Injury Analysis of Powered Two-Wheeler versus Other-Vehicle Urban Accidents

S Piantini, M Pierini, M Delogu, N Baldanzini, A Franci, M Mangini, A Peris

Abstract Motorcyclists are particularly vulnerable since worldwide they represent 23% of all road traffic deaths. Fatalities are decreasing but still not at the same rate of car occupants. Continuous monitoring of traffic accidents and their in-depth comprehension (i.e. relationship between injuries and causes) are necessary to develop effective countermeasures and thus to reduce the number of crashes as well as the injury severity. In this paper 40 powered two-wheeler to other vehicle urban accidents have been analysed from the InSAFE database. All accidents involved at least one seriously injured rider or pillion passenger. Results are presented in terms of accident configurations, injury analysis, and impact to injury correlation. The analysis pointed out that the main crash configuration was the head-on side collision (45%). In 75% of the cases, the motorcyclist hit other vehicle with the frontal part of the powered two-wheeler. Twenty-two percent of motorcyclists lost motorcycle control and fell down before the crash. Head and thorax were the body regions most seriously injured. The scooter's front glove compartment is accountable for a relevant injury percentage. The results allowed the identification of possible countermeasures in terms of safety devices or re-design of vehicle sections in order to reduce the injuries in this subset of accidents.

Keywords injury source, motorcycle, motorcyclist injury, powered two-wheelers, road accident,

I. INTRODUCTION

Globally in 2012, road accidents were the first cause of death among people aged 15-29 (this subset of the population accounted for nearly a quarter of all road traffic deaths). For each person who died in a road traffic crash, at least 20 people sustained non-fatal injuries. These injuries could have a considerable impact on life quality, and often entailed significant economic costs [1].

Powered Two-Wheelers (PTWs) are increasingly considered a viable mobility solution, especially in metropolitan areas with intense traffic. Thus, the urbanisation trend is supporting a wide use of PTWs and the number of registered vehicle (circulating park) has slightly increased during recent year of financial crisis [2]. Worldwide motorcyclists are particularly vulnerable since they represent 23% of all road traffic deaths [1]. Similar figures apply also for Italy where motorcyclists account for 24% of all road traffic deaths [3]. Even if Italian urban roads have a moderate mortality index (1.13) compared to extra-urban roads and motorways, they have a higher number of road accidents and people injured [3]. A high number of road accidents, although not fatal, unavoidably lead to an increased likelihood of severe injuries, more serious disabilities, and a higher social cost. Even if changes in traffic laws are useful to decrease traffic accidents and traffic-related deaths [4], they are not the unique way to reach the goal. In order to develop effective countermeasures addressing reduction of injuries and crashes, an in-depth knowledge about the behaviour of a motorcyclist's body under impact in real world crashes is essential.

The In-depth Investigation of Motorcycle Accidents (MAIDS) project pointed out that the majority of the accidents took place in urban environment [5]. Fractures to the lower and upper extremities were the most common injury location in motorcycle crashes [5-8]. In a study of 11.800 injured motorcyclists in France, the most frequent serious injuries were thoracic (50%) and head (44%) injuries and 90% were to the internal organs. Collision with a passenger car was the most frequent (64%) and in nearly 50% of accidents the PTW contact point was its frontal part [9-10].

This paper aims to analyse a sample of forty serious urban road accidents involving PTWs and OVs, in order to provide more recent data on serious motorcycle accidents in terms of crash configurations and injury causes. All

S. Piantini (simone.piantini@unifi.it, phone: +39 055 2758699) is a Research Fellow, and M. Pierini and N. Baldanzini are Associate Professors AND M. Delogu is assistant professor at University of Florence (Florence, Italy). A. Peris and A. Franci are Intensive Care Physicians at Careggi University Hospital (Florence, Italy) and M. Mangini is a Physician postgraduate school of Anesthesia and Intensive Care at University of Florence (Florence, Italy).

the accidents were extracted from the InSAFE database: an Italian in-depth accident investigation study with regard to accident scenario, crash parameters, injuries and injury sources.

II. METHODS

The In-depth Study of road Accident in FlorencE (InSAFE) is conducted by the University of Florence (Italy) jointly with the Intensive Care Unit (ICU) of the Emergency Department of the Careggi Hospital (Florence, Italy). InSAFE has been collecting road accident data since 2009 in the city of Florence and its surroundings [11-12]. The supporting team consist of both technical and medical personnel.

Vehicles involved in the crash are thoroughly inspected to collect data on vehicle body deformation and safety systems. In case of PTWs, inspection is also extended to protective garment and helmet (whenever possible). Furthermore, for each case, retrospective crash site inspection is carried out in order to identify relevant pre-crash events such as manoeuvres, braking actions and possible line-of-sight obstructions. A site diagram of the accident drawn to scale and including the final positions of the vehicles involved, skid marks, debris, point of impact and trajectory are recorded as well. Crash speeds are computed from vehicular deformation, skid marks and witness accounts, and then validated using specific software (e.g. Virtual Crash [13]). Data from the crash site are collected and matched with clinical injuries. All injuries are assessed at discharge from the Emergency Department of a tertiary level trauma centre. The ICU members of the InSAFE team provide information on injury typologies and severities coded with the Abbreviated Injury Scale (AIS) [14] by total body CT scans, X-ray and MRI. A biomechanical correlation among injuries and causes is conducted for each case by a panel of physicians and engineers.

The selection criteria for the query in the present paper were:

1. PTW to OV crashes
2. urban environment, i.e. roads with speed limits lower than 50 km/h
3. OV defined as car or van weighting less than 3500 kg
4. at least one seriously injured person admitted to the ICU with a diagnosis of major trauma.

The present in-depth analysis focused on 40 serious urban PTW-to-OV accidents. The vehicle sample consists of 40 PTWs and 40 OVs. Thirty-six (90.0%) accidents involved cars and four (10.0%) involved vans. The analysis was carried out with a thorough description of crash configurations, vehicle aspects, injury typologies and severity and the related injury mechanisms.

Conservation of momentum was used to compute impact and rider speed. Conservation of energy and the PTW deformation energy, assessed by the wheelbase shortening, were used for a more precise speed estimation. Pearson's Chi-square (χ^2) or likelihood-ratio (L) tests were used to analyse any differences in the proportion of injured riders with respect to variables of crash characteristics. Cramer's V (V) was used to assess the strength of the relationship. A p-value of < 0.05 was considered significant.

III. RESULTS

Crash configurations

Within the dataset considered in this study (40 cases), more frequently observed crash configurations were: head-on-side (45.0%), head-on (20.0%) and sideswipe collisions (15.0%) (Figure 1). The majority of crashes occurred in daylight (57.5%) and clear visibility conditions (77.5%), and more frequently on roads not at intersections (57.5%, 23/40). The most frequent road intersection (17/40) was the crossroad (four-way) (56.5%).

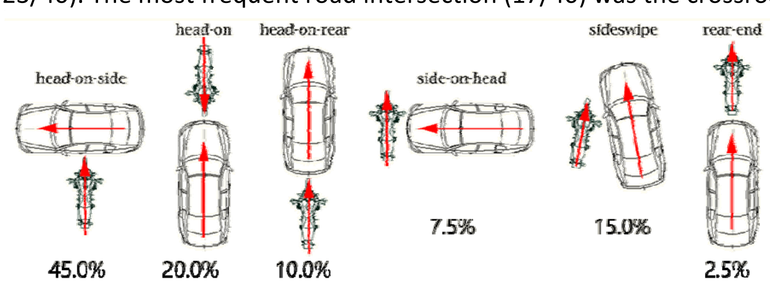

Fig. 1. PTW-to-OV crash configuration (n=40)

PTW typologies and crash characteristics

Among PTWs, the most common vehicle typology was scooter style (67.5%), followed by the standard style (naked) (12.5%) and sport style (10.0%). The majority of PTWs (47.5%) had an engine size included in the range 50-150cc, and the most frequent was 125cc size (10/40, 25.0%) (Figure 2 and Table I). In the latter subset (125cc), the rider age ranges between 17 to 56 years old (mean 33.4, SD 5.03) and it is normally distributed (Shapiro-Wilk test, $p<0.05$). PTWs were never equipped with anti-lock braking systems (ABS), 47.5% (19/40) had a windshield and 37.5% (15/40) had a rear box.

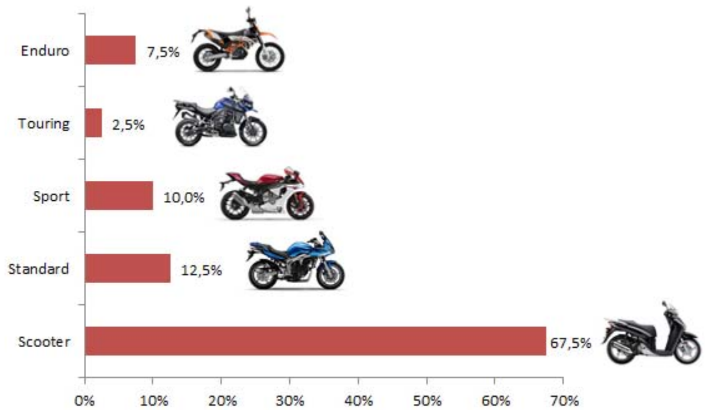

Fig. 2. PTWs' typology

TABLE I
PTWS' ENGINE-SIZE

Engine size [cc]	N.	%
≤50	9	22.5
125-150	13	32.5
151-250	4	10.0
251-400	4	10.0
401-600	4	10.0
601-800	4	10.0
≥800	2	5.0
Total	40	100

The most frequent PTW first impact point was the front area (75.0% of cases). Side impacts were less frequent than frontal ones, with 10.0% on the left side and 12.5% on the right side (Figure 3).

According to ISO 13232, the collision angle changed as shown in Figure 4. The most frequent range is 315°-360° (29.0%) followed by the intervals 90°-135° (16.1%) and 225°-270° (12.9%). In nine crashes (22.5%), the PTW fell down before impacting with the OV: 4 involved a motorcycle (> 600 cc), 2 a maxi scooter (> 300 cc), 2 a scooter (125-150 cc) and 1 a moped. For these cases, the crash angle could not be determined.

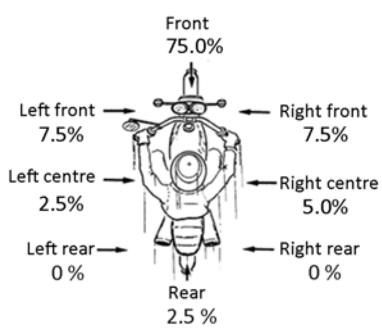

Fig. 3. PTWs first crash impact point

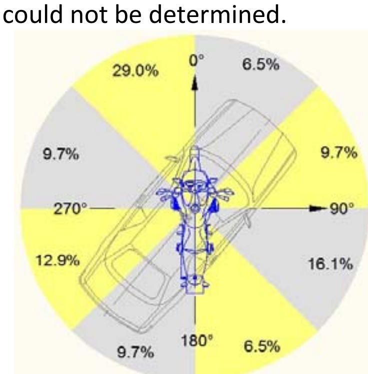

Fig. 4. PTW-to-OV crash angle (n=31)

The PTW impact speed ranged from 20 km/h to 88 km/h with a mean value of 47 km/h (SD 1.88). Velocity values were normally distributed (Shapiro-Wilk test, $p<0.05$). The most frequent range was 41-50 km/h (43.6%) (Figure 5). At crash, the PTWs experienced delta-V values between 1.5 km/h and 128 km/h, with a mean value of 38.0 km/h (SD 4.15). Fifty-five percent of PTWs had a delta-V less than 40 km/h. The most frequent range was 41-50 km/h (23.1%), but also those included in the range 0-20 km/h (33.3%) and 51-60 km/h (17.9%) were usual as well (Figure 6).

OV typologies and crash characteristics

Among Other-Vehicles (OV) 36 cars and 4 vans were involved in the accidents. Small (32.5%) and compact (15.0%) cars were the most frequent vehicle typologies; only 1/8 were large or executive cars. The majority was registered after 2000.

According to the Collision Deformation Classification (CDC), the first contact point was fairly distributed among frontal (27.5%) and side parts (L: 30.0%, R: 30.0%), while only in 12.5% of cases impact occurred to the rear part.

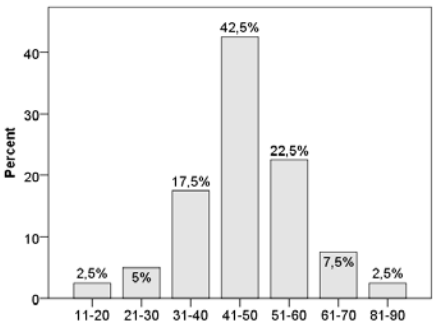

Fig. 5. PTWs impact speed fequency [km/h]

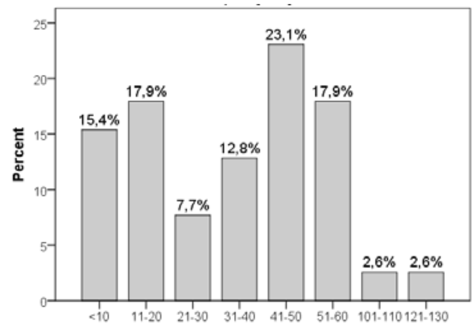

Fig. 6. PTWs delta speed fequency [km/h]

The most common frontal specific contact area was on the left (L0, 36.4%, 4/11) and on the right (R1, 36.4%, 4/11) parts. Sideways, the most frequent area was the frontal-compartment (F0): 50.0% (6/12) overall for both left and right sides, followed by the front-passenger-compartment (P1) (33.3%, 4/12), on the right side, and the driver and rear-passenger compartment (P1 and P2) on the left side (16.7%, 2/12) (Figures 7 - 8).

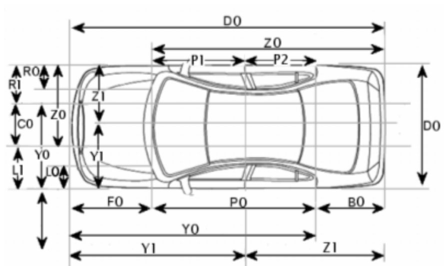

Fig. 7. Impact location according to 4th and 5th digit of Collision Deformation Classification (CDC)

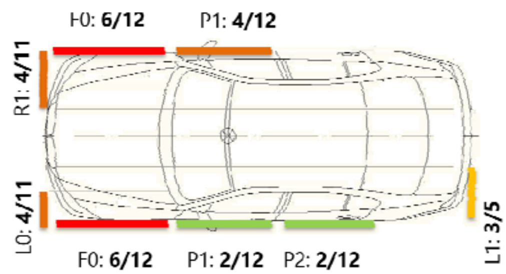

Fig. 8. Frequency of first impact location (freq. > 1)

The OV impact speed was between 0 km/h and 65 km/h, with a mean value of 27.5 km/h (SD 2.85), but more than 50% of the subset crashed with a speed below the mean value (< 23 km/h). The delta-V was included among 0.5 km/h and 22.4 km/h with a mean value of 4.6 km/h (SD 0.66). About ninety-two percent of the subset experienced a delta-V lower than 10 km/h.

Motorcyclist characteristics and outcome

In the analysed accident dataset, 40 motorcyclists were seriously injured and admitted to the Intensive Care Unit (ICU) due to a diagnosis of major trauma (seriously injured). Thirty-eight motorcyclists and two co-passenger made up the subset.

Motorcyclists were principally male (97.5%). In all cases, the motorcyclists wore a helmet. Forty-five percent wore an open-face helmet and only 15.0% of motorcyclists wore a full-face helmet type (40.0% was unknown). The sample age ranged from 15 to 72 years old (normal distribution, Shapiro-Wilk test, $p<0.05$). The mean age was 32.9 years old (SD 2.28), the median was 30 and the most frequent was 17 years old.

Concerning the outcome, all seriously injured motorcyclists were alive after 30 days from the crash event. The median Injury Severity Score (ISS) was 22 (range 4-43) and the most frequent was 29. Severity relevance of the study was highlighted by the limited share of people (20%) with ISS lower than 15.

Motorcyclist injury analysis

Figure 11 shows the percentage of motorcyclists' uninjured, slightly injured and seriously injured per body-region within the sample. The injury severity was assessed with the Maximum Abbreviated Injury Scale (MAIS) for each region. Slight injuries were coded as MAIS1-2 and serious injuries as MAIS3+.

Head (40.0%), thorax (70.0%), spine (2.5%), abdomen (20.0%) and lower limbs (37.5%) were the body-regions where at least one MAIS3+ injury was observed. Ninety percent of the motorcyclists were subjected to thorax injuries. The head was the second region with a high frequency of serious injuries (16 out of 40 people with MAIS3+ injuries), followed by lower-limbs. Thorax and abdomen were comparable in terms of minor injuries; although the abdomen was less subject to serious injuries.

Figure 12 shows the injury frequency and the severity distribution per body-region. The distribution is statistically significant ($L = 294.3$, $p<0.01$) and the relationship is significative ($V = 0.43$, $p<0.01$). In total 407 injuries were collected on 40 people. The maximum severity registered was critical (AIS5) and located to the head and the abdomen. Fifty-five percent of motorcyclists suffered head injuries (Figure 11). The head was the second body region most injured with 20.1% (82/407) of injuries (Figure 12) and more than 60% were serious ones (AIS3+). Although the motorcyclists were wearing a helmet during the crash, the head and face were the body regions with the highest number of lesions. The thorax was the most frequently seriously injured body-region, with 23.1% (94/407) injuries on 70.0% of motorcyclists. The abdominal region shows a higher percentage (14.3%) of severe to critical injuries (AIS4-5). Overall, skeletal (57.2%) and internal organs (33.9%) were the anatomical structures that suffered the majority of injuries. At skeletal level, the structures with an injury frequency higher than 15 were the transverse process (12.0%), the rib cage (12.0%), the skull base (7.7%) and the orbit (6.9%). Internal organs more subjected to injuries were cerebrum (or brain) (37.0%), lungs (27.5%) and pleural cavity (thoracic injury) (15.2%) (Figures 27-28).

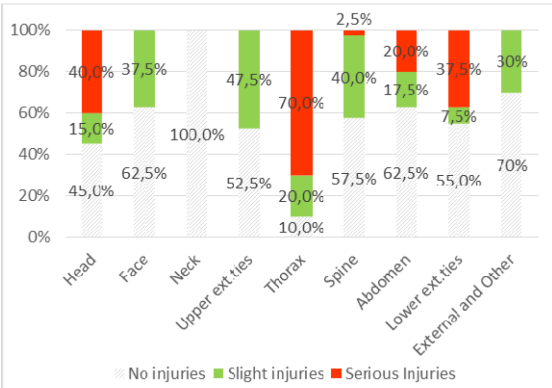

Fig. 11. Percentage of rider uninjured, slight and serious injured per body-region (n=40)

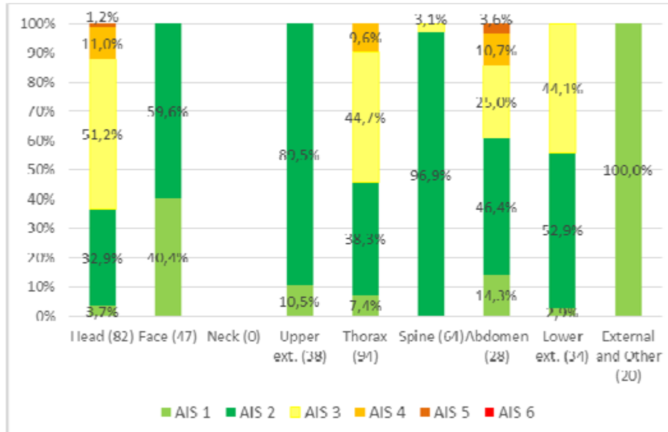

Fig. 12. Injury frequency and percentage severity distribution per body-region (n=407)

Figures 13 and 14 show the injury frequency distribution per body-region and PTW / OV typologies normalized by PTW and OV frequencies, respectively. Both distributions are statistically significant at 0.01 level (L=97.465, V=0.242 and L=56.774, V=0.180). Dividing the sample in two different frame style: scooter and motorcycle, figure 13 shows that the motorcycle-style is more responsible of injuries for all body-regions than the other one. Standard type seem to be most correlate with facial injuries, while the sport type with abdominal and lower limbs injuries. Despite the majority of OVs are small-cars, compact and large cars are responsible for 50.1% of head injuries. In the same manner, they have produced more than 50% of thoracical, spinal and abdominal injuries (Figure 14).

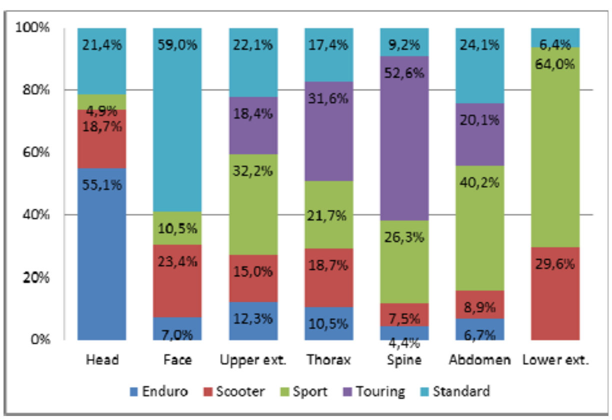

Fig. 13. Percentage of injuries per body regions and PTW typologies (normalized by frequency of PTW typology)

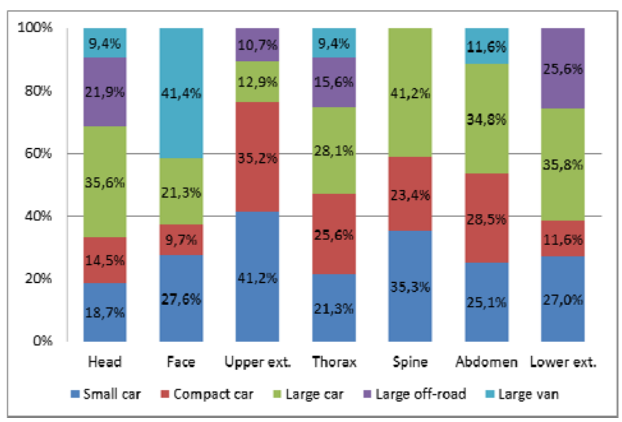

Fig. 14. Percentage of injuries per body regions and OV typologies (normalized by frequency of OV typology)

The crash angle was weakly correlated with the body injury distribution not normalized (L=45.78, <0.01 and V=0.215). The normalized distribution shows that the range 315°-45° have a higher impact on head injuries (39.7%) (Figure 15). Spine and abdomen seem to be more damaged in impacts occurred with angle ranges between 135-225° (55.6% and 45.6%). Figure 16 shows that severe injuries reach the maximum in the 135°-225° range (57.9% of AIS4). The number of serious injuries (AIS3) is evenly distributed. The two not normalized variables were significant at 0.01 level (L=24.714, V=0.164).

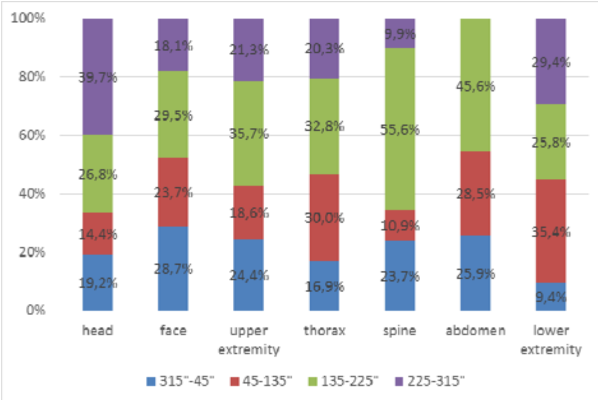

Fig. 15 Frequency of injuries per body regions and crash angle (normalized by frequency of crash angle)

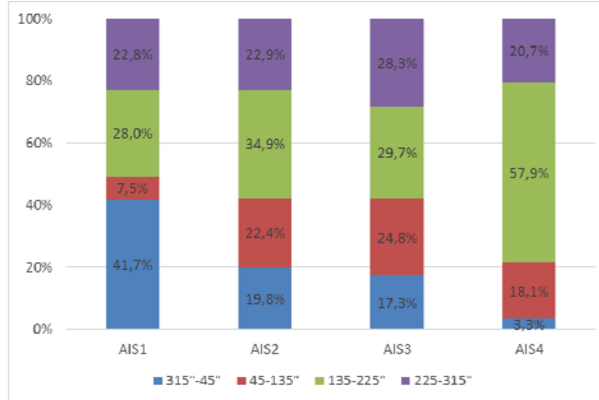

Fig. 16 Frequency of injury severity per crash angle (normalized by frequency of crash angle)

Regarding the effects of impact speed on injury location, they were significant at 0.01 level (L=60.216, V=0.225). As expected, they present a normal distribution with a slight positive skew within each body region (Figure 17). Figure 18 shows the injuries incidence normalized by accident frequency. Head, facial and thoracic injuries increase with the impact speed. High speed seems to be most responsible of abdominal, upper and lower limbs injuries (more than 60%).

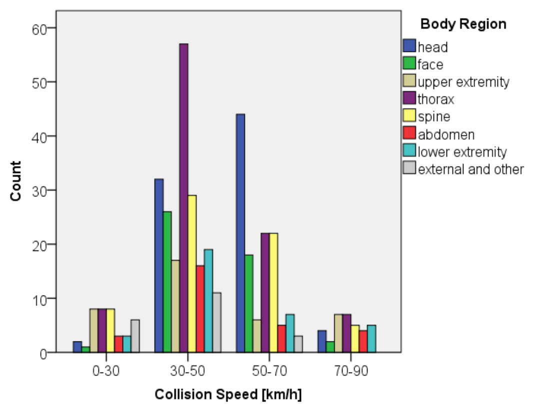

Fig. 17 Frequency of injuries per body regions and PTW's collision speed (n=407)

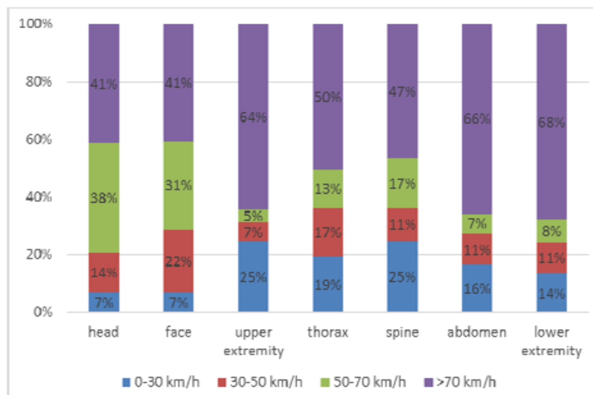

Fig. 18 Frequency of injuries per body regions and PTW's collision speed normalized by accident freq.

Accidents occurred at intersection have a higher injury severity in comparison to the ones far from it. AIS3+ injuries were more frequent at intersections. The correlation was significant at 0.01 level but the strength was weak (χ^2=10.9, V=0.162) (Figure 19). Differences in the injuries distribution per body regions were also significant at 0.01 level and the strength moderate (χ^2=38.3, V=0.307) (Figure 20). The figure shows that head and thorax suffered more injuries in crashes occurred at intersection. On the contrary, abdomen, spine and upper extremities were less subject. The frequency of lower extremity injuries was comparable in both cases.

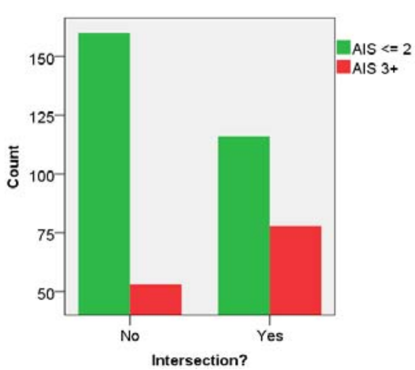

Fig. 19. Injury severity differences between intersection and non-intersection crashes

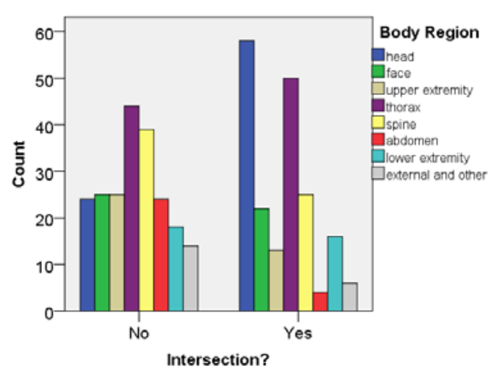

Fig. 20. Differences in the injuries distribution between intersection and non-intersection crashes

Head injuries: 22 out of 40 motorcyclists reported 82 head injuries. Sixty-five percent (64.6%) to internal organs and 31.7% to skull. Cranium suffered injuries mostly to the base (69.2%, 18/26) and vault (26.9%, 7/26).

Cerebrum is the head internal organ most subject to injuries (96.2%, 51/53), while injuries to the brain stem and cerebellum were less common. The most frequent injury type was contusion (28.3%) followed by intraventricular haemorrhage (18.9) and subdural hematoma (17.0%) (Table II). The first contact with the OV has been responsible for 55.0% of head injuries. The residual percentage was ascribed to the secondary impact with infrastructure. The windscreen (centre or header rail) was the major injury source with 53.3%, followed by pillars (15.6%, equally distributed among A, C and D) and door (11.1%) (Table III). For secondary impacts, the ground was the most harmful cause (Table IV).

TABLE II

BRAIN INJURIES TYPOLOGIES

	N.	%
Contusion	15	28.3
Intraventricular haemorrhage	10	18.9
Subdural hematoma	9	17.0
Subarachnoid haemorrhage	7	13.2
Intracerebral hematoma	4	7.5
Laceration	3	5.7
Pneumocephalus	2	3.8
Other injuries < 2%	3	5.7
Total	53	100.0

TABLE III

OV FIRST CONTACT

	N.	%
Windscreen	24	53.3
Pillar (A, C, D)	7	15.6
Door (lateral)	5	11.1
Bumper	3	6.7
Side mirror	2	4.4
Sill	2	4.4
Bonnet	1	2.2
Cantrail	1	2.2
Total	45	100.0

TABLE IV

INFRASTRUCTURE CONTACT

	N.	%
Ground	31	83.8
Barriers	6	16.2
Total	37	100.0

Figures 21 and 22 show the effects of PTW and OV typologies on head injuries. Both distributions are only descriptive since they are not statistically significant. Bumping in an urban area with sport-style motorcycle causes less head injuries than bumping with a standard-style motorcycle. Scooter riders seem to be most subject to wide typologies of head injuries. Large vehicles seem to be most responsible for edemas and pneumocephalus than other vehicle typologies. Differently fractures and subarachnoid hemorrhage do not appear to have a specific trend.

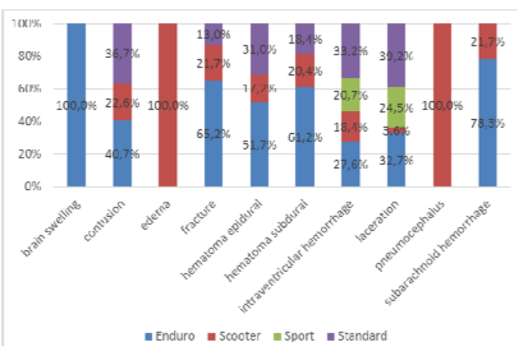

Fig. 21. Head injuries per PTW typologies (normalized by frequency of OV typology)

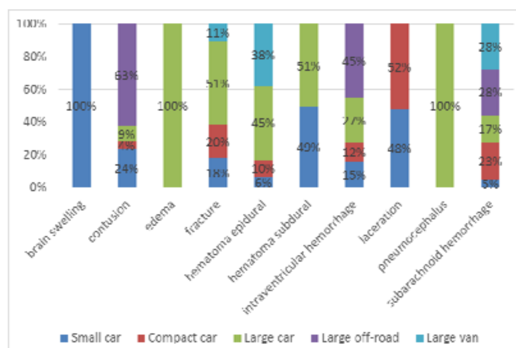

Fig. 22. Head injuries per OV typologies (normalized frequency of OV typology)

The head injury severity is not correlated neither with the impact speed nor with the delta speed, while it is statistically associated with the OV typologies at 0.01 level (L=33.61, V=0.316). Figure 23 shows that generally large cars seem to have a greater influence on AIS3+ head injuries then others OV typologies.

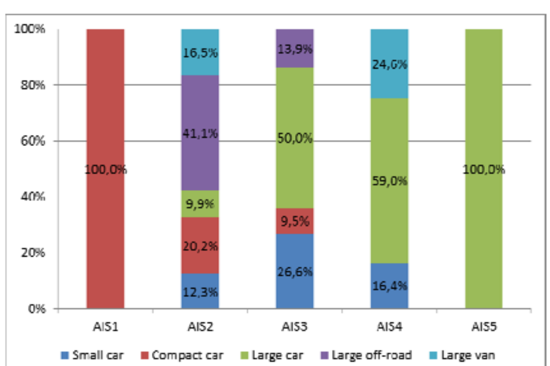

Fig. 23. Head injury severity per OV typology (normalized by OV typology)

Thoracic injuries: 39 out of 40 motorcyclists reported 94 thoracic injuries. Thoracic organs were the anatomic structures most subject to injuries (63.8%) followed by skeletal (33.0%) and vessels (2.0%). Lungs were the organ most injured (63.3%, 38/60) with 53% of contusions and 10.0% of lacerations. The most frequent pleural injury was pneumothorax (23.3%), followed by the hemopneumothorax and pneumomediastinum (3.3%) (Table V). Doors (27.9%), bumper (22.1%) and pillars (19.1%) were the car parts most responsible for injuries, as well as the ground (27.9%) for the infrastructure (Tables VI and VII).

TABLE V
THORACIC INJURIES TYPOLOGIES

Injury type		N.	%
Lung	Contusion, bilateral	12	20.0
	Contusion, unilateral	20	33.3
	Laceration, unilateral	6	10.0
	Others < 2%	2	3.4
Pleural cavity	Pneumothorax	14	23.3
	Hemopneumothorax, major	2	3.3
	Pneumomediastinum	2	3.3
	Other injuries < 2%	2	3.4
	Total	60	100.0

TABLE VI
OV FIRST CONTACT

OV	N.	%
Door	19	27.9
Bumper	15	22.1
Pillar	13	19.1
Bonnet	7	10.3
Windscreen	6	8.8
Sill	3	4.4
Others	5	7.4
Total	68	100.0

TABLE VII
INFRASTRUCTURE CONTACT

Infrastructure	N.	%
Ground	19	73.1
Barrier/wall	2	7.7
Curb	1	3.8
Pole/post	1	3.8
Others	3	11.5
Total	26	100.0

Spinal injuries: 17 out of 40 motorcyclists reported 64 spinal injuries and only two of them were at the spinal cord. The spine section more injured was the thoracic one (59.4%) followed by the lumbar (25.0%) and cervical (15.6%) ones. Transverse processes (43.8%) and vertebral bodies (17.2%) were the spinal structures more frequently hurt. Nineteen percent of the injuries were generally localised at the vertebrae. Among the thorax vertebrae, the preponderance of the injuries was found between T6 and T10. In this section we found all fracture severities and typologies, included the contusion of spinal canal. Sixty-one percent of the spinal injuries were caused by OV impacts and 35.0% by infrastructure impacts. The OV sources more accountable for spinal injuries were the front bumper (25.0%), the windscreen (12.5%) and the door (12.5%). Concerning the secondary impact with the infrastructure, the ground was the most frequent cause of spinal injuries (21.9%) (Tables VIII and IX).

TABLE VIII
SPINAL INJURIES TYPOLOGIES

Injury type	N.	%
Fracture with or without dislocation	39	60.9
Multiple fractures of same vertebra	9	14.0
Burst fracture, minor compression	7	10.9
Burst fracture, NFS	4	6.2
Fracture, NFS	3	4.7
Contusion within spinal canal	2	3.1
Total	64	100

TABLE IX
OV AND INFRASTRUCTURE CONTACT

		N.	%
OV	Bumper – Front	16	25.0
	Windscreen	8	12.5
	Door	7	12.5
	Sill – left	4	6.3
	Windscreen - Lower frame	2	3.1
	Bonnet	1	1.6
Infrast.	Ground	14	21.9
	Pole/post	4	6.3
	Curb	4	6.3
	Person - other	3	4.7
	Total	64	100.0

Abdominal injuries: 15 out of 40 motorcyclists reported 28 abdominal injuries. Eighty-two percent of the injuries were ascribed to internal organs and 11.0% to vessels. Spleen (43.5%), kidney (26.1%) and liver (17.4%) were the internal organs most frequently injured. They suffered both hematomas and lacerations (Table X). The most frequent spleen injury was the "*laceration no hilar or segmental parenchymal disruption or destruction; >3cm parenchymal depth or involving trabecular vessels; moderate [OIS III]*" (AIS 544224.3). Abdominal vessel injuries were prevailing in comparison to other body regions. All of them were codified as serious injuries. Two out of three were intimal tear to the right renal artery, indirectly caused by an impact to the car lower-belt (bumper or sill). Main causes were impacts with OV (68.0%), infrastructure (21.5%) and their own PTW (10.5%) as well. Bumpers, sill and doors were the OV parts most responsible for injuries, as well as the handlebars for the PTW (Table XI). In terms of infrastructure, ground was the most dangerous (33.3%) (Table XII).

TABLE X

ABDOMINAL INJURIES TYPOLOGIES

Liver, Spleen, Kidney	N.	%
Contusion, hematoma, NFS	5	21.7
Laceration, no hilar or segmental etc.	4	17.4
Laceration NFS	3	13.0
Contusion, hematoma, sub capsular	2	8.7
Laceration, involving segmental etc.	2	8.7
laceration, simple capsular tears	2	8.7
laceration, <1cm parenchymal depth etc.	2	8.7
Laceration, extending through renal etc.	1	4.3
Laceration, parenchymal disruption etc.	1	4.3
Laceration minor, superficial etc.	1	4.3
Total	23	100.0

TABLE XI

OV FIRST CONTACT

		N.	%
OV	Bumper	7	29.2
	Sill	5	20.8
	Door	4	16.7
	Fender	2	8.3
	Side mirror	1	4.2
PTW	Fuel tank	1	4.2
	Handlebars	2	8.3
	Total	24	100.0

TABLE XII

INFRASTRUCTURE CONTACT

	N.	%
Ground	1	33.3
Curb	2	16.7
Barrier/wall	1	16.7
Total	6	100.0

Lower limbs: 18 out of 40 motorcyclists reported 34 lower limb injuries. The femur and pelvic ring were the anatomical parts most frequently injured with 33.3% and 30.3%, respectively. Tibia showed a higher percentage of distal fractures (57.1%) in comparison to complex shaft fractures (42.9%). All femur injuries were serious and the majority were diaphysis fractures (72.7%) (simple or complex). Pelvic fractures always showed the entirety of the posterior arch with a severity from moderate to serious (Figure 25 and Table XIII). The fender was the car source most accountable of lower limbs injuries (39.4%), followed by door (15.2%) and bumper (12.1%). The front-glove-compartment (18.2%) was the most unsafe scooter part for the motorcyclist (Figure 26).

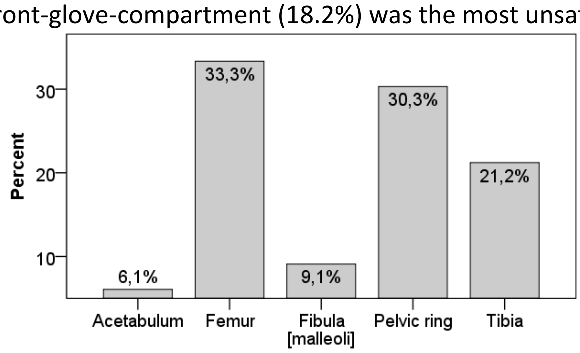

Fig. 25. Lower limbs injury location

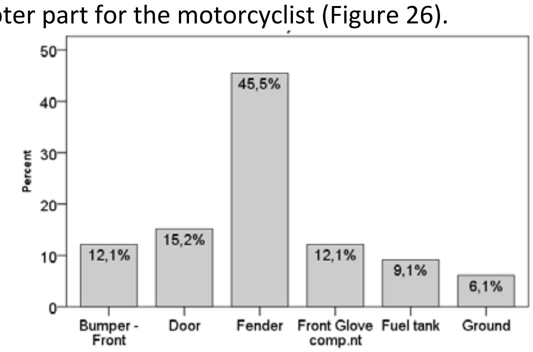

Fig. 26. PTW, OV and Infrastructure contacts

TABLE XIII

LOWER LIMB INJURIES TYPOLOGIES

	Femur (n=11)	Tibia (n=7)	Fibula (n=3)	Acetabulum (n=2)	Pelvis (n=10)	Row % (N.)
Distal fracture	18.2	57.1	-	-	-	18.2 (6)
fracture NFS	9.1	-	100.0	50.0	30.0	24.2 (8)
Fracture partial articular	-	-	-	50.0	-	3.0 (1)
Fracture, with posterior arch intact	-	-	-	-	70.0	21.2 (7)
Shaft fracture, complex	54.5	42.9	-	-	-	27.3 (9)
Shaft fracture, simple	18.2	-	-	-	-	6.1 (2)
Total	100.0	100.0	100.0	100.0	100.0	100.0

IV. DISCUSSION

This paper describes the typologies of PTW-to-OV urban collisions involving seriously injured motorcyclists and the related injury typologies and causes. Forty seriously injured motorcyclists (rider and pillion-passenger) were involved in 40 road accidents.

The leading crash configuration registered was the head-on side (45%). The majority of accidents (57.5%) happened far from intersections, i.e. while the PTW was travelling along a straight road, but the intersections are still more dangerous than the straight road.

The main pre-crash cause is OV performing a U-turn, or left/right turn manoeuvres in front of the PTW. Also in the "injuries sustained by motorcyclists" report [16] we found that most crashes occurred while the PTW was traveling along a straight road. This result points out the need for motorcyclists to monitor the surrounding environment and to anticipate other road users' manoeuvres, while for drivers the need to avoid any risky behaviour. PTW active systems have the potentiality to avoid or mitigate a crash. Specifically motorcycle autonomous emergency braking system (MAEB) was found to be applicable in a broad range of multivehicle motorcycle crashes to achieve reductions in impact speed and, therefore, increasing the benefits in terms of crash avoidance and crash mitigation [17-19] .

In terms of rider pre-crash emergency braking manoeuvre, the sample showed a high frequency (22.5%) of wheel locking before the impact, which resulted in an early PTW loss of control. Findings are valid for both motorcycles and scooters. These events were correlated to the absence of ABS systems. Similar results were obtained by several researches on all PTW typologies [20-25]. Through the emergency phase, in order to avoid the PTW loss of control, another important aspect is the performance of the braking manoeuvre [26]. Literature shows as an improvement of rider's emergency braking skills, by specific training systems, can be useful to reach the optimal braking level (i.e. maximum deceleration for each ground condition) avoiding an early PTW loss of control [27].

Despite all motorcyclists seriously injured were wearing a helmet during the crash, the head still needs for a more adequate protection level. Approximately 40% of the sample suffered at least one serious injury. Sixty-five percent of head injuries were to the brain and only 32.0% to the skull. The skull base was the area mostly fractured, while the cerebrum was most subject to contusions, haemorrhages and hematomas. The most frequent causes of injuries were the windscreen, the pillars and the doors. Also head ground impacts were not negligible: the high relevance was mainly due to a frequent loss of the helmet after the primary impact with the OV. Losses were mainly due to helmets not properly fastened (i.e. the chin-strap was too long and not close-fitting well to the throat), or to an unfit helmet size. Forman et al. [8] shown that traumatic brain injury generally conduct to high long-term disabilities. Referring to the normalized values (Figure 14), the large cars seem to have a greater influence on injuries than the small and compact ones. Similarly crash angles between 135°-225° are overrepresented in AIS3+ injuries. Angle ranges 135°-225° and 225°-315° are linked to the majority of head injuries. Further efforts both in terms of in-depth investigation that helmets design are necessary (e.g. distinguish between injuries due to translational and rotational acceleration and impact mechanisms could be useful to better optimize the helmet framework).

Thorax is the body region mostly in need of protection: 36 out of 40 motorcyclists had at least one thoracic injury and 28 people had at least one serious injury (AIS3+). This conclusion was not only suggested by a high percentage of serious injuries, but also considering that thorax injuries could put people's at life risk (e.g. respiratory failure, haemorrhagic shock, etc.). Lungs were the most injured (mainly contusions). Pneumothorax and hemopneumothorax were important although a low frequency. Scooters, sport and standard-style motorcycles have a similar percentage of thoracic injuries, but percentage of injuries increase with the OV size (small, compact, large). Moving from a delta speed of 0-15km/h to 16-30km/h the frequency of thoracic injuries increase of 50%. The principal causes of thoracic injuries were impacts with door (tab. VII), A-pillar and bumper.

Despite having suffered a lower percentage of serious injuries (44.1%) in comparison to other body-regions, the abdomen have a higher percentage of severe and critical injuries suggests needs to be more protected too.

A study on traffic-related fatalities occurred in the Milan metropolitan area (Italy), between 2001-2012, confirms the importance to improve the protection of thoracic and abdominal regions in urban traffic. Results demonstrate that 64.0% of 570 motorcyclists' death was due to multiple injuries (i.e. presence of two or more injuries that even alone would have resulted in death) mostly at thorax and abdomen [28]. The main causes for the abdominal injuries were bumper, sill and ground (Tables XII-XIII). For both thorax and abdomen, the bumper and sill were causes of injuries because of a relatively high percentage (22.5%) of motorcyclists that fell down before the PTW hitting OV. Future actions to improve motorcyclist protection should also include the abdomen related findings. In fact, even if only 20% of the sample suffered serious abdominal injuries (AIS3), the highest percentage of critical injuries (AIS5) were reported in this body region (Figure 11). Although protection of the abdomen is not easy without influencing the freedom of movement for motorcyclists, protection activated in specific crash configurations should be investigated and their effectiveness properly assessed.

Exception for the head, the others body-regions suffered many injuries starting from an impact speed less than those registered to the head (Figure 18). In spite of a small dimension of the sample, a value of 30 km/h could be taken as a threshold speed beyond which the number of injuries sharply increases (Figure 17). Femur (33.0%), pelvis (30.0%) and tibia (21.0%) were the lower extremities most subjected to injuries. Their severity never exceeded AIS3. This is due to by the fact that in the AIS code only few lower limbs injuries are codified as severe (AIS4) or critical (AIS5). Nonetheless, the disabilities following by these injuries are not negligible. Literature shows as 80% of the lower limbs have experienced some functional limitation one year post discharge, despite lower limbs injuries accounted only 26% of the totality. The main causes of injury were the impacts with the fender and door and with the PTWs front glove compartment (for scooter).

The "Injuries sustained by motorcyclists" report showed that head and thorax were the body-regions more at risk of serious injury [16]. This report also pointed out that arms and legs sustained the highest proportion of slight injuries. The authors' did not find this evidence in the current dataset because of the data collection method, which concentrated strictly on seriously injured motorcyclists. From the car point of view, if on one hand improvements of their side parts would probably be difficult to achieve due to their stiffness requirements at side impacts, on the other hand it would be easier to improve the safety performance, e.g., by the use of external airbags [29][29]. The share of injuries, caused by the front glove compartment in scooter type vehicles, require either a re-design of this part or the introduction of energy distributing/absorbing devices like airbags or cushions/pads in order to reduce the incidence and severity of functional disabilities to the lower limbs.

The share of injuries due to sport-style PTW seem to be more responsible of lower limbs injuries and thus more dangerous than the other types. Also the front glove compartment in scooter, require either a re-design of this part or the introduction of energy distributing/absorbing devices like airbags or cushions/pads in order to reduce the incidence and severity of functional disabilities to the lower limbs.

V. CONCLUSIONS

In this paper, 40 PTW-to-OV crashes were studied in order to identify accident configurations and to correlate the injuries with the causes. All the cases were extracted from the InSAFE in-depth database. Accidents were thoroughly reviewed in order to understand the pre-crash, crash and post-crash motions of both the PTWs and the OVs, as well as the injury typologies and sources.

The following key findings can be summarised: i) the main crash configuration was the head-on side collision (45%); ii) the majority of accidents (57.5%) happened while the PTW was travelling along a straight road and impacted a car; iii) in 75% of the cases, the motorcyclist hit an OV with the frontal part of the PTW; iv) the sample included a high frequency (22.5%) of motorcyclists that lost control of the motorcycle and fell down before the crash; v) thorax was the body region, which required more protection, followed by the head and lower limbs; vi) 65% of head injuries were to the brain and 32% to the skull; vii) femur (33%), pelvis (30%) and tibia (21%) were the lower extremities most subjected to injuries; vii) the percentage of injuries caused by the scooter front glove compartment (18%) cannot be neglected.

The data analysis resulted in a number of possible topics, which could lead to increase of safety for motorcyclists. Some technological solutions are already under investigation (i.e. MAEB), but other devices or systems can be developed and assessed using real-world crash data. Specifically there is the need to improve PTW/car interaction in order to avoid the contact of the motorcyclist with those car sections proved to be most harmful.

Acknowledgement

RASIF is a project supported by the European Commission Mobility and Transport. DG MOVE/SUB/01-2011 under the Grant Agreement n. MOVE/C4/SUB/2011-294/SI2.625719.

VI. REFERENCES

[1]WHO. (2015) WHO World Health Organization, *Global status report on road safety*, Switzerland.

[2]ACEM. (2013) ACEM Association des Constructeurs Europeens de Motocycles, *The Motorcycle industry in Europe 2013 Statistical overview. Registrations and deliveries circulating park production top 10 models contents*, Belgium.

[3]ISTAT. (2014) ISTAT Italian National Statistical Institute, *Road Accident Report*, Italy.

[4]Montag J. A radical change in traffic law: Effects on fatalities in the Czech Republic. *J Public Health (Oxford)*, 2014, **36**(4):539-545.

[5]ACEM. (2008) ACEM Association des Constructeurs Europeens de Motocycles, *MAIDS In-depth investigations of accidents involving powered two wheelers (final report)*, Belgium.

[6]Bachulis, B.L., Sangster, W., Gorrell, G.W., et al. (1988) Patterns of injury in helmeted and no helmeted motorcyclists. American J Surg, **155**: pp.708-711.

[7]Rogers, C.D., Pagliarello, G., McLellan, B.A., Nelson, W.R., (1991) Mechanism of injury influences the pattern of injuries sustained by patients involved in vehicular trauma. Can J Surg, **34** (3): pp.283-286.

[8]Forman, J.L., Lopez-Valdes, F.J., Pollack, K. Heredero-Ordoyo, R. Molinero, A. Mansilla, A. (2012) Injuries among powered two-wheeler users in eight European countries: A descriptive analysis of hospital discharge data. Accid Anal Prev, **49**: pp.222-236.

[9] Serre, T., Masson, C., Perrin, C., Martin, JL., Moskal, A., Llari, M. (2012) The motorcyclist impact against a light vehicle: Epidemiological, accidentological and biomechanic analysis. Accid Anal Prev, **49**: pp.223-229.

[10] Moskal, A., Martin, J.L., Lenguerrand, E. (2015) Injuries among motorized two-wheelers in relation to vehicle and crash characteristics in Rhone, France. *Proceedings of Conference Enhanced Safety of Vehicles (ESV)*, 2007 Lyon, France.

[11] Piantini S, Grassi D, et al. (2012) A Pilot Study of an Integrated Accident Research System Based on a Medical and Engineering Data in the Metropolitan Area of Florence. *Proceedings of Conference IRCOBI, 2012*, Dublin (Ireland).

[12] Piantini, S., Grassi, D., et al. (2013) Advanced accident research system based on a medical and engineering data in the metropolitan area of Florence. BMC Emerg Med, **14** (1): 3.

[13] Belobrad, M., Sucha, V. *Virtual Crash Technical Manual*, pp.57. Virtual Crash Software.

[14] Gennarelli, TA., Wodzin, E. (2008) *The Abbreviated Injury Severity Scale, AIS, 2005 update 2008*. AAAM Association for the Advancement of Automotive Medicine, Barrington, IL.

[15] Penumaka, A.P., Savino, G., Baldanzini, N., Pierini, M. (2014) In-depth investigations of PTW-car accidents caused by human errors. Safety Science, **68**: pp.212-221.

[16] Frampton, R., Lenard, J., Grant, R. (2011) VSRC Vehicle Safety Research Centre, *OTS Road Collision Research: Injuries sustained by motorcyclists*, UK.

[17] Savino, G., Pierini, M., Baldanzini, N. (2012) Decision logic of an active braking system for powered two wheelers. Proceedings of the Institution of Mechanical Engineers, Part D: J Automob Eng, **226** (8): pp.1026-1036.

[18] Savino, G., Giovannini, F., Baldanzini, N., Pierini, M., Rizzi, M. (2013) Assessing the Potential Benefits of the Motorcycle Autonomous Emergency Braking Using Detailed Crash Reconstructions. Traffic Injury Prevention, **14**: sup1, S40-S49.

[19] Savino, G., Pierini, M., Rizzi, M., Frampton, R. (2013) Evaluation of an autonomous braking system in real-world PTW crashes. Traffic Injury Prevention, **14** (5): pp.532-43.

[20] Savino, G., Rizzi, M., Brown, J., et al. (2014) Further development of Motorcycle Autonomous Emergency Braking (MAEB), what can in-depth studies tell us? A multinational study. Traffic Injury Prevention, **15** suppl 1: S165-72.

[21] Savino, G., Giovannini, F., Piantini, S., Baldanzini, N., Pierini, M. (2015) Autonomous emergency braking for cornering motorcycle. *Proceedings of Conference Enhanced Safety of Vehicles (ESV)*, 2015 Gothenburg, Sweden.

[22] Teoh, E.R. (2010) Insurance Institute for Highway Safety, *Effectiveness of Antilock Braking Systems in Reducing Fatal Motorcycle Crashes*, USA.

[23]Rizzi, M., Strandrot, J., Tingvall, C. (2009) The effectiveness of Antilock Brake Systems (ABS) on Motorcycles in Reducing real-life Crashes and Injuries. Traffic Injury Prevention, **10**: pp.479-487.

[24] Rizzi, M., Strandroth, J., Johansson, R., Lie, A. (2011) The potential of different countermeasures in reducing motorcycle fatal crashes: what in-depth studies tell us?. *Proceedings of Conference Enhanced* Safety of Vehicles (ESV), 2011 Washington DC, USA.

[25] Rizzi, M., Strandroth, J., Kullgren, A., Tingvall, C., Fildes, B. (2015) Effectiveness of motorcycle antilock braking systems (ABS) in reducing crashes, the first cross-national study. Traffic Injury Prevention, **16** (2): pp.177-83.

[26]Baldanzini, N., Huertas-Leyva, P., Savino, G., Pierini, M., (2016) Rider behavioural patterns in braking manoeuvres. *Transportation Research Procedia* (in press). DOI: 10.1016/j.trpro.2016.05.359

[27] Savino, G., Giovannini, F., Baldanzini, N., Pierini, M. (2012) Training system for optimal braking on a powered two-wheeler. Driver Behaviour and Training Vol 5, pp.101-125. Ashgate Publishing Limited, UK.

[28] Amadesi, A., Cerutti, E., Spagnoli, L., Blandino, A., et al. (2016) The toll of traffic-related fatalities in a metropolitan Italian area through the experience of the Department of Legal Medicine. Int J Inj Contr Saf Promot, **23** (2): pp.197-205.

[29] Fredriksson, R., Sui, B. (2015) Fatal Powered Two-Wheeler (PTW) crashes in Germany – an in-depth

study of the events, injuries and injury sources. *Proceedings of Conference IRCOBI*, 2015, Lion, France.

VII. APPENDIX

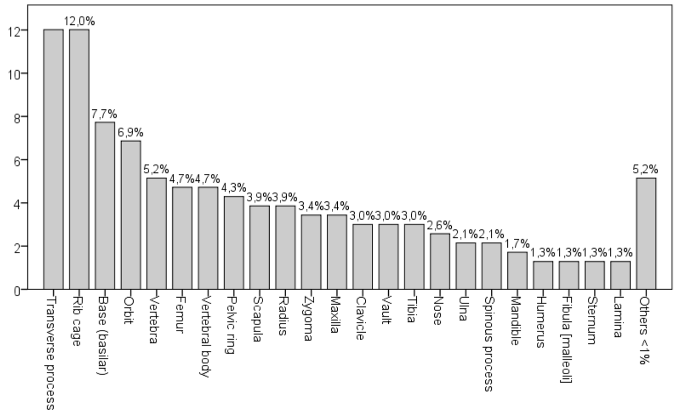

Fig. 27. Percentage of injuries per specific skeletal structures (n=234).

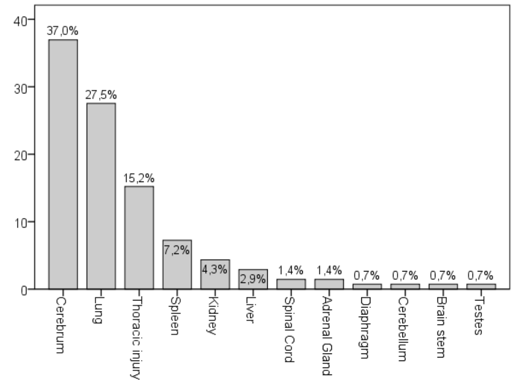

Fig. 28. Percentage of injuries per specific organs (n=138).

TABLE XIV

FREQUENCY OF INJURIES PER BODY REGION AND PTW TYPOLOGIES (NOT NORMALIZED)

PTW type	N	head	face	upper ext.	thorax	spine	abdomen	lower ext.	ext.	Total
Enduro	3	17	1	2	4	2	1	0	1	28
Scooter	27	52	30	22	64	31	12	25	14	250
Sport	4	2	2	7	11	16	8	8	3	57
Touring	1	0	0	1	4	8	1	0	2	16
Standard	5	11	14	6	11	7	6	1	0	56
Total	**40**	**82**	**47**	**38**	**94**	**64**	**28**	**34**	**20**	**407**

TABLE XV

FREQUENCY OF INJURIES PER BODY REGION AND OV TYPOLOGIES (NOT NORMALIZED)

OV type	N	head	face	upper ext.	thorax	spine	abdomen	lower ext.	ext.	Total
Small	18	36	28	23	41	37	13	19	8	205
Compact	11	17	6	12	30	15	9	5	6	100
Large	5	19	6	2	15	12	5	7	3	69
Large Off-road	3	7	0	1	5	0	0	3	2	18
Large van	3	3	7	0	3	0	1	0	1	15
Total	**40**	**82**	**47**	**38**	**94**	**64**	**28**	**34**	**20**	**407**

TABLE XVI

FREQUENCY OF INJURIES PER BODY REGION AND CRASH ANGLE (NOT NORMALIZED)

Crash angle	N	head	face	upper ext.	thorax	spine	abdomen	lower ext.	ext.	Total
315°-45°	11	22	15	9	17	15	5	4	5	92
45°-135°	8	12	9	5	22	5	4	11	0	68
135°-225°	5	14	7	6	15	16	4	5	2	69
225°-315°	7	29	6	5	13	4	0	8	4	69
Total	**31**	**77**	**37**	**25**	**67**	**40**	**13**	**28**	**11**	**298**

TABLE XVII

FREQUENCY OF INJURY SEVERITY PER CRASH ANGLE (NOT NORMALIZED)

Crash angle	N	AIS1	AIS2	AIS3	AIS4	Total
315°-45°	11	23	45	23	1	92
45°-135°	8	3	37	24	4	68
135°-225°	5	7	36	18	8	69
225°-315°	7	8	33	24	4	69
Total	**31**	**41**	**151**	**89**	**17**	**298**

TABLE XVIII

FREQUENCY OF INJURIES PER BODY REGION AND PTW'S IMPACT SPEED (NOT NORMALIZED)

Impact speed	N	head	face	upper ext.	thorax	spine	abdomen	lower ext.	ext.	Total
0-30 km/h	3	2	1	8	8	8	3	3	6	39
30-50 km/h	24	32	26	17	57	29	16	19	11	207
50-70 km/h	12	44	18	6	22	22	5	7	3	127
70 km/h	1	4	2	7	7	5	4	5	0	34
Total	**40**	**82**	**47**	**38**	**94**	**64**	**28**	**34**	**20**	**407**

TABLE XIV

HEAD INJURY SEVERITY PER OV TYPOLOGY (N=81)

OV type	N	AIS1	AIS2	AIS3	AIS4	AIS5	Total
Small	18	0	9	23	4	0	**36**
Compact	11	2	9	5	0	0	**16**
Large	5	0	2	12	4	1	**19**
Large Off-road	3	0	5	2	0	0	**7**
Large van	3	0	2	0	1	0	**3**
Total	**40**	**2**	**27**	**42**	**9**	**1**	**81**