injuries, especially those to the lower extremities (femur and pelvis).

In terms of severity distribution, the Figure 5.31 shows the AIS' frequency for frontal vehicle parts struck by pedestrians and cyclists. In this sample the windscreen is more responsible for AIS 2 and AIS 3 injuries'. The bonnet leading edge and bumper have also been responsible for moderate and serious injuries. As imaginable, the windscreen header rail is the vehicle part that has produced the most severe injuries. Focusing the attention on head contact points against windscreen and bonnet for pedestrian and cyclists, the spatial distribution is shown in Figure 5.32 and Figure 5.33. For pedestrian, the head struck the windscreen or the screen frame, but did not strike the roof, while for the cyclists the head also impacted the roof.

Apparently for the VRU sample analysed, but this is also in accordance to literature, the windscreen frame and locations close to frame are the more likely cause of serious injuries (AIS3+).

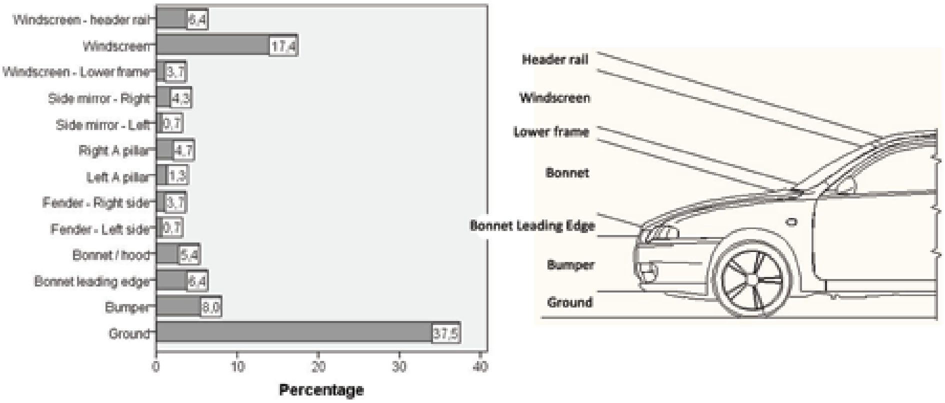


(a) Body Structure

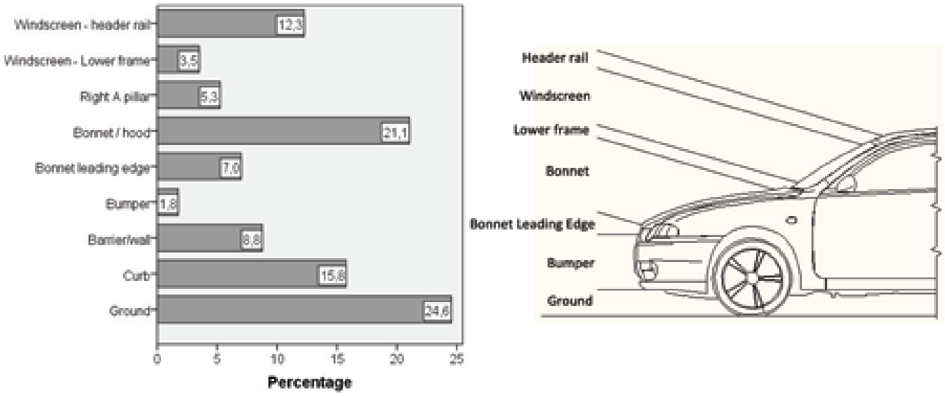


(b) Type of anatomical structure

Figure 5.29: Injury distribution for contact type (383 injuries)

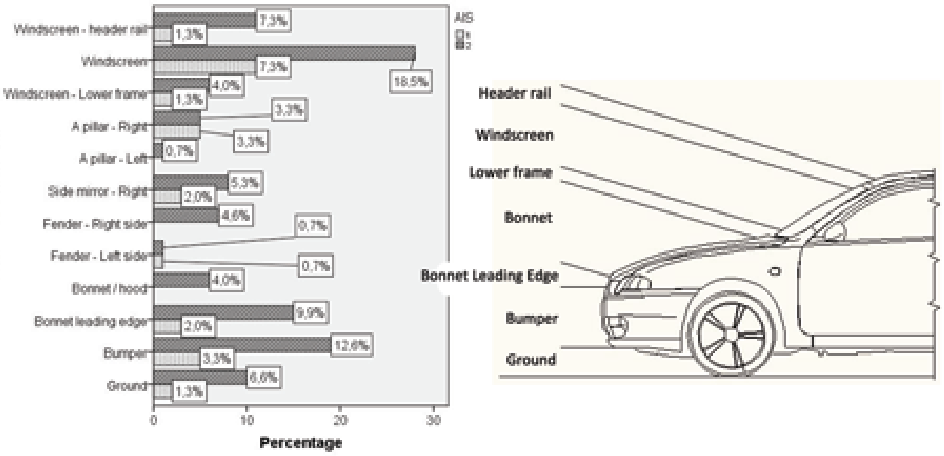


(a) Pedestrians (299 injuries)

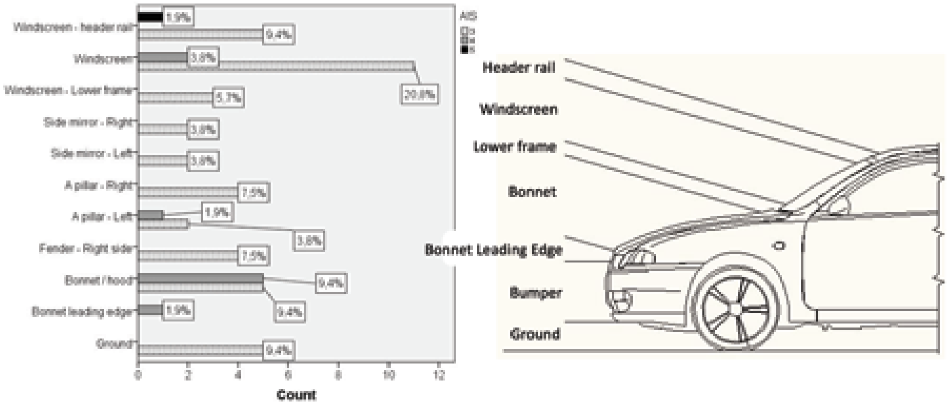


(b) Cyclists (57 injuries)

Figure 5.30: VRU's injury distribution for car parts'



(a) AIS 1-2 injuries (151 injuries)



(b) AIS3+ injuries (53 injuries)

Figure 5.31: Pedestrian injury severity for car's parts

Comparing the specific anatomic structure and impacted object, it appears that cerebrum injuries are caused by various objects with a slight prevalence for windscreen header rail. For cerebellum injuries, the principal cause is due to the impact with ground/side barriers given their position. Skull, vault and base fractures are instead prevailingly caused by the stiffness of the vehicle or environmental parts.

Finally, for the VRU group, the majority of the injuries are been generated by means of a direct contact with an object (around 90%) and only minimally caused by contrecoup.

The cars investigated all had laminated glass because of recent construction (exception one car registered before 2000). All the cars had damage to A-pillars, header or lower frame or hood due to contact against the head or other body parts. In this case the injuries on the same side of the impact were correlated to the first impact with the car. In case of evidence of contact with the ground (e.g. hair or biological material on the ground or excoriations due to the ground contact) and the injuries were on the opposite side of the head (with respect to those injuries caused by the impact with the car), these injuries were correlated to ground impact. For the cerebrum injuries where the countercoup damage is more frequent, the previous discrimination was very difficult and the results are approximate and in this case the correlation has been based on the injury position shown by TC scan. Every correlation has their individual confidence level on each single correlation done, but at the moment, due to the small dimension to the sample, this value was not considered.

5.4.2 PTWs' users: rider and pillion

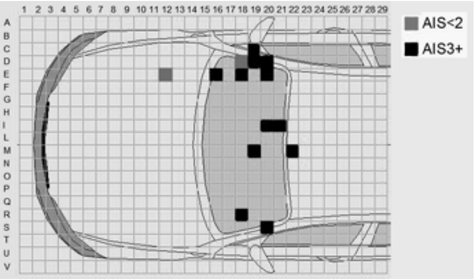
Overall, among the motorcyclists involved in a crash, the body regions most affected by injuries are the head and thorax, with about 43% of the total injuries suffered by the PTW's users (Figure 5.24(b)).

Also the spinal region receives a significant amount of injuries (15.8%), followed by the face (11.8%) and the upper and lower extremities (respectively 10.2%, 8%). The abdominal region is the body part least injured.

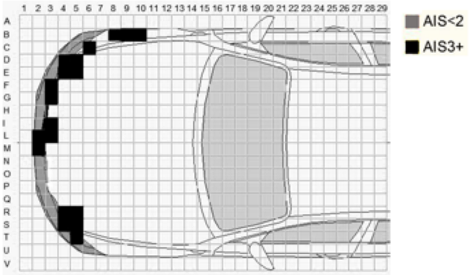
The head and face is the most injured area with 33% of lesions. This is principally due to the prevalent use of open face helmets (42% of the cases) and by the notable percentage of helmets lost during or immediately after the crash (21%, Figure 5.13). That value could increase given the large amount of unknown information on helmet movements.

As previous seen for VRUs, also the skeleton *anatomical structure* of PTW's users is significantly damaged, followed by internal organ injuries (31.6%). At the "level of injury" (specific anatomical structure), *fractures with or without dislocation, but with no cord involvement* (15.3%), *cerebrum* (13.9%) and *lungs* (8.6%) are the most frequently injured (Figures 5.34 and 5.35).

Within the *skeletal* injuries group (165 totals) 14.5% are *rib cage* fractures, followed by head basilar fractures (10.3%) and pelvic fractures (6.6%). Clustering the fractures by body region, the majority are located in the head/face regions (26%) and in the upper extremities (22%) (Figure 5.36). This is the confirmation



(a) Head-face



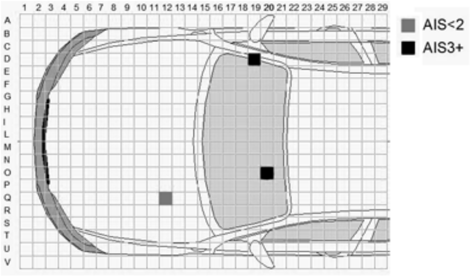
(b) Lower extremities

Figure 5.32: Pedestrian head-face and lower extremities injuries distribution

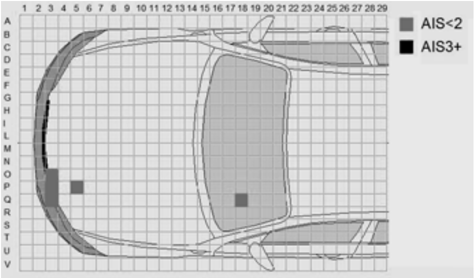
that in many accidents the motorcyclists have lost their helmets.

With regard to the *internal organs*, the most frequent organ injured is the cerebrum (44%), followed by the lungs (27%) and thoracic injuries (15%) (see Table 5.24).

In the cerebrum area (a total of 52 injuries) *single, small and superficial contusions* are the most prevalent with 13.5%, followed by *intraventricular hemorrhages* (11.5%), *pneumocephalus* and *single tiny contusions* (9.6%). With regard to the lung area (32 total injuries,) the majority are *minor unilateral contusions* (31%) and *major unilateral contusions with involvement of 1 or more lobes* (15.6%). While for thoracic injuries (a total of 18 injuries), the typology most prevalent is *pneumothorax NFS* (72%). There is a difference for VRUs, motorcyclists have 97% of extremity injuries (upper and lower) at skeletal level. Figure 5.37 shows the majority are related to the radius and ulna, clavicle, pelvis and femur. Comparing the severity of the impacts against *car exterior* and the *environment* for PTW users, both in terms of *body region* and *anatomical structure*, from Figure 5.38 it is possible to conclude that for PTW users, in a urban scenario, an impact against an environmental object is approximately as dangerous as an impact against other vehicles. In both cases the percentage of injuries is approximately the same (50%). Head and face injuries are more frequent in impacts against environmental elements and this is due to the high prevalence of helmet loss. While in terms of anatomical structures, there are no great differences between impacts against



(a) Head-face



(b) Lower extremities

Figure 5.33: Cyclists head-face and lower extremities injuries distribution

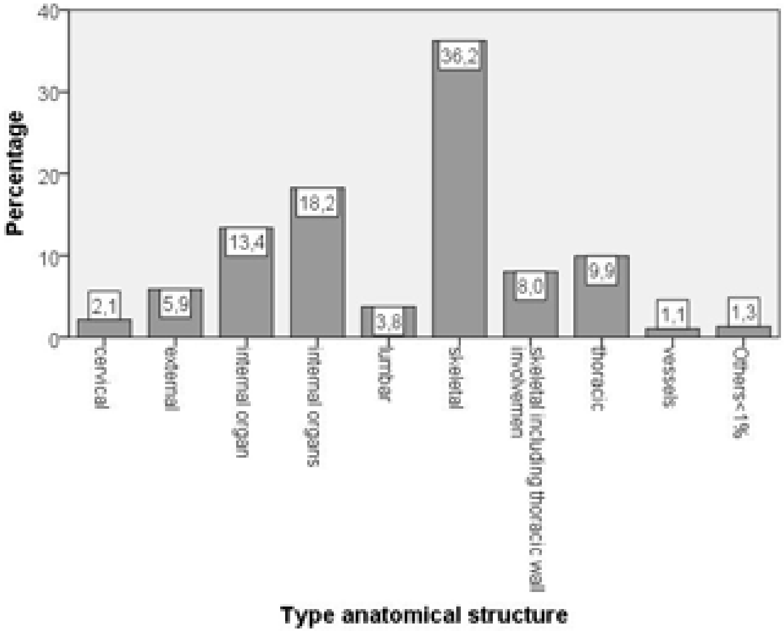


Figure 5.34: PTWs' injuries per type of anatomical structure (373 injuries)

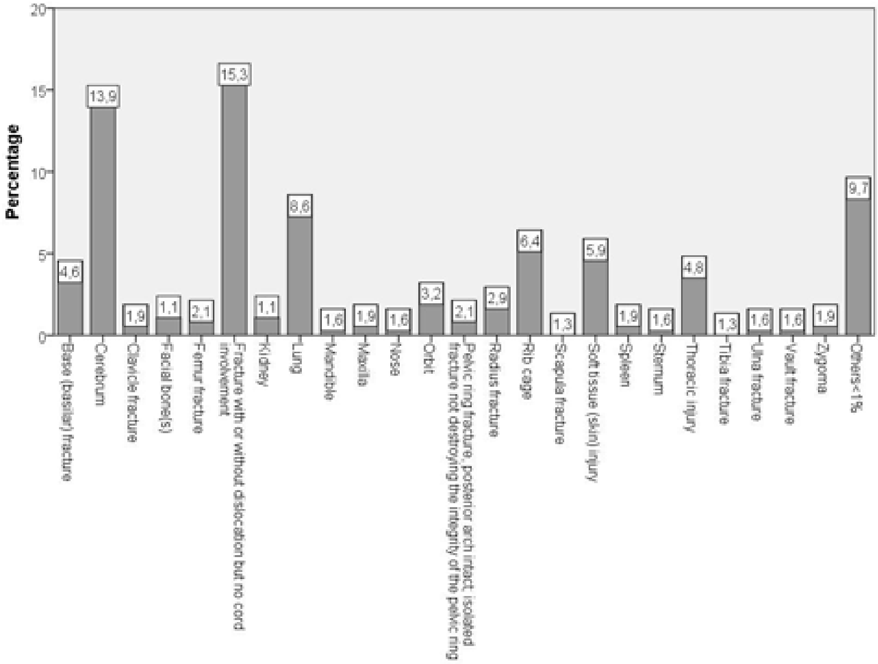


Figure 5.35: PTWs' injuries per specific anatomical structure (373 injuries)

Table 5.24: PTW users' internal organ injuries

	N	%
Adrenal Gland	1	0,8
Cerebellum	1	0,8
Cerebrum	52	44,1
Kidney	4	3,4
Liver	2	1,7
Lung	32	27,1
Spleen	7	5,9
Testes	1	0,8
Thoracic injury	18	15,3
Total	118	100

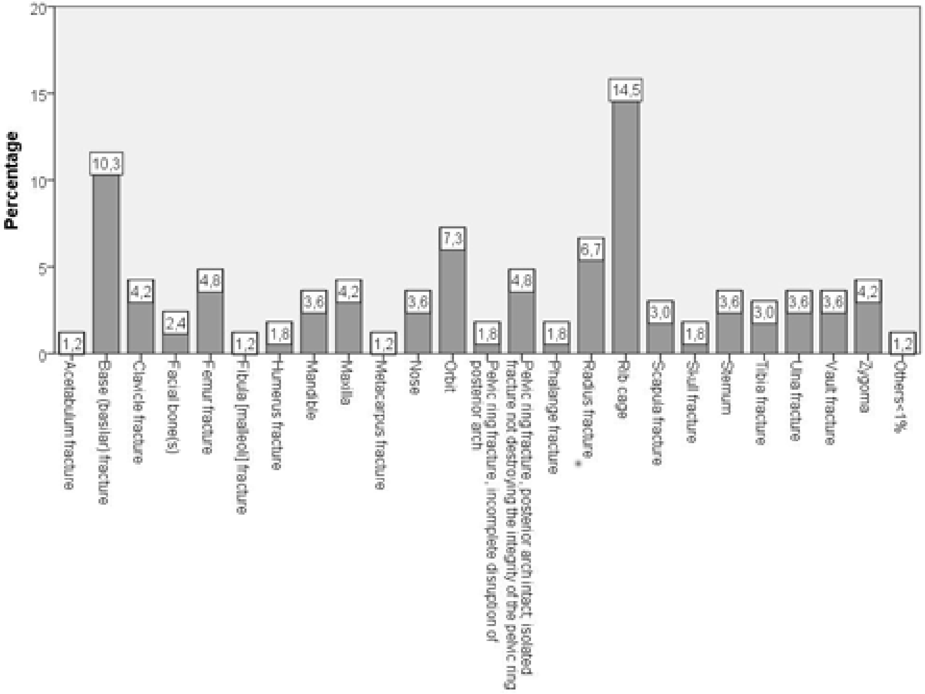


Figure 5.36: Ptw users' skeletal injuries (165 injuries)

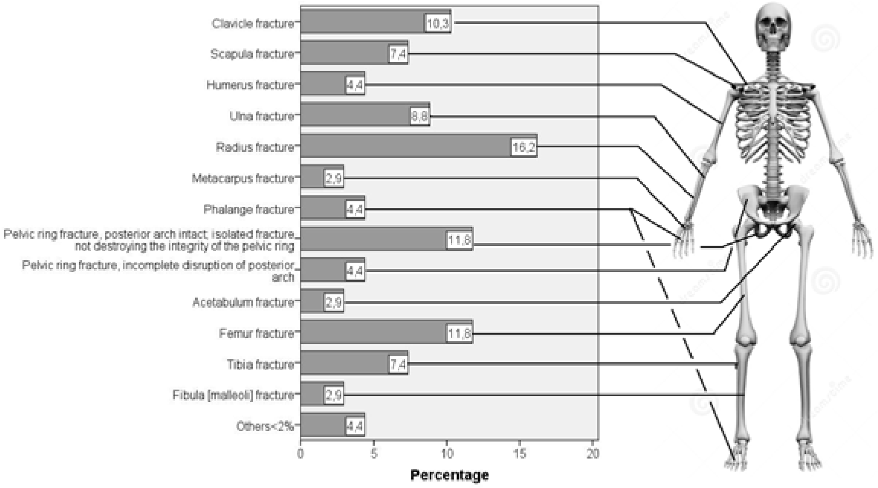


Figure 5.37: Upper and lower extremities skeletal injuries for PTW users

Table 5.25: Cerebrum, Lung and Thoracic typology injuries

		N	%
Cerebrum	contusion multiple, on same side small; superficial; total volume $< 30cc$ or $< 15cc$ if $< age10$; midline shift $< 5mm$	2	3,8
	contusion multiple, on same side tiny; each $< 1cm$ diameter	2	3,8
	contusion single small; superficial; $< 30cc$ or $< 15cc$ if $< age10$; 1-4cm diameter or 1-2cm if $< age10$; midline shift $< 5mm$	7	13,5
	contusion single tiny; $< 1cm$ diameter	5	9,6
	hematoma (hemorrhage) epidural or extradural [include perilesional edema for size] small; moderate; $< 50cc$ or $< 25cc$ if $< a$	2	3,8
	hematoma (hemorrhage) NFS	2	3,8
	hematoma subdural small; moderate; $< 50cc$ or $< 25cc$ if $< age$ 10; 0.6-1 cm thick bilateral [both sides 0.6-1 cm thick]	2	3,8
	hematoma subdural tiny; $< 0.6cm$ thick [includes tentorial (subdural) blood one or both sides]	4	7,7
	intraventricular hemorrhage	6	11,5
	laceration [not from penetrating injury] $< 2cm$ length or depth	2	3,8
	pneumocephalus	5	9,6
	subarachnoid hemorrhage associated with coma > 6 hours	2	3,8
	subarachnoid hemorrhage NFS	2	3,8
	Others injuries < 1%	9	17,3
	Total	52	100
Lung	contusion - bilateral - major; 1 or more lobes, at least on one side	4	12,5
	contusion - bilateral - minor; ¡1 lobe	4	12,5
	contusion - unilateral - major; 1 or more lobes, at least on one side	5	15,6
	contusion - unilateral - minor; < 1 lobe	10	31,3
	contusion - unilateral NFS	2	6,3
	contusion NFS	2	6,3
	laceration - unilateral - minor; < 1 lobe	4	12,5
	laceration - unilateral NFS	1	3,1
	Total	32	100
Thoracic	Hemopneumothorax NFS	1	5,6
	Hemothorax NFS	1	5,6
	Pneumomediastinum	2	11,1
	Pneumothorax - major; > 50% collapse of lung documented on xray; persistent air leak	1	5,6
	Pneumothorax NFS	13	72,2
	Total	18	100

a vehicle or the ground. The unique exception is the internal organs for which environmental elements cause more internal injuries (54% versus 46%).

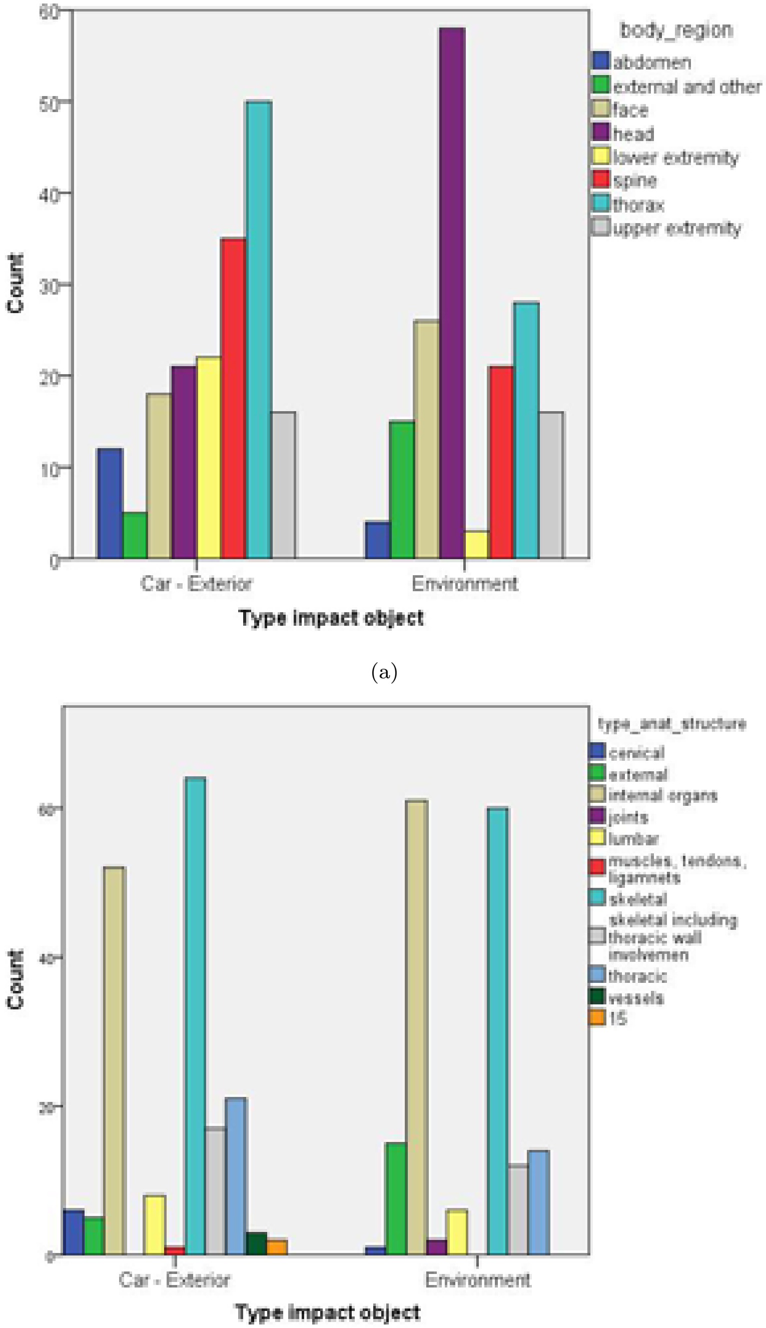
As opposed to the impact against another vehicle, the thorax sustains the most injuries (64% versus 36%) as well as the spine (62.5% versus 37.5%), the abdomen (75% versus 25%) and the lower extremities (88% versus 12%).

Due to the significant absence of the use of specific motorcyclist clothing, external injuries are principally the consequence of interactions with environmental elements, in particular with the ground.

Of a total of 350 injuries 28.3% of these are caused by an impact against the ground and approximately 9% due to barrier or wall impacts. Within the subset of impacts against the car, the car part most frequent responsible for injuries is the bumper or in general the car's front (13%). The second most dangerous part is the windscreen with a total of 9.7% injuries, in particular the upper frame (or header rail) and the central area of the windscreen (Figure 5.39).

In terms of injury severity the ground is most responsible for AIS2+ injuries, as well as the more rigid car parts, i.e. pillar, doors, upper and lower windscreen frame, etc. The level of AIS4 injuries are due to impacts against the ground, wind screen upper frame and the frontal part of the car (see Figure 5.41).

Proceeding with the evaluation of the correlation between head injuries and different bumped objects, in Figure 5.40 it is possible to highlight how the highest frequencies for internal organ injuries are due to an impact with the ground. While fractures are caused by an impact against the most rigid car components or environmental elements. This is also confirmed, with a confidence level of 90% by the Pearson Chi-Square, that is 51.36 with an exact significance to 0.107.



(a)

(b)

Figure 5.38: Frequency of PTWs' injuries per type of impacts (350 cases)

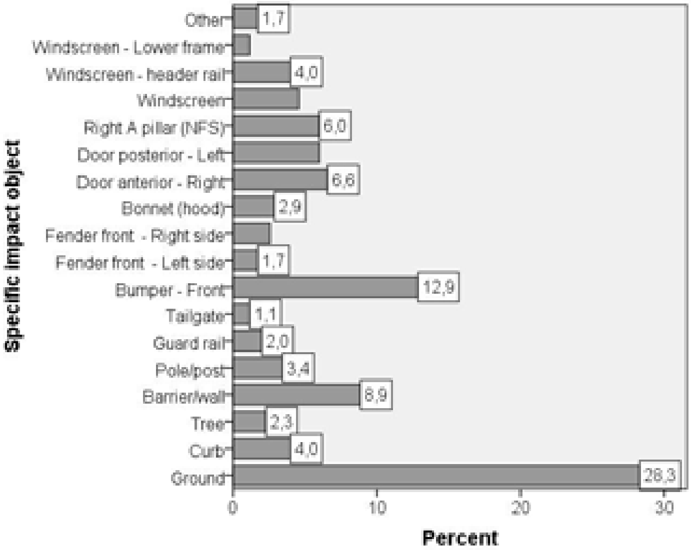


Figure 5.39: Percentage of impacted objects by PTW users (350 injuries)

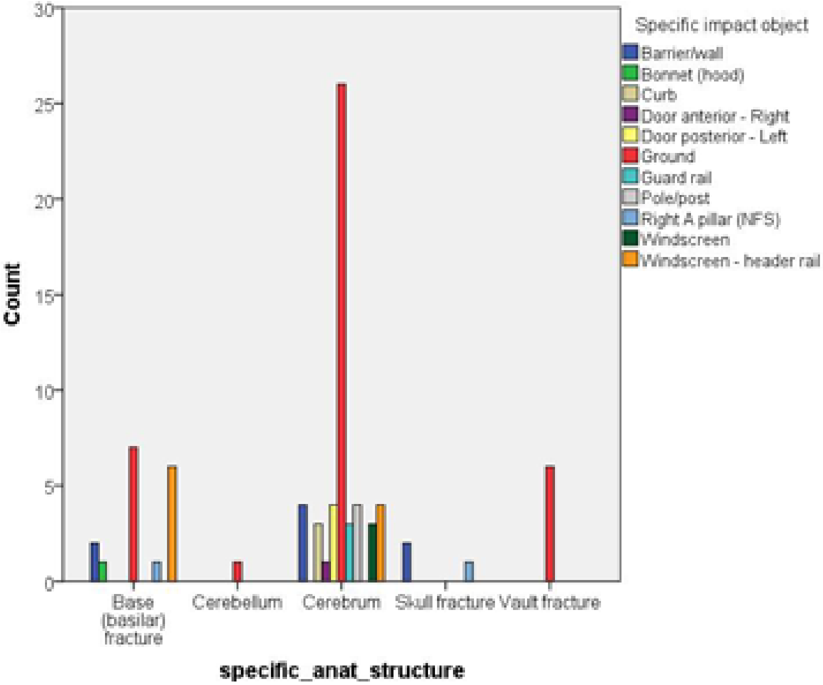
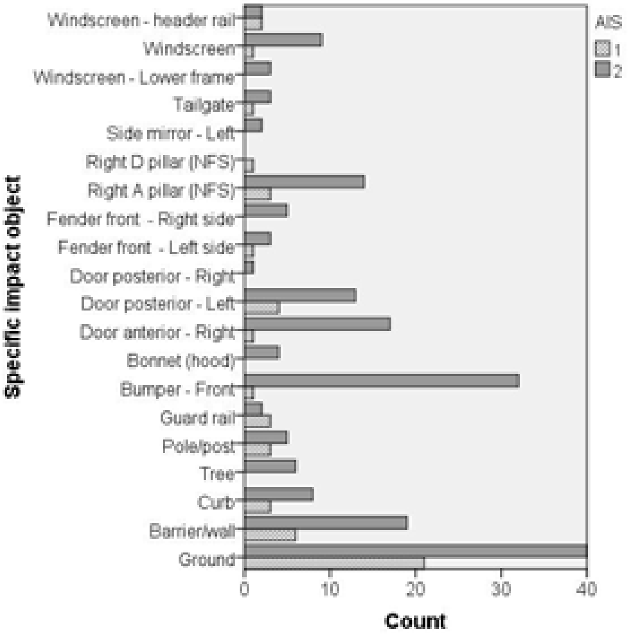
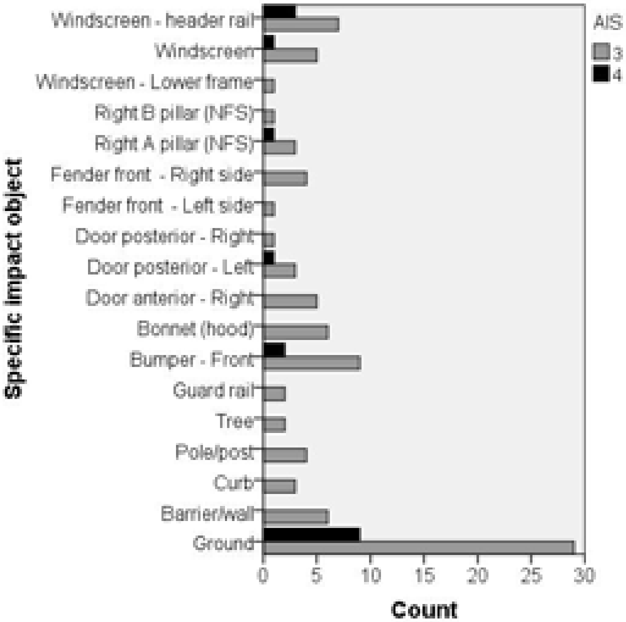


Figure 5.40: Frequencies of head injuries per impacted object (79 injuries)



(a) AIS1-2 (239 injuries)



(b) AIS3+ (109 injuries)

Figure 5.41: PTW users injury severity for vehicle parts

Chapter 6

Analysis of road accident causation

In 2000 Mackay [126] wrote that the reasoning around causation of road crashes is poorly understood and not very well defined. Clarke et al. [127] state that the phenomenon of causality of real road accidents can be difficult to study and that one possible way of studying them is to investigate the accidents when they have taken place, rather than studying the behaviour of the driver in "controlled environments".

Modern road traffic is a complex, rapidly changing and dynamic environment, which makes it a good example of a socio-technical system. In this system the task of the driver becomes gradually more and more complicated, and at the same time society demands a greater reduction in the number of accidents.

For this reason it is important to obtain answers to the questions on how and why accidents occur, to be able to develop efficacious policy countermeasures and active safety systems to prevent accidents.

6.1 State-of-the-art on the accident causation models

Many theories have been used in the field of the road safety for the study of accident causations and many of these are still in use today. Elvik [128] showed that these studies began in the early 1940's with the causal accident theory.

These theories were based on the triad: vehicle, human and environment and they see the human to be at the centre of the regulation. The individual interacted with the vehicles (e.g. driving the car or the ptw), with the environment (e.g. weather conditions, road surface and geometry), and with other users (pedestrians, cyclists, ptw users, etc.).

Many of these theories were also based on the systemic approach. A method that views the system as an organized system which works, evolves and is finalized [129].

The system can be viewed with four axes (see the Figure 6.1):

- the ontological, axis which defines the component of the studied object;
- the teleological, which allows a definition of the purpose associated to the object;
- the functional, which defines its function or process;

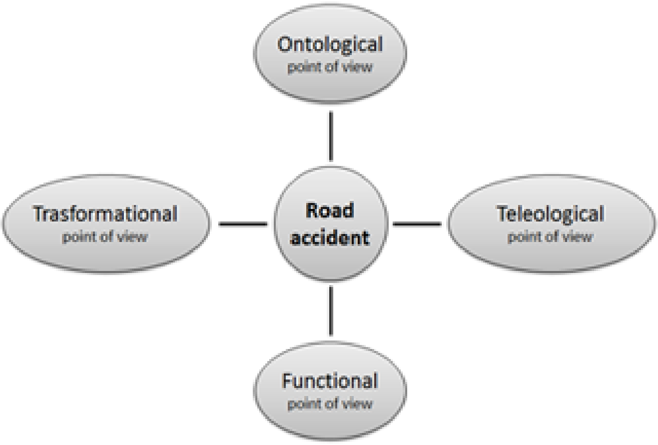


Figure 6.1: The four axis of the systematic approach

- the transformational, which takes into account the development of the object.

More in particular, if we look at the road safety field, the systemic approach can be seen as an approach that contains all the models normally used in accident research. For example,

- in the ontological axis we find models which allow a description of the three main components of the accident (HVE, Human, Vehicle, Environment) and help the stakeholder to understand to whom or to which environment their actions are addressed;
- in the teleological axis we have the different elements more or less structured (social aspects, driver task, etc.) but not a real model for the moment. The stakeholder can understand the constraints and the needs of each component of the system (why a driver is driving? why users use their car instead of public transport? etc.);
- the functional axis considers the human functional failure model which allows an analysis of the precess of the human malfunction, and, in general, how the system is functioning; and finally in
- the transformational axis we find the sequential model which allows a description of the dynamic aspect of the accident process.

From the ontological point of view we have models like the DVE (Driver-Vehicle-Environment) and the Haddon matrix.

The first models were principally proposed by traffic engineers and psychologists to asses crash risk. DVE models are not generally multidisciplinary, so lack the concept that expresses the complexity of interactions between the driver, vehicle and environment. The principal limits of these models are the lack of methodology that leads to the impossibility of a systematic gathering and exchange of data.

The Haddon matrix, developed by Wiliam Haddon in 1964, is the most commonly used model in the injury prevention field. It has a matrix framework composed of nine cells. This model is complementary to the DVE model because it adds information within the sequence of accidents. But, unfortunately, there is not a clear methodology to apply to such model. It can be used for organizing the factors that produce the accident, and also the results of other models.

Within the functional models we find models like the HFF - Human-Functional-Failure and the ACASS (Accident Causation Analysis with Seven Steps) developed by Otte [130] in 2009.

In the HHF model the failures are not seen as the causes of road accidents, but as the result of driving system malfunctions which can be found in its components (user/road/vehicle) and their defective interactions. The failure are delineated as sequential to the human function involved in information gathering, processing, decision and action.

The ACASS is a more recent causational model. The main reasons for the development of this model are the utility of having a methodology which is not exclusively applied by psychologists and which determines accident causes even if the interviews of accident-involved users are not available.

Finally, the DREAM method is an example of a model that can be inserted into the transformational axis. This method is a tool that allows the systematic classification and storage of the factors contributing to accidents which have collected in in-depth accident investigations.

This method has also been used in more recent EU projects like the SafetyNet and DACOTA and these also indication that this method is a useful tool for gathering uniform and comparable data.

In order to build a data bank more sharable, it was decided to use this model in our research.

6.2 DREAM Method

The Driving Reliability and Error Analysis Method (DREAM) is a tool that systematically classifies and stores information about the factors contributing to accidents which have been collected from in-depth accident investigations. But it is also used to analyse the factors that contribute to the development of an incident scenario.

The model was originally developed with the aim of identifying traffic situations for which the development of technical solutions had the potential to decrease the incidence of future accidents.

DREAM is based on the Cognitive Reliability and Error Analysis Method (CREAM) [131]. The latter was developed to analyse accidents within process control domains, such as nuclear power plants or train operators. In 2002 Ljung [4] adapted CREAM to the road accident domain and the method took the name DREAM.

DREAM uses the same accident model as CREAM, but with the classification scheme adapted to the driving domain since the time available for the driver to make observations, interpretations and plans is much shorter than the time available for operators in the process control domain. The method was principally used for accident analysis in Sweden.

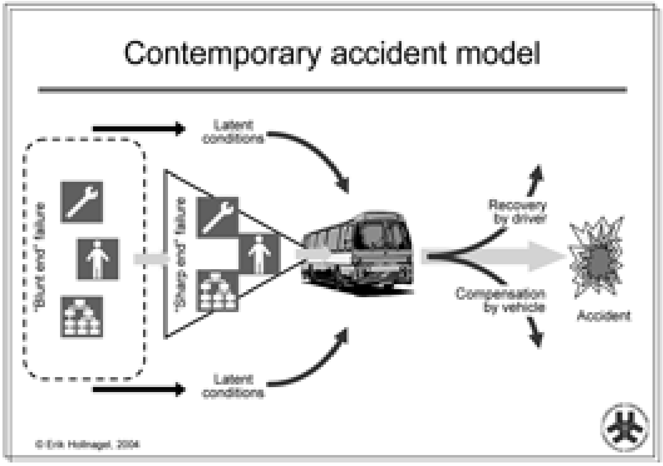


Figure 6.2: DREAM accident model

In 2006 this method was used in the SafetyNet project where it was updated and adapted to suit the traffic environment in the participating countries [4]. This version was called SNACS (SafetyNet Accident Causation System). In 2008 the DREAM 3.0 [132] version was released providing a method usable in all European countries. The latest version is DREAM 3.2 [133] where some problems specific to genotypes related to PTW have been solved.

The DREAM method has 3 main elements: an *accident model*, a *classification scheme* and a *method*.

An *accident model* is an abstract conceptual representation of the occurrence and development of an accident. The accident model is based on an MTO prospective (Man, Technology, Organization), which implies that accidents happen when the dynamic interaction between people, technologies and organisations fail in one or more ways, and that there are a variety of interacting causes creating the accident.

This method takes into account failure that occurs at the "sharp end" and/or the "blunt end". At the "sharp end" are the humans which are interacting with the systems in real time, while at the "blunt end" there are events remote in terms of space and time that have contributed to the development of the context in which the accident occurred. When a "blunt end" failure is not discovered or resolved, the consequences will remain in the system and they are called "latent conditions". The *classification scheme* is made up of *phenotypes*, *genotypes* and the *link* between them, which builds the accident causation chain.

The *phenotypes* or critical events classify the moment when the driver loses control from the physics point of view. That is the codification of the dysfunctional behaviour that precedes an accident with a limited set of codes (6 general phenotypes) based on the dimensions of time, space and energy.

The genotypes, or contributing factors, are the factors that may have contributed to the observable effects (i.e. relative to why control was lost); and in

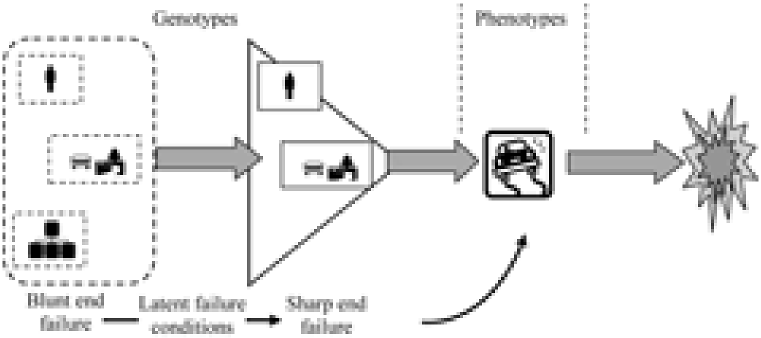


Figure 6.3: Blunt end and Sharp end failures [4]

general cannot be observed but only deduced from direct interviews and police reports. The genotypes are divided into 4 categories: driver, vehicle, traffic environment and organisation. Within these categories there are 51 general genotypes, some of which are linked to one or more specific genotype (see Table 6.1).

The *Driver* category includes: observation, interpretation, planning, temporary personal factors and permanent personal factors. THE *Vehicle* category includes: temporary HMI problems, permanent HMI problems and vehicle equipment failure. The *Traffic environment* includes: weather conditions, obstruction of view due to objects, state of the road and communication. Finally, the *Organisation* category includes: organisation, maintenance, vehicle design and road design. The aim of this method is to find a probable connection among these factors; a connection that can explain the observed consequences or the event phenotype. These connections are the links between phenotypes and genotypes and represent the existing knowledge about how different factors (causes and consequences) can interact with each other.

Table 6.1: Main genotypes and phenotypes of the DREAM method

Genotypes				Phenotypes
Driver	Vehicle	Traffic environment	Organization	
B: Observation	G: Temporary HMI problems	J: Weather conditions	N: Organization	Timing
C: Interpretation	H: Permanent HMI problems	K: Obstruction of view due to object	O: Maintenance	Speed
D: Planning	I: Vehicle equipment failure	L: State of road	P: Vehicle design	Distance
				Direction
E: Temporary personal factors		M: Communication	Q: Road design	Force
F: Permanent personal factors				Object

The strength of this method is that the phenotypes, genotypes and relative links are not subjective. Their choice is made based on specific rules which define

Table 6.2: Phenotypes or observable effects

	General	Specific
A1.1	timing	too early action
A1.2		too late action
A1.3		no action
A2.1	speed	too high speed
A2.2		too low speed
A3.1		too short distance
A4.1	direction	wrong direction
A5.1	force	surplus force
A5.2		insufficient force
A6.1	object	adjacent object

these links.

Finally, the method has 3 stop rules to aide the user in knowing when to stop the analysis. These rules are:

- specific genotypes have the status of terminal events; therefore, if a specific genotype is the most likely cause of a general consequence, that genotype is chosen and the analysis stops;
- if no general or specific genotypes exist that are linked to the chosen consequence, the analysis stops;
- if none of the available specific or general genotypes for the chosen consequence are relevant, given the information available about the accident, the analysis stops.

As suggested by the authors of this method for reducing the uncertainty in the causation chain, it is necessary to assign each chain a confidence level as follows:

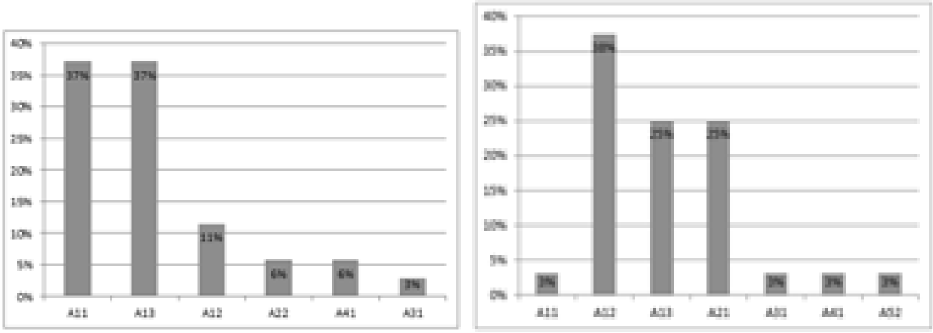
- confident: high level of confidence;
- probable: reasonable level of confidence;
- possible: low level of confidence.

6.3 DREAM analysis

The causation analysis is been conducted on vehicle-to-VRU and car-to-PTW accidents selected only in causation chains with a confidence level of "probable" or "confident".

Two different analyses have been conducted for both previous subsets and for each type of user (driver/VRU and driver/rider). The global behavior of the driver and VRU and their behavior on a straight road have been investigated afterwards for vehicle-to-VRU accidents. For the car-to-PTW subset, the global behaviour of both road users and their behaviour at the intersection have been investigated.

In both cases the choice is due to the fact that a majority of the accidents occurred within these scenarios (see Chapter 5).



(a) VRU (b) Vehicle opponent

Figure 6.4: Vehicle-to-VRU accident phenotypes

6.3.1 Vehicle-to-VRU causation analysis

As seen in the Chapter 5, the vehicle-to-VRU subset is composed of 39 cases.

The most frequent critical event for the VRU is the *Timing* (85%). In terms of specific phenotypes the most frequent are ”too early action” (A1.1 - 37%) and ”no action” (A1.3 - 37%), followed by ”too late action” (A1.2 - 11%). With the same percentage it is also possible to highlight the critical events: *Speed* (”too low speed” A2.2) and *Direction* (”wrong direction” A4.1). The latter particularly refers to cyclists (see Figure 6.4(a)).

For the opponent vehicles (driver or rider), *Timing* is the most frequent cause (66%), followed by *Speed*. In terms of specific phenotypes, ”too late action” (A1.2 - 38%) has the highest percentage followed by ”no action” (A1.3 - 25%) and ”too high speed” (A2.1 - 25%) with the same percentage (see Figure 6.4(b) and Table 6.2 for the phenotype definition). In the VRUs at the first level cause, Timing is most commonly linked to the ”misjudgment of the situation” (C2 - 22%), while the genotypes ”missed observation” (B1), ”misjudgment of the time gaps” (C1) and ”incomplete judgment of the situation” (C3) have 14%, 14% and 11.5%, respectively. While overall, the antecedent causes of the most common VRUs are ”expectance of certain behaviours” (F2) with its specific genotype ”rule following expectancy” (F2.2) and ”missed observation” (B1).

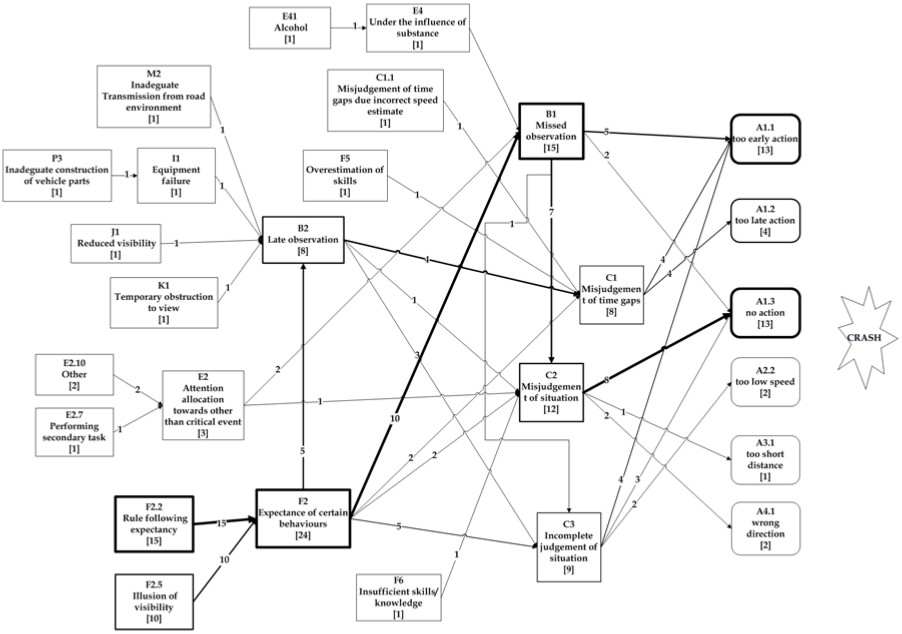
The most frequent genotype at the first level cause of the opponent vehicles is ”incomplete judgment of the situation” (C3 - 19%), followed by ”misjudgment of the situation” (C2) and ”late observation” (B2).

Figure 6.5 is the aggregate chart for vehicle-to-VRU accidents.

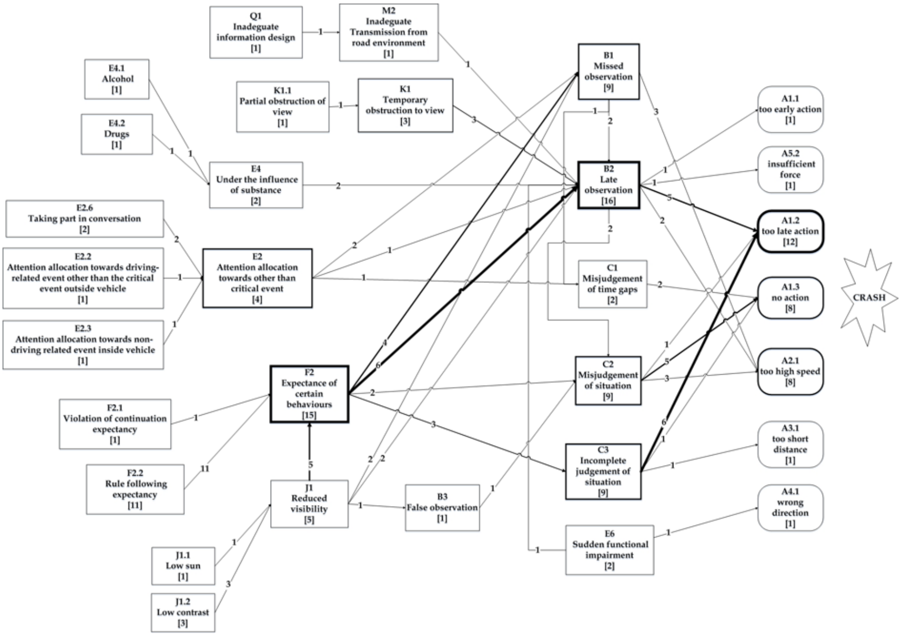
Straight road

As shown in Figure 6.6, the most common critical event for this type of accident scenario is *Timing* but, different from previous analyses, the most frequent specific phenotype is ”no action” (A1.3 - 46%) followed by ”too early action” (A1.1 - 32%).

For vehicles, the most frequent phenotype is *Timing* specifically ”too late ac-

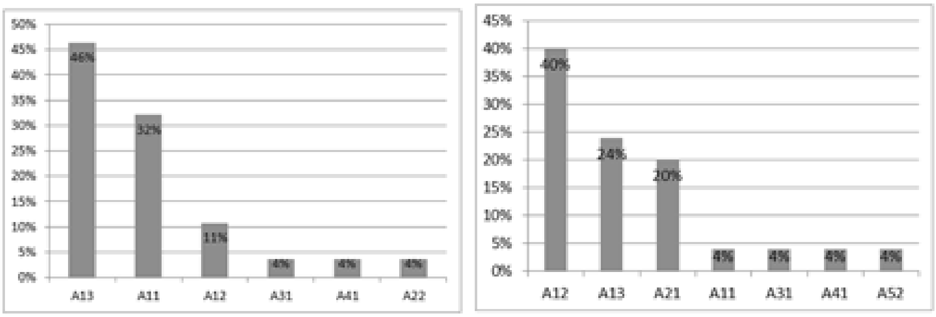


(a) VRU



(b) Vehicle opponent

Figure 6.5: Aggregate chart for Vehicle-to-VRU crashes



(a) VRU

(b) Vehicle opponent

Figure 6.6: Phenotypes for Vehicle-to-VRU accidents on straight roads

tion" (A1.2 - 40%) followed by "no action" (A1.3 - 24%) and *Speed* with the specific phenotype "too high speed" (A2.1 - 20%).

Genotypes C2 and B2 are the most frequent, followed by B1 (missed observation), C1 (misjudgement of time gaps) and C3 (incomplete judgement of the situation) with 21% respectively. At the second level cause, the link between "missed observation" (B1) and "misjudgement of the situation" (C2) have a recurrence of 21.4%, and this is followed by "expectance of certain behaviours" (F2) linked to "missed observation" (B1) (14.3%). Overall, the most frequent genotype is "expectance of certain behaviours" (F2), followed by "rule following expectancy" (F2.2) and "missed observation" (B1).

For vehicles, the more common link at the first level is "incomplete judgement of the situation"→"too late action" (C3→A1.2) (19%), followed by "late observation"→"too late action" (B2→A1.2) (16%). At the second level cause the links with the highest percentages are "late observation"→"incomplete judgement of situation" (B2→C3) (20%) and "expectance of certain behaviours"→"late observation" (F2→B2) (16%).

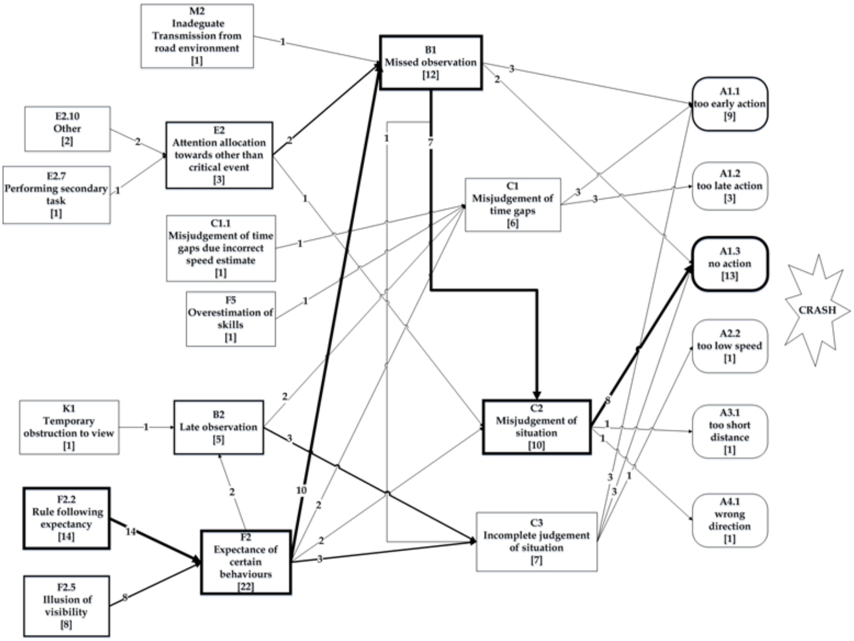
Figure 6.7 is the aggregate chart for vehicle-to-VRU accidents that occurred on straight roads.

6.3.2 Car-to-PTW causation analysis

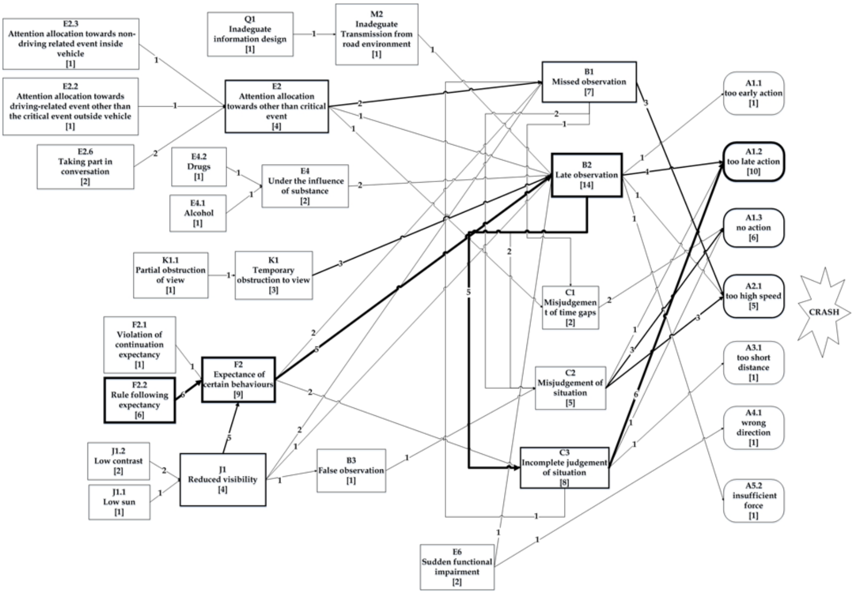
The subset car-to-PTW is composed of 27 road accidents which predominantly occurred at intersections (61.5%) (see Chapter 5).

Figure 6.8 shows the critical events for riders and drivers irrespective of the accident scenario. Thirty-eight percent (38%) of the riders experience a *Timing* critical event without any actions before the crash (A1.3 "no action"), followed by "too high speed" (A2.1 - 19%). Even if it is a lower percentage, riders also experienced other specific phenotypes: too early action, too late action surplus of force and/or wrong direction.

The most frequent driver phenotype is "too early action" (A1.1, followed by no action (A1.3), too late action(A1.2), wrong direction (A4.1) and too high speed

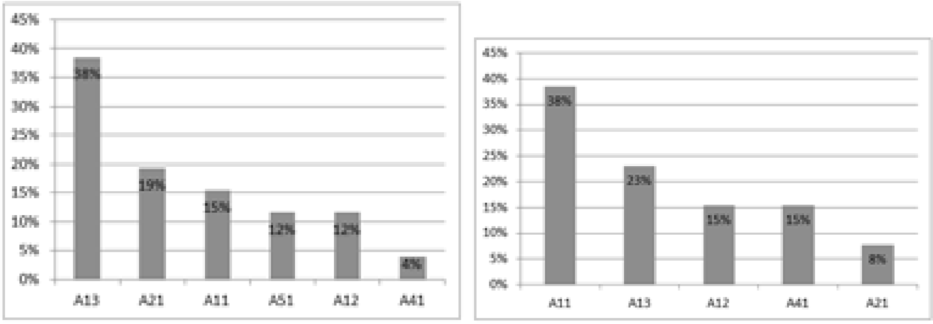


(a) VRU



(b) Vehicle opponent

Figure 6.7: Aggregate chart for Vehicle-to-VRU crashes on straight roads



(a) PTWs (b) Cars

Figure 6.8: Car-to-PTW accident phenotypes

(A2.1).

In terms of links between the critical event and the first level cause, riders highlight the link ”misjudgement of situation” with ”no action” (C2→A1.3) followed by ”misjudgement of situation” with ”too high speed” (C2→A2.1).

Overall C2 is the most prevalent genotype at this level cause.

At the second level cause the link ”misjudgement of situation” with ”incomplete judgement of situation” (B1→C2) is the most common with 28%.

For drivers at the first level cause, the most frequent link is ”misjudgement of situation” with ”too early action” (C2→A1.1) in 23% of the cases, followed by ”misjudgement of situation” with ”no action” (C2→A1.3) and ”misjudgement of situation” with ”wrong direction” (C2→A4.1) both at 15.5%.

Instead at the second level cause the links ”missed observation” with ”misjudgement of situation” (B1→C2) and ”late observation” with ”Misjudgement of situation” (B2→C2) are the most frequent.

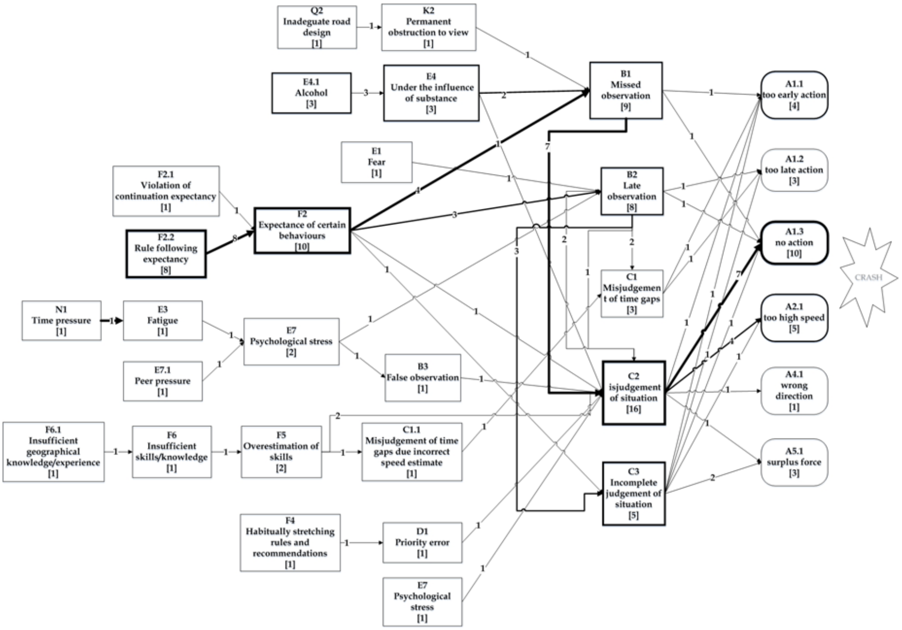
Finally, Figure 6.9 is the aggregate chart for car-to-PTW.

Intersection

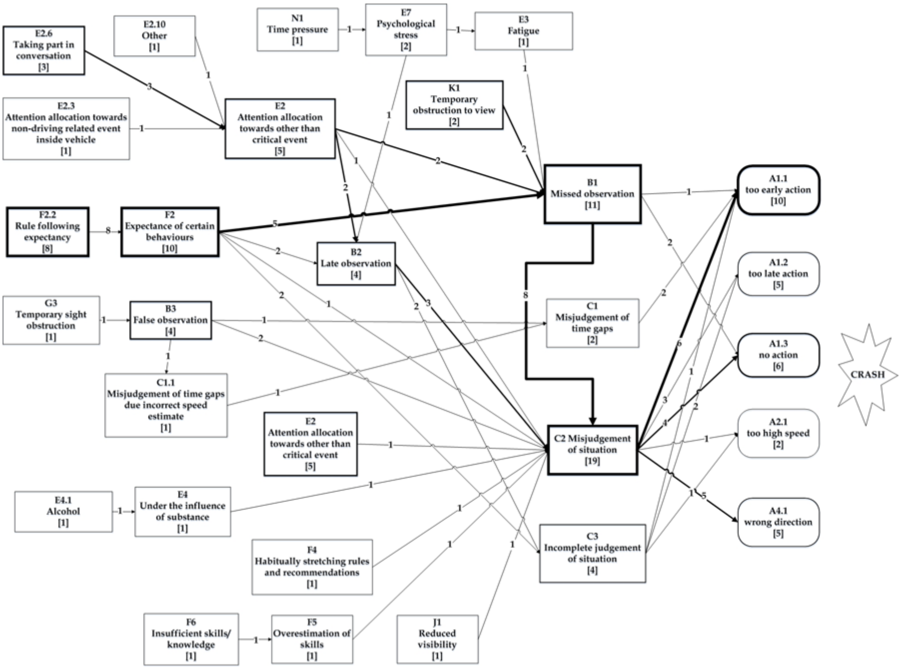
Analyzing the phenotypes of the 16 car-to-PTW accidents which occurred in intersections, it is possible to see that for the rider *Timing* (A1) and *Speed* (A2) are predominant, but immediately followed by *Force* (A5). In more detail the most frequent phenotype is ”no action” (A1.3) 31% followed by ”too high speed” (A2.1) 25%. As previous highlighted, ”surplus force” (A5.1) had a significant percentage (13%). For the driver, the most frequent specific phenotype is ”too early action” (A1.1) 44% followed by ”no action” 38% (Figure 6.10).

Finally, for the rider the most frequent first level cause link is ”misjudgement of situation” with ”no action” (C2→A1.3) 31%, followed by ”misjudgement of situation” with ”too high speed” (C2→A2.1) 19%. While within the second level cause, the most recurrent link is ”missed observation” and then ”misjudgement of situation” (B1→C2) 40%.

For the driver the most frequent first level cause links are ”misjudgement of

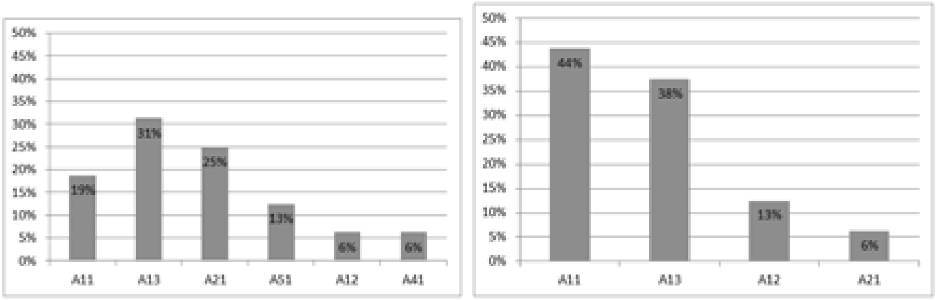


(a) PTWs



(b) Cars

Figure 6.9: Aggregate chart for car-to-PTW crashes



(a) PTWs (b) Cars

Figure 6.10: Phenotype for Car-to-PTW accidents at intersection

situation" with "too early action" (C2→A1.1) and "misjudgement of situation" with "no action" (C2→A1.3) both at 25%. At the second level cause there is "missed observation" with "misjudgement of situation" (B1→C2) 40%, followed by "expectance of certain behaviour" with "missed observation" (F2→B1) and "expectance of certain behaviour" with "incomplete judgement of the situation" (F2→C3) 13%.

Figure 6.11 is the aggregate chart for car-to-PTW.

6.4 Conclusions and limitations

The causation chains highlight that the VRUs expect the vehicles to behave in the manner prescribed by the rules. In some cases the VRU also has reduced visibility principally due to parked vehicles or fixed obstacles.

Therefore, while the environment presents all the necessary cues to interpret the event, most frequently VRUs usually misjudge the appropriate action to take. Also, a missed or incomplete observation of the surrounding scenario and the misjudgment of the time gap between the VRU and the opponent vehicle, are two important aspects that lead to VRU accidents.

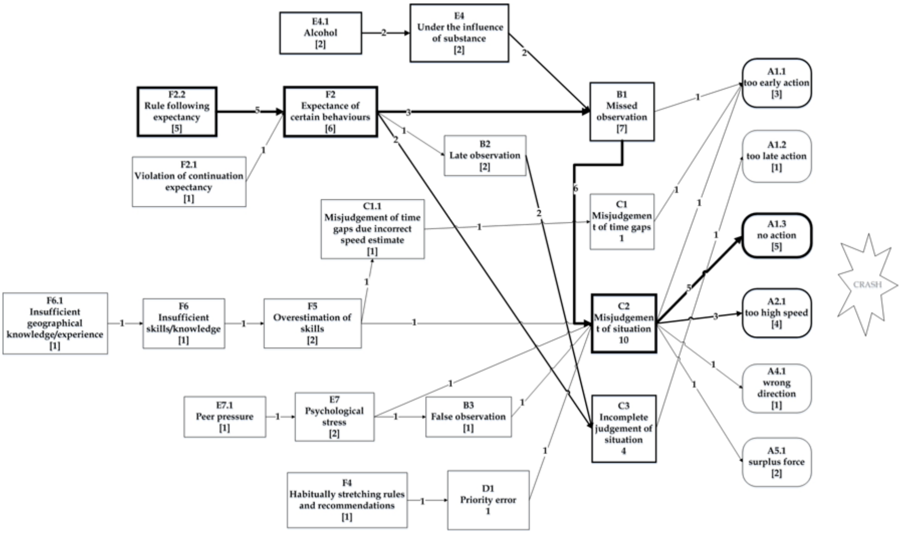
For the opponent vehicle the most critical event is timing, i.e., it is inclined to take late action or no action, but also high speed is an important factor.

Many VRU accidents happen because the drivers see the VRUs too late, especially on a straight road. This could be a consequence of a lack of attention while driving in specific situations (e.g. straight road) or in the expectation that the VRU will follow the rules. VRUs often cross the road outside the crosswalk or begin to cross when an obstacle has reduced their visibility.

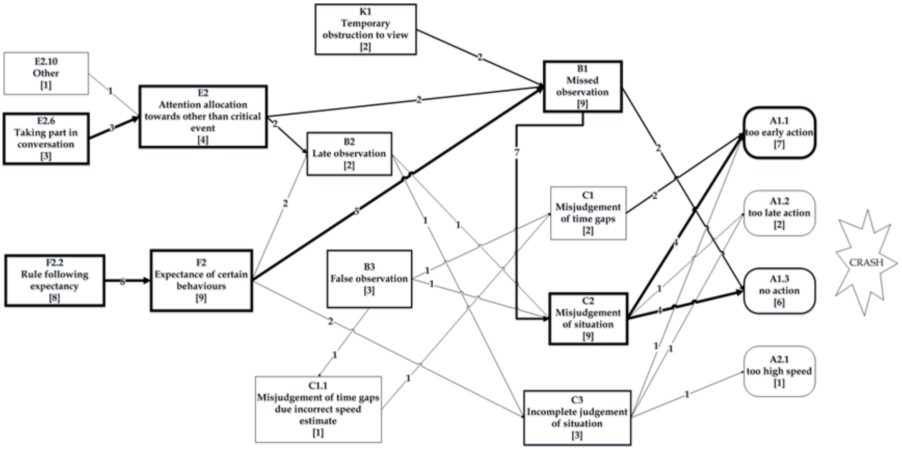
Speed is also a significant contributing factor in taking delayed action.

The PTW-to-car accident sample is principally crashes at intersections or head-on side collisions. For this subset of crash, timing is the main critical event for both road users.

For PTW users other critical events are speed and force. Usually action is not taken or is taken too early. When the riders make an avoidance manoeuvre, generally braking, it applies such force that the wheels become blocked and leads to



(a) PTWs



(b) Cars

Figure 6.11: Aggregate chart for car-to-PTW crashes at intersections

the lost of control of the motorcycle. Riders also overestimate their driving ability compared to the traffic environment and this leads to dangerous manoeuvres or driving at a high speed.

In general, in both cases riders and drivers fail to understand the situation that is in front of them. This is principally due to both of the road users expecting that the other will follow the rules.

Unfortunately, there are limitations for this study due to the fact that it was not possible to have direct interviews with the participants of the samples. The previous considerationss/analyses were done based on police documents, statements and crash reconstruction. This is one of the major limitations of these results, since the behaviour taken before the precipitating event is often unclear and can lead to making an erroneous choice of the genotype or the exclusion of certain genotypes.

I believe that this method is not very user friendly and requires appropriate training for the correct choice of genotypes.

This method only partially solves the problems of the subjectivity in the selection of the casual factors. A definition of phenotypes and genotypes helps to reduce the problem, but does not eliminate it. Training in the method might help in the reduction of this problem, although the developers do not consider it necessary.

I also believe that an enlargement of the manual through a more detailed and comprehensive description of the various genotypes would be useful, even more efficient. All this would make the discrimination between different casual factors or the avoidance of making the obvious choices more easy.

Also, the quality of the evidence and the interviews/witnesses gathered is very important. The quality will be greater and the discrimination between the various casual factors simpler. The witnesses will always give us their version of the accident that often does not coincide with the real circumstances. Therefore, for each road user examined it is extremely natural to find more than one causation chain. The choice of which chain is the most probable is once again too subjective.

A possible solution to this last problem could be the following. To estimate the committed error of the causation chain based on the certainty of the selection of the individual genotypes; assigning a level of reliability for each choice (function of the quality of the data input) the system indicates the causation chain most likely by calculating three different error levels.

Furthermore, a good description of the motivation of the analyst that led them to make each single choice can be very useful for a better understanding of why some behaviours occurred. Certainly, to have these answers require further studies and cannot be directly derived from the DREAM method.

In conclusion, I believe the DREAM method would be useful for sorting the causation of the accident in a more systematic way. However, new genotypes must be defined. To achieve this, I believe that the involvement of other road safety specialists is necessary, and more detailed and useful information on the genotypes can be derived from naturalistic driving research.

Chapter 7

Evaluation of the effectiveness of the AEB Protection System

7.1 Introduction

Nowadays the passive safety assessment is well established in regulation and consumer testing, while the active safety assessment has only emerged recently. In 2014 the Euro NCAP will introduce the active safety assessment in its consumer ratings tests.

The Euro NCAP assesses the passive protection offered for pedestrians with well-defined and consolidated test protocols at fixed test speeds and impact angles [134] [135] [136], but it is not the same for the active safety assessment. Assessment for active safety systems is currently under discussion and most probably will be tested by the Euro NCAP beginning in 2016.

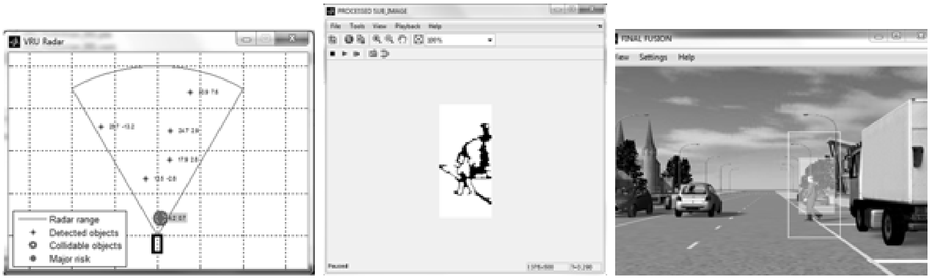
The importance of the use of active safety systems is well known both in terms of accident avoidance for injuries and severity reduction. For these reasons some of these systems have already been introduced in new car models.

The Autonomous Emergency Braking (AEB) Pedestrian System is the active safety system specifically developed for the protection of VRUs. These systems are designed to identify shapes and human features through a camera and radar system and calculate the VRU moving with respect to the vehicle path. If the system determines that an impact between the vehicle and the VRU is unavoidable, the AEB system applies full braking to bring the car to a complete stop.

The aim of this chapter is the study of the influence and the efficacy of these systems on real-world pedestrian accidents, based on real-life crash data coming from urban scenarios. The effectiveness is evaluated both in terms of crash avoidance and reduction of injury severity.

7.2 PreScan's AEB pedestrian system

The Pedestrian Protection System (PPS) is a particular AEB system specifically developed to avoid or reduce the severity of collisions with pedestrians. The main difference between an AEB system and a PPS system is the sensor used by the system to decrease the velocity of an unavoidable impact.



(a) Radar (b) Pedestrian detection (c) Camera sensor

Figure 7.1: Radar and camera sensor

In both cases the systems use two detection sensors. An AEB device has a Long Radar Range (LRR) system with a working field up to 150m and 9 degrees of beam width. A Short Radar Range (SRR)system has a working field up to 30m and 80 degrees of beam width. But the PPS system has radar and camera sensors.

PreScan is a physics-based simulation platform used for the development of Advanced Driver Assistance Systems (ADAS) that are based on sensor technologies such as radar, laser/lidar, camera and GPS. This software is also used to design and evaluate vehicle-to-vehicle and vehicle-to-infrastructure communication applications as well as autonomous driving applications.

7.2.1 PreScan PPS features

The PPS development in PreScan uses two different sensors: radar and camera sensor. There is the assumption that in all cases the sensors have no drift, noise or distance uncertainty.

The radar sensor is used to determine objects on the road and the relative speed between the car and a obstacle. This data is then used to determine the point where the collision will take place. The Time-To-Collision (TTC) is then calculated. The radar output, shown in Figure 7.1(a), highlights the objects detected by the system (in blue), the collidable objects in green, and those with the major risk of collision in red. The information from the camera sensor is used to recognize if the obstacle detected is a pedestrian or not. The pedestrian detention algorithm processes the image from the camera and marks the area around the object detected by the radar (white rectangle). The pedestrian classification system works on only the part of the image within this rectangle. Finally, the objects recognized as pedestrians are marked with red rectangles (see Figure 7.1(c)).

The system will consider an object as dangerous if the TTC of the car is less than 2 seconds ($TTC < 2$). The pedestrian detention algorithm will be activated in this case.

If the TTC drops below 1.6s and the camera sensor has identified the object as a pedestrian, a warning for the driver is turned on. If impact with the pedestrian is unavoidable and it is too late to steer away ($TTC < 0.6s$), full braking pressure is applied and maintained until a complete stop is achieved. The main parameters

Table 7.1: Summarizing of the PreScan PPS's actions

N	Pedestrian recognition	warning signal TTC<1.6	braking TTC<0.6s	action
1	yes	x	yes	full braking pressure
2	yes	yes	no	warning to driver
3	yes	no	no	do nothing
4	no	x	x	do nothing

Collidable object detected TTC = 1.20

Pedestrian classified TTC = 0.92

Driver warning TTC = 0.92

Full braking TTC = 0.56

Collision avoided

Vehicle Speed 42 km/h

Brake 100 %

RPM 1222

Figure 7.2: PPS's interface

of the operation of the system displays of the PreScan console are the TTC for the collidable object detected, TTC for pedestrian detected, departed driving warning (in seconds), TTC for full braking, status and speed of the collision (if not avoided), speed, RPMs and braking (see Figure).

Radar

The principal radar parameters are summarized in Table 7.2. When the radar recognizes potentially dangerous objects, human recognition is activated. The sensor is located in front of the car at a height of 40cm from the ground (see Figure 7.3(a)).

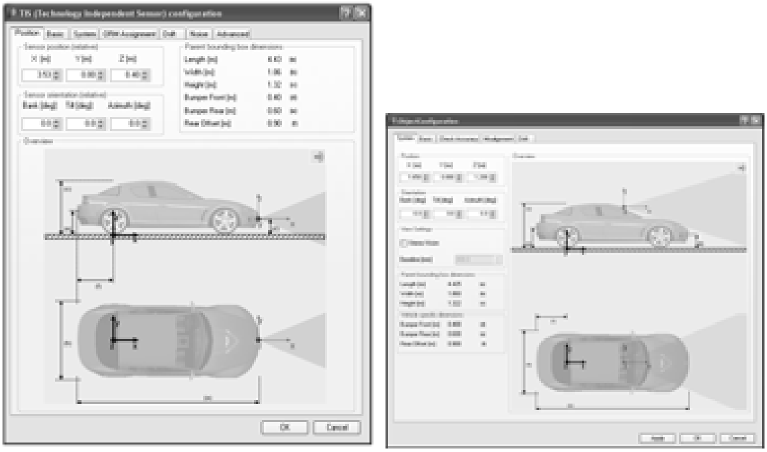
Camera sensor

The principal camera sensor parameters are summarized in Table 7.3.

Within the car the camera sensor is located in correspondence to the interior rear view mirror. Since the camera works like a human eye and can see only what the driver can see, it can also be affected by weather conditions or light pollution (see Figure 7.3(b)).

Table 7.2: Radar sensor properties

scan pattern	line scan
beam type	elliptical
beam range [m]	40
beam $\triangle\theta$ [deg]	60
beam $\triangle\vartheta$ [deg]	monochrome
coherent system	enable
capture freq. FoV [Hz]	25
beams	1
Max objects to detect	32



(a) Radar (b) Camera sensor

Figure 7.3: Radar and camera sensor location within the car

Table 7.3: Camera sensor properties

stereo vision	disabled
horizontal resolution [pixel]	500
vertical resolution [pixel]	375
frame rate [Hz]	50
colour/monochrome	monochrome
intensity factor [RGB]	01/01/2001
specify parameters	enabled
focal length [mm]	7.5
CCD chip size	1/2” (6.4x4.8mm)

7.2.2 Assumptions and limitations

Assumptions and limitations of the PreScan system are summarized below.

- sensors have no drift, noise or distance uncertainty represented;
- current and previous time step data is used in calculating velocity;
- turning the indicator on deactivates the system;
- autonomous braking, if activates, bring the car to a halt;
- human recognition is enabled only when radar recognizes potentially dangerous objects;
- camera sensor can be affected by weather conditions or light pollution;
- driver's behaviour/manoeuvres are not modeled;
- environmental conditions are modeled only in terms of light (night or daylight) and weather (rain or dry) and road shape (excluded slope);
- weather conditions influence only the camera sensor and radar, but not the friction coefficient. That result is always set at the maximum value.

7.3 Relationship between VRU's outcome and impact speed

7.3.1 Sample description

The evaluation of the effectiveness of the PPS in urban areas was conducted after that a correlation between the pedestrian injury severity and car's impact speed was determined.

For the evaluation of the previous correlation, due to the small dimension of the sample (23 cases) and a similarity between the kinematics of the pedestrians and cyclists subjected to head-on-side crash, both the two road users were included.

The sample was set up with car-to-VRU crashes that occurred in urban areas, both residential or commercial and also rural (more in general where the speed limit was 50 km/h). For car-to-bicycle accidents only the head-on-side crashes were selected. The VRUs injured included in the sample were all admitted to the ICU with a major trauma diagnosis.

Fifty-six percent of the cars were classified as a *compact car* (e.g. Toyota Yaris, Ford Fiesta, etc.); 8.7% as a *small car* (e.g. Smart fortwo); 13% as a *medium car* (e.g. Volkswagen Golf, Audi A3, etc.); 17.4% as a *SUV* (e.g. Land Rover Evoque) and, finally; 4.3% as a *VAN*.

The bumper, front panel and leading bonnet edge (LBE) are the main sources of lower extremity injuries. In particular, the LBE is one of the leading causes of injuries of the abdominal region and the upper part of the legs. The average height of the BLE is 0.76m (SD 0.0745).

The pedestrian's most frequent trajectory is a wrap trajectory in 47.8% of the cases, followed by a fender vault trajectory (43.5%).

In terms of impact parameters, the mean impact speed is 41.5 km/h (SD 12.85) while the angle between car and VRU[1] is, on average, 79 degrees (SD 18.8) (see Table 7.1).

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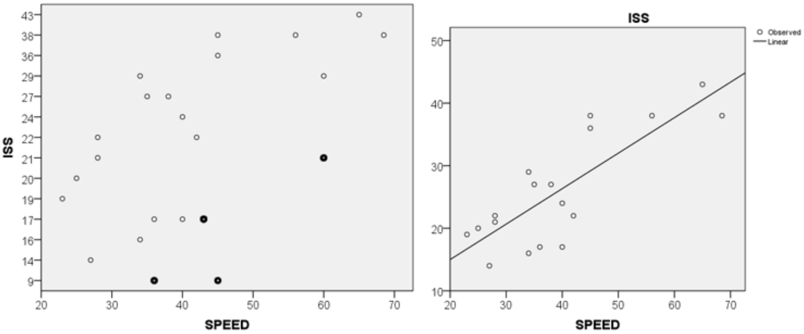
[1] angle between the car's longitudinal axle and the sagittal plane

Table 7.4: Sample features

ID	Car type	Mass [kg]	BLE [m]	V_imp [km/h]	Age	MAIS head	MAIS face	MAIS chest	MAIS abd.en	MAIS ext.ies	MAIS ext.l	MAIS	ISS	NISS	GCS on-s	GCS ER
25	Medium	1400	0,73	45	64	5	2	3	0	0	0	5	38	50	8	8
26	Compact	950	0,81	36	45	3	0	0	0	0	0	3	9	27	15	15
32	Compact	950	0,81	34	18	4	0	0	0	0	0	4	16	34	15	8
35	Compact	930	0,66	40	28	4	0	2	0	2	0	4	24	41	7	3
47	Compact	720	0,79	68,5	43	5	2	2	3	2	1	5	38	43	12	11
49	SUV	1300	0,88	65	23	5	0	3	2	3	0	5	43	50	6	3
51	Compact	940	0,72	42	20	3	0	3	0	2	0	3	22	27	7	3
54	Compact	1010	0,68	40	59	3	2	2	0	2	1	3	17	22	15	15
56	Compact	970	0,72	38	90	0	0	3	3	3	0	3	27	27	15	14
58	Medium	1450	0,72	60	33	0	0	3	2	4	1	4	29	48	15	14
60	Small	830	0,79	56	26	5	2	3	0	2	0	5	38	43	5	5
62	Compact	1125	0,77	25	79	4	0	2	0	0	0	4	20	34	12	12
66	Medium	1420	0,73	46	49	4	2	2	2	4	1	4	36	48	6	3
69	VAN	2300	-	35	78	3	0	3	2	3	1	3	27	27	11	11
70	Compact	975	0,69	28	44	4	2	0	0	0	1	4	21	41	11	11
72	Compact	1050	0,73	28	71	3	2	3	2	0	1	3	22	27	11	11
73	Compact	1200	0,67	60	56	4	1	0	2	1	0	4	21	34	3	3
74	SUV	1770	0,92	23	63	3	0	3	0	0	1	3	19	22	15	15
76	Compact	1050	0,73	45	72	2	0	2	0	0	1	2	9	12	3	3
77	Small	830	0,79	34	39	4	2	3	2	0	1	4	29	41	7	9
88	Compact	1170	0,71	27	76	3	2	0	0	0	1	3	14	17	15	14
91	SUV	1300	0,88	36	78	3	2	2	2	2	1	3	17	17	13	9
94	SUV	1300	0,88	43	86	3	2	0	0	2	1	3	17	22	8	9



(a) ISS(V) scatter plot (b) ISS(V) linear regression

Figure 7.4: Scatter plot and linear regression per ISS(V)

7.3.2 ISS and impact speed correlation

The Pearson correlation shows the impact speed is well correlated to the ISS, with a value of 0.59 and a significance at the 0.01 level.

The nonparametric correlation highlights that the *impact speed* is correlated to the *GCS* (both on-scene and in the ER) with a Spearman's rho of -0.5 and a significance less than 0.05. It is also weakly correlated to the *age* of the VRU (Spearman's rho to -0.336, p=0.017) and to the MAIS4+ (Spearman's rho to 0.355, p=0.096). Finally, the *age* results well correlated to the MAIS4+ (Spearman's rho to -0.551, p<0.01), while, at the contrary to how reported by Rosen et al.[137], Demetriades [138] Baker [139], and Bull [140], the age is not correlated with the ISS (Spearman's rho to -0.336, p<0.117).

From the previous cases and after highlighting some of the outlier values, as shown in the Figure 7.4(a) (bold points), the sample was been reduced to 18 cases in order to improve the quality of the regression model. The accidents excluded from the sample were principally those considered most affected by accident reconstruction errors due to lack of data or particular dynamics (e.g. glancing).

By means of linear regression, the equation is

$$ISS = 3.64 + 0.567 \cdot V \tag{7.1}$$

with a R-Square = 0.66 and an adjusted R-Square = 0.64 (see Figure 7.4(b)).

7.3.3 Risk function of severe injuries

Finally, using a logistic regression, two injury risk functions as a function of impact speed are also calculated. One for the risk of sustaining an ISS≥20, and one for the risk of sustaining at least one severe[2] injury (MAIS4+).

$$P_{injuries}(V) = \frac{1}{1 + exp(-a_i - b_i V)} \tag{7.2}$$

---

[2] minor = AIS 1, moderate = AIS 2, serious = AIS 3, severe = AIS 4, critical = AIS 5, maximum = AIS 6

The coefficients a_i and b_i are summarized in Table 7.5.

Table 7.5: Logistic regression results

Injuries		Estimate	S.E.	Wald	p-value
Severe	a_1	0.086	0.05	3.548	0.06
	b_1	-3.406	1.86	3.342	0.07
ISS≥20	a_2	0.072	0.05	2.389	0.12
	b_2	-2.210	1.82	1.481	0.22

As shown in the Table 7.5, the significant level of the severe risk function is 0.1; while for the ISS>20, the correlation is not statistically significant. This is probably due both to the extremely small dimensions of the sample and to the absence of minor traumas (AIS≤2).

Rosen, in his studies [141] [6] based on a sample of 753 pedestrian impact including 38 fatalities, find the regression parameters shows in Table 7.6.

Table 7.6: Regression coefficients by Rosen [6]

Injuries		Estimate	S.E.	Wald	p-value
Serious (MAIS3+)	a	0.078	0.01	3.548	<0.0001
	b	-4.6	0.37	3.342	<0.0001

Comparing the serious risk function with that found by Rosen et al. (see Figure 7.5)), it is possible to highlight a similar curve's shape but with a shift towards a minor impact speed. Afterwards, the risk curve overestimates the severity of pedestrian impacts, especially at medium-low speed.

This difference could apparently be due to a different size and typology of the sample. Rosen et al. [137] in his paper points out that the main reasons for this problem are due to the following points:

- absence of a weighting procedure for the injury severity (bias error);
- limited number of cases;
- errors in the reconstruction phase (systematic and random errors);

The absence of a weighting procedure produces a risk function that is not representative of the complete population (national data), i.e. introduces a bias error. Unfortunately, this problem cannot be solved because national data does not consider the differences between slight, severe and fatal injuries, but also because our sampling plan is focused only on the outcome.

Also, the errors in the reconstruction phase may have conditioned the results, but I believe that the main cause is due to the high percentage of fender vault trajectories. In this case the impact against a more rigid car part causes a more serious injury at a lower impact speed.

In conclusion, this risk function cannot be applied to the general population, but can be used as an elemental of comparison for the evaluation of the effectiveness of the PPS.

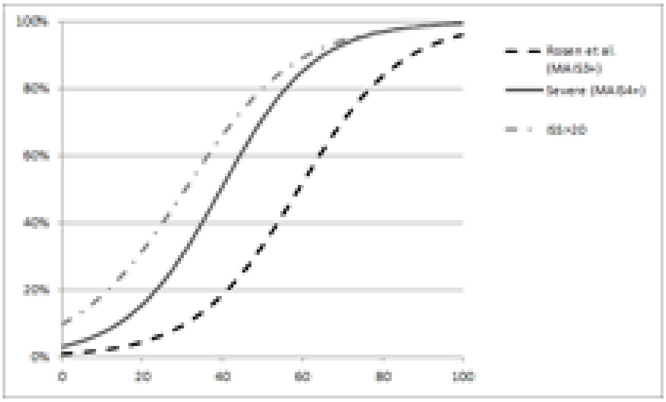


Figure 7.5: Risk curve for severe pedestrian injuries

7.4 Reproduction of the urban environment with PreScan ®

The PreScan®software is able to reproduce the real environment of road traffic in all its aspects: infrastructure, lighting, weather and road users' behaviour. But it cannot reproduce the dynamics of the crash and post crash phases or evaluate the crash dynamics parameters. The software calculates the impact speed in case an impact is occurs.

7.4.1 Sample description

The pedestrian impacts studied were a sample of 17 cases, all of which occurred in urban areas.

The study was done under these assumptions:

- road straight and level;
- lighting: daylight or night;
- weather: cloudless or rain;
- vehicles: reduced to four typologies;
- driver manoeuvres: braking.

Overall, all the 17 pedestrian impacts occurred on straight and level roads and in daylight or night conditions (not at sunset or sunrise). Since detailed information on the lighting conditions was not available, the default PreScan condition for daylight and the absence of public illumination for night was assumed. Since the software is not available for all types of vehicles that were involved in the crashes studied, the vehicle typologies used are the *Toyota Yaris* and *Ford Fiesta* for the *small* and *compact* categories, the FIAT Bravo for the *medium* category and the *Toyota Previa* and *BMW X5* for *VAN* and *SUV* categories, respectively.

The pedestrian point of impact is defined in terms of angle between vehicle and pedestrian trajectories and in terms of position compared to the vehicle's width. Due to the different types of vehicles available in the software, the front width has been divided into three areas (Right, Center and Left) and the point of impact classified according to them.

Only a braking action has been considered for the driving manoeuvres before the crash , while all objects that could affect the visibility of the pedestrians have been reproduced.

The principal features of the sample are summarized in the Table 7.7.

Table 7.7: Sample's features

ID	Weather condition	Lighting condition	Car type	PreScan vehicle	Speed [km/h]	Action	Time [s]	Angle [deg]	Impact speed [km/h]	Pedestrian speed	Impact position
32	dry	daylight	Compact	Yaris	50	braking	1,25	75	34	Walking	R
35	dry	daylight	Compact	Yaris	58	braking	1,25	108	40	Walking	R
47	dry	daylight	Compact	Yaris	68,5	none	-	85	68,5	Walking	C
51	dry	daylight	Compact	Yaris	54,6	braking	0,6	76	42	Walking	R
54	dry	daylight	Compact	Fiesta	50	braking	0,6	83	40	Walking	L
56	dry	night	Compact	Yaris	60	braking	1,25	87,5	38	Walking	L
60	dry	night	Small	Yaris	58	braking	1,25	56,5	56	Walking	C
62	dry	daylight	Compact	Yaris	49	braking	1,25	65	25	Walking	L-C
66	dry	night	Medium	Bravo	70	braking	1,25	98	46	Walking	R
69	dry	daylight	VAN	Toyota Previa	49	braking	1	75	35	Walking	R
72	dry	daylight	Compact	Yaris	48	braking	1	86	28	Walking	R
73	rain	daylight	Compact	Fiesta	60	none	-	69	60	Walking	L
74	rain	night	SUV	Bmw X5	33	braking	1,25	100	23	Walking	R
76	dry	daylight	Compact	Yaris	59	braking	1,25	67	45	Walking	R
77	rain	daylight	Small	Yaris	51	braking	1,25	100	34	Walking	L
88	dry	daylight	Compact	Yaris	47	braking	1,25	90	27	Walking	R
91	dry	daylight	SUV	Bmw X5	55	braking	1	90	36	Slow Walking	R

7.4.2 Case study

The case study is a pedestrian accident that occurred in a crosswalk on a morning in mid-September. The weather was cloudless and it was daylight.

The car coming from the roundabout proceeded on a straight road with some cars parked on the right side. Between the last parked car and the crosswalk there were some motorcycles that compromised the driver's visibility. The pedestrian started across the crosswalk and then was hit (see Figure 7.6).

From the accident reconstruction the driver was driving at 48 km/h when, one second prior the crash, the driver saw the pedestrian and started to brake. The impact occurred at 28km/h between the right corner of the car and the left side of the pedestrian. What followed was a fender vault trajectory (see Figure 7.7).

The pedestrian's major injuries were due to impact of the left side of the head against the A-pillar and the thorax with the outside rearview mirror. Reproducing the previous scenario with the PreScan software and applying the pedestrian protection system to the car, this accident could have been avoided. The radar recognizes all obstacles present on the right side of the road and among these, at 1.5s to the collision, it finds the possible collided object (see the green circle in Figure 7.8). At 0.24s prior to the collision, the system classifies the collidable object as a pedestrian and applies full braking until the car stops.

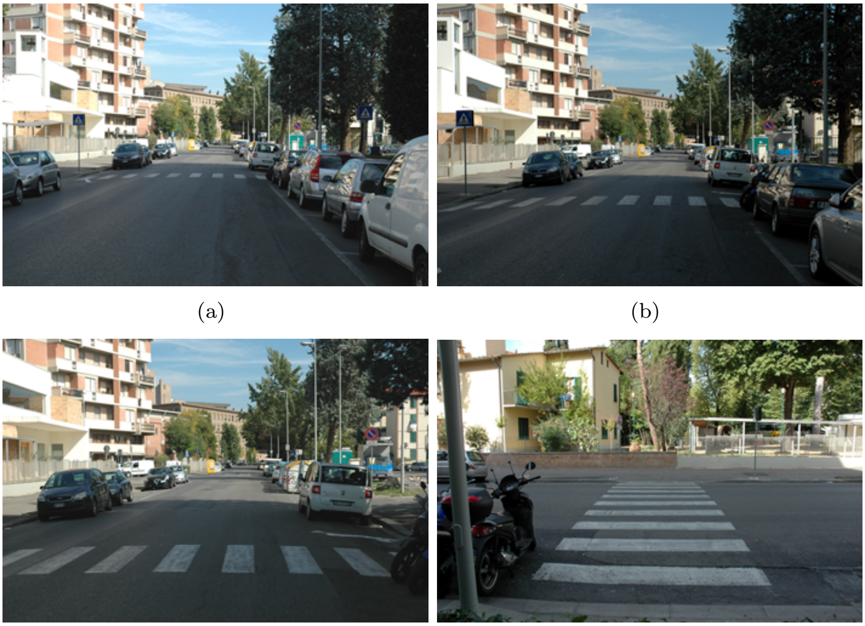
7.4.3 Simulation results

Table 7.8 shows that 2 of the 17 accidents were avoided while in the other cases, the mean value of the impact speed has been reduced 63.6%, from 41.5 km/h (SD 12.85) to 26.4 km/h (SD 13.4).

As a consequence of more efficacious braking, in two cases the pedestrian impact occurs later, thus the point of impact moves towards the center of the front of the vehicle where the level of danger is less.

Finally, in three cases ID 32, 60 and 69, the PPS recognized the object as collidable but the camera sensor did not detect the pedestrian. In these cases the PPS did not have any effect, and thus the impact speed was not subject to any variations. For ID 32 and 69 some possible causes were the high speed and more likely the radar beam had a reduced angle (60) combined with a short distance between the position in which the pedestrian became visible and the front corner of the car. While for ID 60, the high velocity (more than 50 km/h) and the night vision likely caused a camera sensor misjudgment.

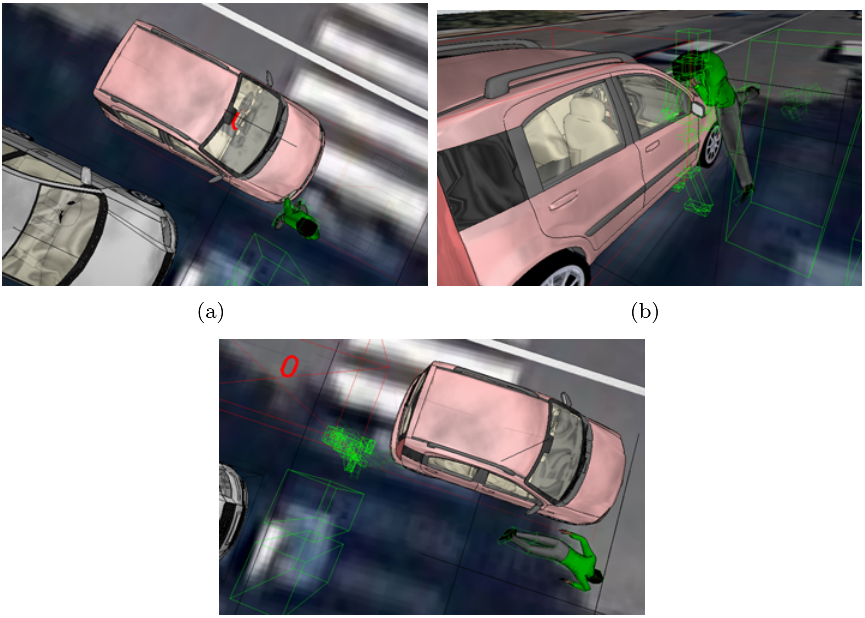
Using the relationship between the ISS and impact speed previously found in Equation 7.1, the new pedestrian severity outcome is also been estimated (see Table 7.8). The mean value of the ISS has been reduced 20%, from the 23.3 to 18.6 (SD 7.44).



(a) (b)

(c) (d)

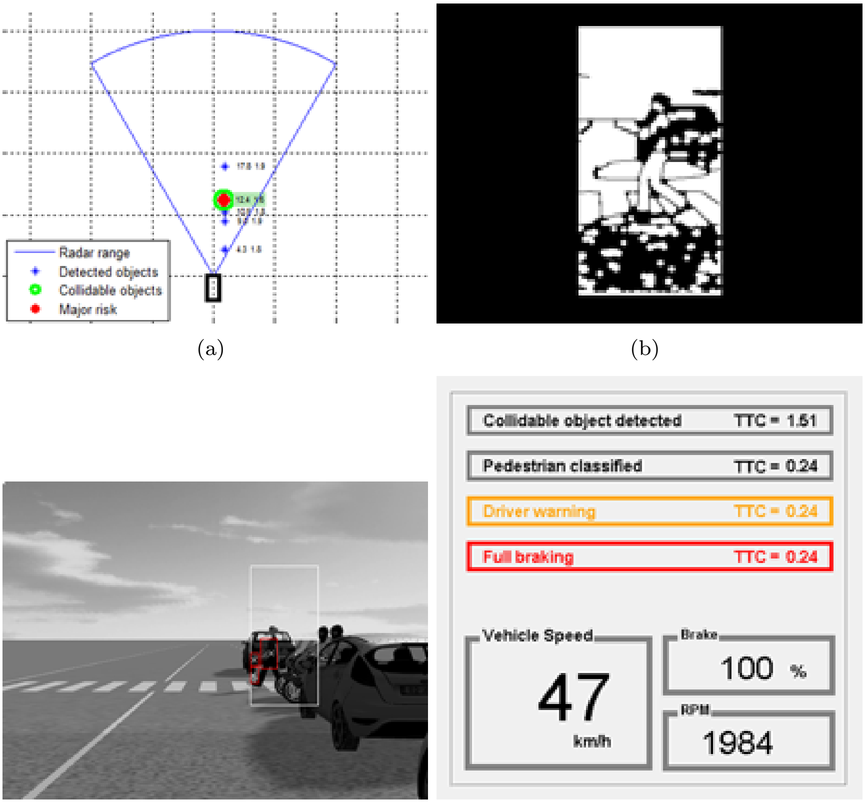
Figure 7.6: Driver and pedestrian line of sight



(a) (b)

(c)

Figure 7.7: Pedestrian's kinematics



(a) (b)

(c) (d)

Figure 7.8: PPS - pedestrian identification

Table 7.8: Simulation results and injury outcome

ID	Impact?	Impact position	Impact speed [km/h]	Collidable object	Collidable object [s]	Pedestrian detection	Pedestrian detection [s]	Driver warning [s]	Full braking [s]	Status	ISS
32	yes	R	34	yes	0,8	no	0	0	0	injured	23
35	yes	C-R	25	yes	0,87	yes	0,87	0,87	0,59	injured	18
47	yes	C	44,6	yes	1,97	yes	0,93	0,93	0,57	injured	29
51	yes	R	26,7	yes	1,01	yes	0,51	0,51	0,51	injured	19
54	yes	L	19,1	yes	2	yes	1,08	1,08	0,59	injured	14
56	yes	L	25,3	yes	2	yes	0,69	0,69	0,57	injured	18
60	yes	C	56	yes	0,43	yes	0	0	0	injured	35
62	yes	C-L	12,3	yes	1,96	yes	0,84	0,84	0,58	injured	11
66	yes	R	36,7	yes	0,59	yes	0,59	0,59	0,59	injured	24
69	yes	R	35	yes	1,97	no	0	0	0	injured	23
72	no	–	0	yes	1,51	yes	0,24	0,24	0,24	not injured	0
73	yes	L	18,8	yes	1,21	yes	0,81	0,81	0,81	injured	14
74	no	–	0	yes	1,98	yes	0,43	0,3	0,43	not injured	0
76	yes	C-R	24,7	yes	2	yes	1,14	1,14	0,57	injured	18
77	yes	L	5,4	yes	1,99	yes	1,2	1,2	0,58	injured	7
88	yes	C-R	9,1	yes	1,43	yes	0,82	0,82	0,57	injured	9
91	yes	R	23,1	yes	1,1	yes	0,71	0,71	0,71	injured	17

7.5 Efficacy of the pedestrian protection systems in real-world accidents

Although the dimension of the sample considered is small, the efficacy of the PPS in real-world accidents has been evaluated. The pedestrian Relative Risk (RR) of being impacted by a car equipped by the PPS is reduced 13.3% (significant level 0.001) (see Table 7.9).

Table 7.9: Pedestrian Relative Risk of being impacted by a car

		Injured		Total
		no	yes	
PPS	no	0	17	17
	yes	2	15	17
Total		2	32	34

Table 7.10: Pedestrian Odds Ratio of sustain am ISS>15

		$\text{ISS} > 15$		Total
		no	yes	
PPS	no	2	15	17
	yes	7	10	17
Total		9	25	34

In case of pedestrian accidents the probability of sustaining a major trauma (ISS>15) has been reduced 26.7% (Odds Ratio 0.267, McNemar test 0.041).

The probability risk of sustaining serious (MAIS3+) and severe (MAIS4+) injuries, has been assessed and the effectiveness has been calculated by the equation 7.3.

$$E = 1 - \frac{\sum_{i=1}^{n} P_{injury}(V_i^{'})}{\sum_{i=1}^{n} P_{injury}(V_i)} \tag{7.3}$$

The estimated effectiveness of the pedestrian AEB systems is 59% with the Rosen regression model and 50% with the ”severe (MAIS4+)” regression model.

In conclusion this confirms the benefit of these safety devices in urban scenarios.

Chapter 8

Conclusion

The objective of this research is a pilot collection, study and in-depth analysis of severe road accidents. That is those accidents in which there was at least one person injured having an Injury Severity Score greater than 15 or major trauma and which occurred principally, but not limited to, the urban environment.

In the field of road safety, real-world accident data and in particular, that at an in-depth level, are of vital importance for the progressive development of solutions to mitigate injuries or the evitable occurrence of such events. This data is also useful for the evaluation and development of countermeasures in terms of rules of the road and best practices. The importance of this data is evident by EU directives and the automotive industry, and the fact that both groups have always given great value to the data.

The state-of-the-art inherent in the principal European and American road accident databases was initially analysed; among with the most important research projects that defined the guidelines for the uniformity of the typologies and modalities of the collection of this data (STAIRS, PENDANT, MAIDS, SafetyNet, DaCoTA). As a consequence of this analysis, a database has been created that collected approximately 1500 variables for each accident and which followed the guidelines of the previous projects for a more efficacious exchange of the variables themselves and among other research organizations.

The state-of-the-art inherent in the principal injury mechanisms and the most frequently occurring injuries, both for user types (car occupants, motorcyclists, pedestrians and cyclists) and for impact configurations, were analysed.

The investigative process was based on a retrospective method. After the team was alerted by the ICU, information was collected from police data and on-scene and vehicle investigations were initiated within 72 hours.

The study of the dynamics of the event followed; the estimation of the principal physical parameters of the crash (velocity, impulse, principal direction of force, etc.); the evaluation of whether safety devices (seat belts, pretensioner, airbags, etc.) were used, and if so, their efficacy; and the evaluation, by means of the DREAM method, the principal factors that led to the cause of the insurmountable critical event.

At the same time the physician team member collected information regarding the injuries sustained, coded it using the AIS Scale and then localized the injuries using the InSAFE system equipped with a three-dimensional injury localization tool. Finally, the principal outcome scores (ISS and NISS) have been calculated.

The study of every individual accident resulted in the correlation between the injury-to-cause linkage process developed in a meeting of the various team members. The valuation of the reconstruction of the dynamics of the event determined the object(s) impacted by the injured person.

The collection of road accident data began in 2009 in a pilot program and has been active since 2011, effectively following the methodology illustrated in this work.

Since 2009 the team has collected 207 out of 363 road accidents transmitted by the ICU and has studied 80 in depth. These accidents occurred more frequently in urban environments and principally involved PTWs and VRUs (pedestrians and cyclists).

There were multiple causes for the conspicuous loss of information for 43% of the accidents. Notwithstanding the authorization received by the research team, the police involved in the investigations did not always respond positively or provide the information necessary for the research. There were also accidents where data was submitted but it was incomplete and; therefore, could not be included in the study. In a very few cases it was impossible to determine the responsible police that were involved in the accident investigations

The retrospective methodology used had some disadvantages, such as the impossibility of directly interviewing the persons involved in the accidents, the absence of relevant information (loss of helmet) because it was not obtained by the police, but also the difficulty in examining the vehicles involved. In this particular case, even if the accident caused serious injuries, the police did not always sequester the vehicles involved (rarely both vehicles, often only one) and the owners rarely authorized examination of the vehicle by the team.

From the sample analysed (80 cases) it emerged that VRUs were approximately 50% of the sample, while 35% of the crashes a PTW was seen involved. The latter were predominantly involved in head-on side crashes (67%) or frontal collisions (25%) with cars.

The VRU accidents principally occurred on a straight road with or without crosswalks. The analysis of the accidents evidence that in 60% of the cases the drivers/riders braked before impact and this action was initiated too late or was not efficacious (generally there was no evidence of brake marks on the road). As was confirmed by the causation analysis of the accident, the time factor was most frequently the most critical event: i.e. either an action was initiated too late or no action taken at all.

The most recurrent cause that led to the critical event time was the incomplete judgment of the situation on the part of the driver/riders (e.g., the driver/rider could see the VRU in time and therefore had the time to make the correct decision). This factor was generated by the reduction of attention (attention directed toward other than the critical event), or the driver/rider anticipated the pedestrian to be more attentive to the circumstances.

The average cruising speed of the vehicles was 49 km/h, while the average impact speed was 38 km/h. This highlights that the speed of the vehicle is still an important causation factor. Especially in Florence, where the road environment is not necessarily wide and the line-of-sight of the driver/rider is lower, speed has an important role in the driver's/rider's reaction time.

In these cases a reduction of the speed limits has advantages in terms of stopping distance, the use of ADAS systems which can also reduce the driver's/rider's problems due to inattention and/or unexpected events.

With regard to car-to-PTW crashes, a collision at an intersection where a motorcycle hits with its front-end the side of the car, a head-on side collision is the scenario that most frequently leads to serious injuries for motorcyclists in an urban environment. This is followed by the head-on crash on a two-way urban road.

Compared to the driver, the rider most frequently makes an avoidance manoeuvre before impact (67% of riders braking vs. 33% of drivers), and in 14% of the cases loses control of the motorcycle (falls to the ground). This is caused by the subsequent blockage of the front wheel before impact. The average impact speed is 47 km/h for PTWs and 33 km/h for other vehicles. This highlights that the PTW is frequently travelling at a speed that is not appropriate for the urban environment.

Another important aspect is the loss of the helmet, either during or after the first impact, in 50% of the cases we were able to investigate. This is due to the helmet not being worn properly or not being in good condition.

From the causation analysis also in car-to-motorcycle crashes, timing is the principal critical event both for driver and rider. The rider tends to brake too late, takes no action or applies the brakes with excessive force. The principal causes that leads to the critical event are the absence or incomplete observation of the situation or the inability to brake within the critical time.

Overall, we have gathered and codified 876 injuries of 81 people admitted to the ICU. The data evidences that motorcyclists more frequently have injuries over all their body compared to the other users. Pedestrian injuries are concentrated on the head and legs. The head, above all, is the body region that suffers the majority of injuries for all road users. The average value of the ISS is equal to 19.7, while severe injuries (MAIS4+), are located principally on the head, thorax and legs.

For VRUs' severe injuries, especially to the head, are predominantly caused by impact with the ground. This is confirmed by a significance slightly less than 95%. While in the impact with a car, the windscreen, pillars, BLE/bonnet are the objects that produce the most serious injuries.

For motorcyclists, the impact against the opposing vehicle predominantly causes fractures, while the impact against the ground results in injuries to the internal organs. The injuries to the head are principally caused by impact with the ground due to the loss of the helmet and this is confirmed by a significance level of 0.01 (90%).

Since inattention and high velocity are the principal causes of the pedestrian hit, the efficacy of the pedestrian protection system in urban scenarios based on the real data is also evaluated. The results of this evaluation (Chapter 7) show the efficacy of these systems in reducing the seriousness of injuries to the VRU or avoiding the impact entirely.

The use of this system contributes to the reduction of the impact velocity, since it limits the problems linked to too late or the absence of action on the part of the driver/rider (as seen in Chapter 6), increasing the efficacy of the braking action and then reducing the braking distance useful.

To quantify the injury reduction, a direct relationship between ISS and the impact velocity as a risk function of severe injuries was determined. Using this relationship, it is seen that the average ISS of the sample was reduced by 20%, while the probability of experiencing major trauma was reduced by 26.7% (Odds Ratio 0.267, McNemar test 0.041). In terms of the risk of severe injuries sustained, the pedestrian protection system has an effectiveness equal to 50%.

The sample used in this work has a small dimension; therefore, the collection of data and the analysis must continue to follow the scope developed and the number, significance and application of the data produced will increase. In particular, this data could be used to improve the relationship between the ISS and the velocity of impact or the risk function. This could be used within the e-call system as a new parameter to activate the emergency service response team.

In the future this data could also be compared and matched with other EU programs.

This research activity has been conducted within the CISAP (Research Center for Innovation and Safety on Powered 2 Wheelers) of the Department of Industrial Engineering of the University of Florence and in collaboration with the ICU of the Emergency Department of the Florence Careggi Teaching Hospital.

Since 2012 this work has been conducted in parallel with the activities of the RASIF (Road Accident Serious Injures in Florence) project and is continuing at the present time.

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International peer reviewed journal articles

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