A review of Powered-Two-Wheeler behaviour and safety

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Powered-Two-Wheelers (PTW) constitute a very vulnerable type of road users. The notable increase in their share in traffic and the high risk of severe accident occurrence raise the need for further research. However, current research on PTW safety is not as extensive as for other road users (passenger cars, etc.). Consequently, the objective of this research is to provide a critical review of research on Power-Two-Wheeler behaviour and safety with regard to data collection, methods of analysis and contributory factors and discuss the needs for further research. Both macroscopic analyses (accident frequency, accident rates and severity) and microscopic analyses (PTW rider behaviour, interaction with other motorized traffic) are examined and discussed in this study. The research gaps and the needs for future research are identified, discussed and put in a broad framework. When the interactions between behaviour, accident frequency/rates and severity are co-considered and co-investigated with the various contributory factors (riders, other users, road and traffic environment, vehicles) the accident and injury causes as well as the related solutions are better identified.

Key words: Powered-Two-Wheelers; safety; behaviour; interaction; accident frequency; accident severity

1. Introduction

There is a significant increase in motorcycling activities in many countries worldwide during the last years. Over the last two decades the number of PTWs in Europe has doubled (Yannis et al., 2010). This mode shift is high likely to be attributed to economic, mobility, flexibility and also environmental benefits that mopeds and motorcycles, together referred to as Powered-Two-Wheelers (PTW) offer to the users.

Furthermore, a survey conducted by Jamson and Chorlton (2009), provided evidence that the nature of motorcycling seems to be changing as older riders appear and motorcycling becomes a leisure pursuit. Due to the increased numbers in the percentage of PTWs in the motorized fleet and their lack of protection, it is not surprising that the motorized two-wheelers are considered a dangerous transport mode as the risk of being severely injured is significantly higher than car occupants (Wegman et al., 2008; Aare and von Holst, 2003; Zambon and Hasselberg, 2006). Per vehicle mile travelled, motorcycle riders have a 34-fold higher risk of death in a crash than of motor vehicles users (Lin and Kraus, 2009).

Moreover, PTW fatalities accounted for 18% of the total number of road crash fatalities in 2009 in the EU-23 countries (ERSO, 2011). In spite of the number of measures that have been implemented in the last decade regarding PTW safety, the number of fatalities in accidents involving PTWs in EU is not reduced compared to traffic fatalities as shown in Figure 1. Table 1 illustrates the number of PTWs, the fatalities and the fatality rates for year 2010 in Europe and some other countries as well.

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It is suspected that developing countries are likely to face the same phenomenon, mainly as a result of a generally low economic status. In the western Pacific region 36% of deaths occurred among motorcyclists (Toroyan et al., 2013). In Nigeria, not only motorcycling has become an increasingly popular means of transport but also riders seem to ignore safety measures (Solagberu et al., 2006). In the same study, it is also mentioned that there is an issue of underreported motorcycle injuries in developing countries. Another study (Iamtrakul et al., 2003), states that a large portion of motor vehicles in Thailand are motorcycles and that the majority of fatalities and injuries regard motorcyclists. Moreover, the reasons why motorcycle deaths have recently been increasing in the US and why middle-aged riders are consistently over-representing in fatal motorcycle crashes have to be investigated (Lin and Kraus, 2009).

PTW safety has become a very important issue for societies either developed or developing and related studies are multiplied lately (Van Elslande and Elvik, 2012; Tiwari 2013). However, existing literature regarding PTW safety and behaviour is still not very extensive compared to other road users' (passenger cars, etc.) and lacks from joint consideration of the various contributory factors. Consequently, there is a clear need for further research in respect to PTWs. Taking into account that existing studies reviewing PTW risk factors are very few, this study attempts to provide a broad overview of Powered-Two-Wheeler behaviour and safety. To achieve this aim, the review included both behavioural aspects and interactions of motorized traffic with PTWs, as well as injury risk. In order to present a complete overview of influential factors, a great variety of identified risk factors were examined in the review.

Moreover, in contrast to previous related reviews (e.g. Vlahogianni et al., 2012c) which mainly focus on identifying the critical PTW risk factors, this study also provides an overview of data collection methods and the main analysis methods, in order to outline the research gaps and propose future research directions regarding PTW safety.

The literature review focused on the most recent and quantitatively substantiated research results in the field of PTW behaviour and safety. A comprehensive search of major databases such as Science Direct and Scopus was carried out. Keywords for the search included motorcycle, moped, powered-two wheeler, safety, accident, crash, behaviour, risk, accident, severity, frequency, rates and so on. Both macroscopic analyses (which are associated with accident frequency, accident rates and accident severity) and microscopic analyses (which examine PTW rider behaviour and interaction with other motorized traffic) are examined and discussed in this study. Furthermore, an effort was made to focus on data and analysis methodologies which are more often found in PTW accident analysis.

The structure of the paper is the following: firstly, the type of data and the collection methods are presented followed by the methods of analysis. Then an overview of contributory factors of PTW accidents is illustrated. Contributory factors are identified as those risk factors which have been found to be examined in international literature. Particularly, sub-section "PTW Rider Behaviour" aims to review the factors that influence risky behaviours such as speeding, violations and so on. The research gaps and suggestions for future research are discussed in the discussion section, followed by a proposal of a framework for future research at the conclusion section. At the end of the paper is the Appendix (Appendix A), where there are four tables (Tables A.1-A.4) which summarize the data, methods of analysis and the main findings of the literature.

The review of existing studies includes four aspects of PTW safety: PTW rider behaviour, PTW interaction with other road users, PTW accident frequency/rates and PTW accident severity.

In the paper, PTW rider behaviour concerns the actions of the rider during driving (risky or not) as well as attitudes, perception and other behavioural and psychological characteristics, such as sensation seeking, aggressiveness and so on.

Particularly, interaction of PTWs with other road users could be entirely incorporated in the examination of behaviour, but it was examined separately in order to emphasize its importance. Of course, this is not always possible, since sometimes it is not clear to discriminate interaction and deal with it separately from behaviour or accidents, because it is involved in some behavioural as well as some accident analysis studies.

It is noted that accident severity reflects the outcome of the accident, and depends on the way it is measured in the respective studies. For example, a number of studies examine the severity of an accident classified as the most injured person involved, while other studies examine the injury severity of occupants.

Potential risk factors for road traffic injuries have been proposed by Haddon (1980) and have been divided to four categories: i) factors influencing exposure to risk, such as economic, demographic factors and mixture of high-speed motorized traffic with vulnerable road users, ii) factors influencing crash involvement such as speeding, alcohol or drugs consumption, being a young male, defects in road design and so on, iii) factors influencing crash severity, such as not using seatbelts or helmets, presence of roadside objects and lastly, iv) factors influencing post-crash outcome of injuries such as delay in detecting crash, delay in transport of injured persons to a health facility, lack of appropriate hospital care, leakage of hazardous materials and presence of fire resulting from collision. More factors have been investigated regarding PTW studies, for example, attitudes, hazard perception, errors and violations.

Potentially respective data could be extracted from statistical files, questionnaires and simulators (mainly for attitudes and behavioural aspects), police records as well as hospital records. Especially for critical pre-crash phase information, data such as braking and handling are extremely difficult to be massively collected, with an exception of a limited number of studies using naturalistic data.

2. Data Collection

The type of data and the collection methods are very critical for every researcher wishing to analyze PTW safety and depend heavily on the specific aspect of PTW safety that is analyzed. This is better illustrated in the next four sub-sections of this chapter (PTW rider behaviour, Interaction with other motorized traffic, Accident frequency/rates and Accident severity). It is noted that the other two chapters of the paper (methods and contributory factors) are structured similarly.

2.1 PTW rider behaviour

Speeding, sensation seeking, aggression, perceived risk, errors, violations and attitudes towards road safety are considered to be very important issues. The primary methods of data collection that have been used so far depend heavily on stated behaviour and attitudes of riders. They mainly involve interviews and questionnaires in order to capture the attitudes and perception of riders (Broughton et al, 2009; Chen, 2009; Cheng and Ng, 2010; Chung and Wong, 2012; Elliott et al., 2007; Haque et al., 2010a; Steg and van Brussel, 2009; Wong et al., 2010) and online surveys as well (Özkan et al., 2012).

Setting experiments is another way of observing and grasping behavioural characteristics of riders via an environment that attempts to simulate reality. They mainly involve neuropsychological tests, video-based tests, conspicuity tests eye tracking (Cheng et al., 2011; Di Stasi et al., 2011; Gershon et al., 2012; Rosenbloom et al., 2011), and simulators (Liu et al., 2009; Di Stasi et al., 2009; Hosking et al., 2010; Filtness et al., 2013). Those methods have been used in order to measure and observe specific actions or choices of participants in an experimental environment under hypothetical situations. Finally, direct roadside observations which offer the possibility to capture the real behaviour have not been excessively preferred with the exception of a few studies (Walton and Buchanan, 2012; Woodcock, 2007).

As a first remark, aside from roadside observations, experiments with naturalistic data that capture the behaviour of riders in real situations are rare. It is obvious that an evident limitation regarding data exists. Only recently, some studies used naturalistic data (Vlahogianni et al., 2012b; Walker et al., 2011).

2.2 PTW interaction with other motorized traffic

PTW interaction with other motorized traffic takes place in many situations, for example in overtaking, manoeuvring, braking and in approaching intersections. The importance of interaction is highlighted by the fact that two vehicle collisions involve PTW and car interactions and although many PTW accidents are single-vehicle accidents, there is evidence that a number of those accidents might have occurred in order to avoid a collision with a vehicle (Preusser et al., 1995).

A common type of interaction takes place in right-of-way accidents, which involve motorcycle conspicuity and motorist's speed/distance judgement (Pai, 2009). The studies that investigated conspicuity and gap acceptance used questionnaires and performed experiments similarly to the studies mentioned previously in the previous section (Cavallo and Pinto, 2012; Crundall et al., 2008a; Gould et al., 2012; Horswill et al., 2005; Ragot-Court et al, 2012) or traffic accident databases (Clarke et al., 2007; Pai et al., 2009; Radin Umar et al., 1996; Thomson, 1979; Williams and Hoffman, 1979). Crundall et al. (2012), investigated why car drivers failed to give way to motorcycles at T-junctions using a series of short video clips and then questionnaires. Data were collected from 74 participants, namely 25 novice drivers, 25 experienced drivers and 24 dual drivers. Shahar et al., (2011), implemented more integrated methods of data collection, such as combinations of questionnaires, use of simulator and video clips. Clabaux et al., (2012), aimed to analyze "looked-but-failed-to-see" accidents with in-depth accident data involving 44 cases.

Summing up, the fact that real-time interactions that take place before and during an accident cannot be captured by simulators and consequently, there is need for naturalistic data that reflect the real and not the stated riding behaviour.

2.3 PTW accident frequency/rates

Investigation of the risk of accident occurrence concerning PTWs, as expressed through accident frequency and accident rates is primarily based on historical statistics. The main source of data concern safety administrations, organizations (Branas and Knudson, 2001; Houston and Richardson, 2008; Law et al., 2009; Paulozzi, 2005; Paulozzi et al., 2007; Preusser et al., 1995; Supramaniam et al., 1984; Teoh and Campell, 2010; Teoh, 2011), safety departments (Schneider IV et al., 2012) and direct police records (Haque et al., 2012; Haque et al., 2009, 2010b; Houston, 2007; Kyrychenko and McCartt, 2006; Morris, 2006; Moskal et al., 2012).

Data from hospitals (Ichikawa et al., 2003; Nakahara et al., 2005), or surveys (Harrison and Christie, 2005) were not so often used. On the other hand, more detailed data collection were used in Wanvik's study (2009), which was based on an interactive Internet database containing a huge amount of data concerning injury accidents and property damage accidents in the Netherlands during 1987–2006.

It is noted however, that most of the previous data sources (administrations, organizations etc.) extract their data from police records. Consequently, police records constitute the main source of data. The quality and potential under-reporting have to be taken into serious account while analyzing that kind of data. Various pre-crash variables such as manoeuvring, braking, acceleration etc. would give very useful information but is difficult to be acquired as has been very correctly stated in other studies (Lord and Mannering, 2010).

2.4 PTW accident severity

The literature indicates that there are many measurements of injury severity. The most common measurements are the Abbreviated Injury Scale (AIS), the ICD, the five-level KABCO scale and the ISS (Lin and Kraus, 2008).

The philosophy behind data collection in studies investigating severity of accidents involving PTWs is in a way similar to those studies addressing accident frequency/rates and crash characteristics. A number of studies used national accident databases (de Lapparent, 2006; Pai and Saleh, 2008a, 2008b; Yannis et al., 2005; Zambon and Hasselberg, 2007), police databases (Albalate and Fernández-Villadangos, 2010; Quddus et al., 2002; Savolainen and Mannering, 2007; Shankar and Mannering, 1996) and data from national statistical institutes or safety departments (Montella et al., 2012; Shaheed et al., 2011). Again, police records are very often the sole source which provides the organizations the data. National or local accident databases have been structured on police data. A combination of different approaches can be found in some studies. For example, Majdzadeh et al., (2008), investigated which factors contribute to injuries among car drivers and motorcyclists in Iran by using interviews in hospitals and also police records. A similar approach was followed by Langley et al., (2000).

Overall, underreporting, quantity and quality of available data remain a concern when examining both accident severity and frequency and have not yet been fully addressed as mentioned previously. For example, Lin and Kraus (2008), argue that motorcycle injuries consistently are less likely to be reported by the police when compared with injuries to other motor-vehicle occupants. There is also need for a harmonised collection of data on fatalities, hospital discharges and external causes of injuries (Kisser et al., 2009). Finally, similar to accident frequencies, the collection of pre-crash driving data would be essential but is yet very difficult to achieve in a large scale extent.

3. Methods of Analysis

3.1 PTW rider behaviour

Behaviour of riders in relation to safety was usually addressed using relatively straightforward statistical methods. Descriptive statistics were carried out in the great number of studies as a preliminary analysis to illustrate the patterns of the data or the results.

Factor analysis is the most common used method, mainly because extracted data depend primarily on questionnaires and interviews. It aims to identify factors that explain the patterns of correlations within a set of independent variables or for data reduction purposes. In this case it is attempted to identify a small number of factors that explain most of the variance that is observed in a much larger number of variables. Many types of factor analysis (exploratory, confirmatory, principal components) have been identified in the literature either as the sole analytical tool (Chen and Chen, 2011; Cheng and Ng, 2010; Özkan et al., 2012; Ulleberg and Rundmo, 2003), or together with another statistical method (Chorlton et al., 2012; Elliott et al., 2007; Rutter and Quinne, 1996; Schwebel et al., 2006). For example, Goldenbeld et al., (2004), applied factor analysis and linear regression in order to investigate the short and long term effects of moped rider training. Steg and van Brussel, (2009), used factor analysis to analyze various attitudes and perceptions towards speeding and also a logistic regression in order to investigate accident involvement. Wong et al., (2010), conducted exploratory factor analysis and a structural equation model based on the derived factors. A slightly different approach was applied by Chen (2009), who explored the relationships between personality factors and attitudes towards traffic safety and risky behaviours among young motorcyclists in Taiwan by means of structural equation modelling.

On the other hand, cluster analysis is an exploratory classification tool and attempts to reveal natural groupings (or clusters) within a dataset. This method was identified very often in PTW literature as well (Brandau et al., 2011; Chung and Wong, 2012; Woodcock, 2007). Moreover, Chang and Yeh, (2007), carried out a two-step cluster analysis to classify risky behaviours and a logistic regression analysis to investigate the effect of age, gender, and risky behaviours on accident involvement.

Regression analysis and discrete choice analysis have been frequently implemented by a number of researchers when the dependent variable is continuous or categorical respectively. More specifically, hierarchical multiple regression (Elliott, 2010), separate hierarchical regression analyses (Tunnicliff et al., 2012), logistic regression (Liu et al., 2009; Rathinam et al., 2007) and multinomial regression (Mannering and Grodsky, 1995) have been used in literature. In addition, survival analysis (for example the Cox regression) which aims to predict the time to event occurrence was also used in some situations (Yeh and Chang, 2009).

Finally, some other methods have been used, such as correlations among some independent variables and behaviour/perception (Cheng et al., 2011), analysis of variance (Di Stasi et al., 2009, 2011; Rosenbloom et al., 2011), log-linear models (Haque et al., 2010a), and non-parametric tests including chi square tests (Broughton et al., 2009; Dandona et al., 2006; Maestracci et al., 2012).

3.2 PTW interaction with other motorized traffic

The basic analytical tools when investigating PTW interaction with other motorized traffic have been the traditional statistical methods and they have many similarities with those investigating PTW behaviour. It is noted though that the analysis methods are heavily dependent upon the kind of data.

For example, factor analysis is preferred when analyzing questionnaires and was chosen by some studies (Crundall et al., 2008a; Horswill and Helman, 2003).

Discrete choice methods have been widely applied. A binary logistic regression analysis and a Cox proportional hazard regression model were selected by Li et al., (2009), in order to investigate the survival hazards of road environment factors between motor-vehicles and motorcycles. Mixed logit analysis was also found to have been performed (Pai et al., 2009) and also linear or log-linear models (Gershon, et al., 2012; Haque et al., 2012).

More straightforward statistical methods, such as chi square tests and analysis of variance (ANOVA) were also found in literature (Clarke et al., 2007; Crundall et al., 2008b; Shahar et al., 2010). Shahar et al. (2011) carried out analysis of variance and regression analysis to analyze attitude change of car drivers towards motorcyclists.

In general, statistical analyses are the predominant tool for analyzing interactions of motorized users. However, an entirely different tool that is totally absent in PTW literature is game theory. According to this approach road users are players, they follow strategies and finally make decisions according to the payoffs. This approach may be fruitful for analyzing such interactions and need further research (Elvik, 2012).

3.3 PTW accident frequency/rates

Examining the frequency of crashes is not always the best way to measure the risk of an accident and road safety. Alternatively, rates of crashes or fatalities per defined unit, describe better this phenomenon. For example, Houston and Richardson (2008), chosen three measures to normalise fatalities by risk exposure, namely motorcyclist fatalities per 10,000 registered motorcycles, number of these fatalities per 100,000 residents and number of fatalities per 10 billion vehicle miles travelled. However, many studies found during the literature review dealt with crash (or fatality) frequency and rates in general and do not examine motorcycles exclusively.

Count-data modelling is a common method to deal with accident frequency because of the fact that the number of accidents (or fatalities) is a non-negative integer and as a result ordinary least squares regression is not appropriate. Typical models such as Poisson regression models have been found in some studies (Houston, 2007; Teoh and Campell, 2010). Poisson models are basic models and easy to estimate but cannot handle under-or-over dispersion (Lord and Mannering, 2010).

Abdul Manan and Várhelyi, (2012) analyzed motorcycle fatal accident data in Malaysia, in terms of frequency and patterns by type of various parameters such as location, area, road, time, crash type, gender and age. A similar approach was followed by Oluwadiya et al., (2009). Lin et al., (2003), investigated the relationship of the risk of a motorcycle crash to the potential risk factors by applying an Andersen–Gill (AG) multiplicative intensity model (Andersen and Gill, 1982), which is a generalization of the Cox proportional hazard model. Factors that increase motorcycle rider risk compared to car driver risk were examined by means of PROC logistic models by Keall and Newstead, (2012). A fixed effects negative binomial regression analysis carried out by Law et al., (2009), aiming to investigate the factors which are associated with the relationship between motorcycle deaths and economic growth. A study carried out by Hyatt et al., (2009), illustrated time-series analysis using ARIMA models to estimate the association between regular-grade gasoline price, injury and mortality rates.

Studies aimed to estimate fatality rates followed a different approach. In those cases, fatality rates were estimated by linear regression (French et al., 2009; Houston and Richardson, 2008; Supramaniam et al., 1984) or generalized linear regression models (Harnen et al., 2003; Morris, 2006). However, discrete choice models, such as logistic regression was also used in some cases. Haque et al., (2009), selected logistic regression in order to differentiate between at-fault and not-at-fault crashes of motorcyclists.

Other statistical tests such as non-parametric tests were also present in literature as they are simple and straightforward methods of statistical analysis (Branas and Knudson, 2001; Daniello and Gabler, 2011; Harrison and Christie, 2005; Kasantikul et al., 2005; Mayrose, 2008; Ouellet and Kasantikul, 2006; Paulozzi, 2005; Teoh, 2011; Xuequn et al., 2011).

International literature indicates that the primary analytical tools were traditional statistical methods. However, more advanced statistical methods were found. For example, Haque et al., (2010b), developed hierarchical Bayesian models to investigate motorcycle crashes at four legged and T- signalized intersections in Singapore. This promising method has not extensively used in analyzing safety data with some exceptions (Yu et al., 2013; Ahmed et al., 2011).

Some alternative methods, such as artificial neural networks have not been applied to motorcycle accident data yet. However, Chang, (2005), conducted and compared negative binomial regression to artificial neural networks (ANN) to analyze freeway accident frequencies. The author concluded that ANN is a well promising alternative method to analyze accident frequency as it does not require any pre-defined underlying relationship between dependent and independent variables and is efficient especially when dealing with prediction and classification problems. To the best of our knowledge there are no PTW safety studies applying this analytical tool.

3.4 PTW accident severity

The dependent variable of severity generally consists of two or more discrete categories, e.g. fatal/non-fatal or no injury, possible injury, evident injury, disabling injury, fatality. The basic factor that defines the selected method is the nature of the dependent variable. When the dependent variable has two categories, logistic regression is the most common approach. Although the nature of accident severity is ordinal, recognizing or denying this nature leads to different statistical approach. For example, ordered logit or probit models are appropriate if accident severity levels are considered ordinal. On the other hand, multinomial or nested (GEV) logit models are appropriate when accident severity levels are considered unordered or nominal.

Literature indicates that various analysis approaches have been selected by researchers to analyze PTW accident severity data, such as ordered logit or probit models (Quddus et al., 2002; Albalate and Fernández-Villadangos, 2010; Pai and Saleh, 2008a and 2008b), multinomial models (Shankar and Mannering, 1996), binary logistic regression models (Keng, 2005; Majdzadeh et al., 2008; Pai 2009; Zambon and Hasselberg, 2006, 2007). For example, Savolainen and Mannering (2007) applied a nested logit and a standard multinomial logit model in order to analyze motorcyclists' injury severities in single- and multi-vehicle crashes at Indiana. Various ordered response logit models were selected by Rifaat et al., (2012) in order to investigate severity of motorcycle crashes in Calgary.

Other analytical methods have also been carried out when a different approach to examine PTW accident severity was selected, such as log-linear models (Haque et al., 2012) and classification trees (Montella et al., 2012). Log-linear analysis was the chosen method followed by Yannis et al., (2005) in order to examine between first and second-order effects between accident severity, driver age and two-wheeler engine size. De Lapparent, (2006), conducted empirical Bayesian analysis for accident severity of motorcyclists (material damages only, slight injury, severe injury and fatal injury) in large French urban areas. More specifically, this approach used an empirical Bayesian method based on the Multinomial-Dirichlet model.

Concluding, it is observed that traditional statistical methods dominate the field of PTW accident severity. To the best of our knowledge, other computational intelligent methods such as artificial neural networks that were also discussed previously have not been applied so far in PTW severity. However, such methods have been applied to analyze severity of crashes or occupant severity (Abdel-Aty and Abdelwahab, 2004; Chimba and Sando, 2009; Delen et al., 2006).

4. Contributory Factors

It is noted that the purpose of the sub-section "4.1 PTW Rider Behaviour" is to demonstrate the factors which influence behaviour and also predict risky behaviours such as speeding and violations.

4.1 PTW rider behaviour

Riding is a complicated task that requires a lot of attention and personal skills. Perceptions and attitudes of PTW riders are considered important because they may reflect their real riding behaviour. Moreover, attitudes toward traffic safety are directly related to risky riding behaviour (Chen, 2009). Ulleberg and Rundmo, (2003), designed a questionnaire and attempted to measure risk perception, attitudes and attitudes towards traffic safety and self-reported risk-taking of adolescents in Norway. Moreover, risky intentions could be predicted by attitudes and sensation seeking (Tunnicliff et al., 2012).

The fact that riding a motorcycle is a dangerous activity may have different effects on the riders' behaviour. For example, risk-seeking individuals may be attracted to this activity (Mannering and Grodsky, 1995). On the other hand, their hazard perception capability is high likely to be better than this of car drivers (Horswill and Helman; 2003; Rosenbloom et al., 2011). However, this result is not always supported (Maestracci et al., 2012) and some recent studies have shown that this difference in hazard perception capability may be moderated by driving experience (Crundall et al., 2012). Hazard perception is related to risky behaviours and PTW riders are aware of the risks but believe that those risks are overcome by their skills and experience (Musselwhite et al., 2012). Aside from hazard perception, the decision of a rider to behave risky could be also affected by the perception that this risky behaviour could be detected and also the chances of receiving punishment (Rathinam et al., 2007).

A factor that significantly affects riding skills, riding behaviour but also hazard perception is riding under the influence of alcohol (Creaser et al., 2009; Hosking et al., 2010). The effect of alcohol seems to significantly increase the odds of severe and fatal injuries regardless of sociodemographic attributes (Vaez and Laflamme, 2005).

Training and experience seem to also have significant effect on riding behaviour. Training can lead to an improvement in the riding skills of first-time riders, reducing the number of accidents (Di Stasi et al., 2011). Liu et al., (2009), found that novice riders were overconfident about their abilities and they perceived hazards in a less appropriate manner than experienced ones. Other studies have shown that experienced riders respond faster to hazards than inexperienced ones (Hosking et al., 2010). However, skills acquired through training may not remain in the long run (Goldenbeld et al., 2004). Self-assessment tests that have been performed in car drivers have revealed interesting results (De Craen et al., 2011) and need to be performed also to riders.

Age and gender are factors which distinguish heterogeneous rider groups in terms of decision making and influence their risky riding behaviour (Chung and Wong, 2012). Being young and male, is associated with risky behaviours (Mannering and Grodsky, 1995; Lin et al., 2003). It is interesting that the three primary attributes of young motorcyclists seem to be sensation seeking, amiability and impatience (Wong et al., 2010). Rutter and Quine (1996), state that age and more specifically youth, plays a more significant role than inexperience. Moreover, young riders do not seem to wear protective equipment (de Rome et al., 2011).

Age and gender are also related with errors and violations and more specifically, young and male riders were more likely to disobey traffic rules (Chang and Yeh, 2007). Young riders were also more likely to be unaware or neglect potential risk. Dandona et al., (2006), interviewed PTW riders above 16 years old at petrol filling stations in India and found that about half of the riders committed at least one (assessed) violation during the last three months.

Errors and violations are affected by some other parameters as well. Schwebel et al., (2006), argue that sensation-seeking seemed to be the most significant predictor of self-reported riding violations compared to the other parameters (anger/hostility, personality etc.).

A common violation and risky behaviour is considered to be excessive speeding and it is probable that it is affected by many factors and their interactions. The PTW riders' attitudes towards speeding are likely to predict actual behaviour. Psychological flow variables, such as perceived enjoyment and concentration seem to positively affect motorcyclists’ speeding behaviour (Chen and Chen, 2011). In the same study, it is argued that personal factors (e.g. personality traits, experience and gender) reflect differences in motorcyclist speeding behaviour. Furthermore, Rathinam et al., (2007), found that young riders were driving faster when they were angry than when they were in any other mood. Steg and van Brussel, (2009), argued that moped riders were more likely to speed and disobey speed limits when they have a positive attitude towards speeding, but also when they think that other road users expect them to speed. These results were consistent with Elliott (2010), who attempted to investigate which cognitive factors affect motorcyclists' intentions to speed. Chorlton et al., (2012), attempted to predict motorcyclists' intention to ride above the speed limit and also at inappropriate speeds. Some interesting findings were that speeding on motorways would allow riders to beat the traffic and also feel exhilarated.

Finally, according to several studies (Cheng and Ng, 2010; Haque et al., 2010a; Rosenbloom et al., 2011) previous involvement in accidents (e.g. past history of accidents), was related to aggressive behaviour (and also sensation seeking) of riders.

4.2 PTW interaction with other motorized traffic

PTW riders are more vulnerable than car drivers and when car drivers deviate from expected and proper behaviour they constitute a potential risk to PTW riders (Ragot-Court et al., 2012). It is interesting that car drivers who also hold a motorcycle licence are less responsible for car-motorcycle crashes than those who hold only car driving licence (Magazzù et al., 2006). Moreover, Shahar et al. (2010), revealed that dual drivers responded better to hazards at junctions and also performed better than either experienced or novice drivers.

The attitudes of car drivers towards motorcyclists may influence the interactions between them but have not been extensively investigated. Most empathy towards motorcyclists stem from male drivers who are or know motorcyclists (Musselwhite et al., 2012). Crundall et al., (2008a), carried out a survey in order to investigate the car drivers' attitudes towards motorcyclists and some interesting findings suggested that car drivers with an amount of experience between 2 and 10 years expressed the most negative views. Shahar et al., (2011), attempted to deploy a strategy in order to reduce the negative attitudes of car drivers towards motorcyclists.

A number of accidents occur because of the fact that car drivers did not detect the motorcyclist or because the car driver detected the motorcyclist but failed to judge correctly the speed/distance of the oncoming motorcycle (Thomson, 1979; Williams and Hoffmann, 1979; Haque et al., 2012). The fact that motorcycles have relatively small size makes their detection by car drivers more difficult. In regard with night driving, it seems that car drivers are more accurate in judging the speed of cars than motorcycles (Gould et al., 2012). On the other hand, the use of the car daytime running lights deteriorates conspicuity (Cavallo and Pinto, 2012). Gershon et al., (2012), concluded that the ability to detect a PTW is affected by a handful of visual factors that have a relation to the PTW, its rider, the driving environment, and the car driver's level of awareness. It is important to note that "looked but failed to see'' accidents are over-represented in intersections and constitute a significant contributory factor to PTW accidents (Clabaux et al., 2012; Clarke et al., 2007; Crundall et al., 2012).

4.3 PTW accident frequency/rates

A variety of accident related factors have been identified during literature review. The road environment such as road type, road geometry and roadside installations have been found to have an influence on PTW accident occurrence (Harnen et al., 2003; Kasantikul et al., 2005; Wanvik, 2009). For example, Haque et al. (2010b), argue that the number of lanes at four-legged signalized intersections significantly increases motorcycle crashes. In the same study, it is stated that motorcycle crashes increase in high speed roadways. In the US, almost 80% of PTW accidents occurred in urban or suburban areas. Haque et al. (2009), examined fault among motorcyclists involved in crashes and indicate that several geometrical and environmental factors were responsible for non-at fault crashes, for example wet road surfaces, single-lane roads and median lanes of multi-lane roads.

Aside from the road characteristics, another category of risk factors is vehicle characteristics such as aerodynamic behaviour and engine size. As indicated in a study made by Teoh and Campbell (2010), rider death rates for super sport motorcycles were four times higher than those for standard motorcycles. On the other hand, some vehicle technological characteristics such as ABS or Autonomous Emergency Braking may be beneficial for the safety of riders (Teoh, 2011; Savino et al., 2013a and 2013b).

Exposure is a also a critical factor (Haque et al., 2010b; Keall and Newstead, 2012). Harrison and Christie, (2005), stated that the rate of crash involvement per kilometre-travelled decreases as current riding exposure rises. Lin et al. (2003), state that some exposure factors (number of riding days, average riding distance) were found to increase the risk of being involved in an accident.

The effect of protective equipment such as helmets, on reducing fatality rates of riders has been addressed in numerous studies (Branas and Knudson, 2001; Dee, 2009; French et al., 2009; Kyrychenko and Mc Cartt, 2006; Mayrose, 2008; Moskal et al., 2012; Ouellet and Kasantikul, 2006). Helmet laws generally enhance PTW safety (Kyrychenko and McCartt, 2006; Morris, 2006). Houston (2007) argues that universal helmet laws result in less fatality rates among young motorcyclists. On the other hand, the widespread use of non-standard helmets in low- and middle-income countries may limit the potential gains of helmet use programmes (Ackaah et al., 2013). However, helmet use seems to have no relation with the risk of a being involved in a crash (Lin et al., 2003). De Rome et al. (2011), found no association between riding unprotected and other risk-taking factors.

Behavioural characteristics constitute another category of factors correlated with accident involvement. It is noted that factors such as age and experience have also an effect on accident occurrence. Those factors have been discussed in previous sections and also how they predict risky behaviour. Alcohol consumption is a very important behavioural factor related to increased PTW risk and high number of crashes (Ahlm et al., 2009; Huang and Lai, 2011; Lin et al., 2003; Ouellet et al., 2005; Preusser et al., 1995; Teoh, 2011).

The interaction of behavioural factors seem to increase the risk of accidents. Moskal et al, (2012), indicated that being male, exceeding the legal alcohol limit and travelling leisure trips are related with increased risk. Bjørnskau et al. (2012), attempted to relate rider characteristics, behaviour and accident risk in Norway. The authors conclude that *"the combination of low age, low experience, risky behaviour and "unsafe" attitudes seems to be a particular potent risk factor for Norwegian motorcyclists"*. Keall and Newstead, (2012), compared the risk between car and motorcycle riders and found that especially young riders or riders who live in more urbanized settings were exposed to more risk.

The interaction of behavioural characteristics with other factors as well was identified as critical for PTW safety. Schneider IV et al., (2012), concluded that younger motorcyclists are more likely to be at-fault in a crash, as are riders who are under the influence of alcohol, riding without insurance or not wearing helmet. Oluwadiya et al. (2009), found that risky behaviour among motorcycle riders interacting with chaotic traffic and road design faults were responsible for the majority of the motorcycle crashes in Nigeria.

Economic indicators seem to be associated with PTW deaths and rates (Law et al., 2009). For instance, Hyatt et al. (2009), observed that, whilst the number of injuries and fatalities in motorcycle-related multi-vehicle crashes rise gasoline price in the United States rises, rates remained in a great extend stable. Furthermore, Houston, (2007) and Houston and Richardson, (2008), identified income per capita and registered motorcycles per capita as contributory factors.

Finally, two factors have not been investigated in a large extent are the weather and traffic characteristics. The effect of those factors on PTW safety has not been deeply explored. Various studies have addressed the effect of weather on vehicle crashes and rates but literature regarding PTW accidents and some weather effects is limited (Branas and Knudson, 2001; Houston and Richardson, 2008; Xuequn et al., 2011). On the other hand, the association between traffic volumes and speed with PTW accidents has not been explored and need further research.

4.4 PTW accident severity

Critical factors which affect PTW accident severity are in a way similar to those which affect accident frequency and rates, for example road infrastructure characteristics, vehicle characteristics, behavioural and environmental factors. Nevertheless, accident severity is influenced in a different way. Consequently, strategies that target accident occurrence are different than strategies targeting mitigation of accident severity.

Road characteristics and roadside installations have been identified as factors that increase PTW accident severity, (Albalate and Fernández-Villadangos, 2010; Rifaat et al., 2012). For example, crashes at curves are associated with fatal injuries (Montella et al., 2012). Daniello and Gabler (2011), indicate that PTW collisions with guardrail are more likely to result in a fatal accident than collisions where the rider hit the ground.

A typical factor often closely related to geometrical characteristics and infrastructure is a right-of-way violation. Pai (2009), argued that accident severity is increased when a travelling-straight motorcycle on the main road crashes with car coming from the minor road and intends to turn right. Moreover, this situation deteriorates particularly at stop-/yield-controlled junctions. Another study (Pai and Saleh, 2008a), indicated that in right-of-way violations the more severe injuries appeared when stop, give-way signs and markings controlled the junction.

Low visibility is related with increased injury severity of motorcycles (Savolainen and Mannering, 2007). Lighting also affects PTW severity. When motorcycle accidents occurred during the night when the lighting conditions were poor, they resulted in higher injury severity (de Lapparent, 2006; Pai and Saleh, 2007).

Some behavioural factors such as speeding, alcohol consumption and non-helmet use are associated with more severe injuries (Albalate and Fernández-Villadangos, 2010; Nakahara et al., 2005; Savolainen and Mannering, 2007; Shankar and Mannering, 1996, Zambon and Hasselberg, 2007). High speed causes more difficulty in manoeuvres than passenger cars due to complex dynamics (Elliott et al. 2007; Horswill and Helman 2003), the stopping distances rise and also results in more severe crashes due to the high amount of kinetic energy. Non-helmet use constitutes a very important factor as it keeps the rider's neck and head unprotected. The effect on this factor has been highly addressed in many studies (Gabella et al., 1995; Keng, 2005). Moreover, the type of collision has also an effect on PTW accident severity (de Lapparent, 2006; Pai and Saleh, 2008a and 2008b; Shaheed et al., 2011).

Riders' age is associated with increased accident severity (Gabella et al., 1995; Nakahara et al., 2005; Pai 2009; Savolainen and Mannering, 2007; Yannis et al., 2005). A study (Donate-López et al., 2010) stressed that each one-year increase in age is related with a 3% increase in the risk of death. De Lapparent, (2006), stated that women riders between 30 and 50 years old driving motorcycles with high engine size are the most exposed to risk of injury.

In most studies the interaction of factors seem to affect PTW accident severity rather than a single type of factor. Quddus et al., (2002) identified the most influential factors that result in higher motorcycle accident severity and they appear to be collisions with stationary objects, collisions with pedestrians and the motorcycle engine capacity. Other studies also support this evidence that motorcycle engine size is a contributory factor to accident severity (de Lapparent, 2006; Langley et al., 2000; Pai, 2009; Yannis et al., 2005). Pai and Saleh (2008b), investigated the factors that increase motorcyclists' accident severity by various crash types at T-junctions in the UK and revealed a very interesting number of factors such as being male and elderly, increased engine size, early morning riding, type of season (spring and summer), fine weather conditions, insufficient lighting, non-built up areas and collisions with heavy vehicles. Savolainen and Mannering, (2007) showed that increasing motorcyclist age, collision type, roadway characteristics, alcohol consumption, non-helmet use and unsafe speed were statistically significant. Similarly to PTW accident frequency, the effect of weather on PTW accident severity has not been excessively explored.

Finally, it is worth mentioning socio-economic factors seem to affect accident severity. More specifically, it was found that young motorcycle riders in lower socioeconomic groups have higher odds for both minor and severe injuries than those in the highest socioeconomic group (Zambon and Hasselberg, 2006).

Concluding, it is obvious that only a few studies investigated the effect of some factors such as real-time speed, weather and traffic on PTW severity. Christoforou et al., (2010), investigated the association between crash severity and traffic characteristics collected real-time during the time of the accident occurred. Quddus et al., (2009), used real-time data from the time of the accident and found that as traffic flow increases the crash severity decreases. To the best of our knowledge, there is a lack of studies examining the effect of real-time traffic and weather characteristics.

5. Discussion

First of all, data basically stem from questionnaires, police records and sometimes experiments. Questionnaires are not the best solution to measure human behaviour, simply because the stated behaviour can be different from the real behaviour. In that context, experiments seem to gain more attention in PTW literature especially these experiments which try to measure physical attributes such as eye tracking that indirectly express human behaviour. The increased use of enhanced simulators is definitely a step towards the right direction. However, there is need for new naturalistic data which may enable the monitoring of participants' observed behaviour in high detail in real-time situations such as seconds before or during an incident or an accident. PTW interaction with other motorized traffic has been dealt with a similar approach. The use of naturalistic data will also supply researchers with information about observed real-time interactions between PTW riders and car drivers in several situations such as overtaking, braking, evasive actions, giving way and so on. Furthermore, simulators that would enable various road users to interact in pre-selected scenarios could be helpful to observe these interactions between them.

As far as PTW accidents are concerned, relying mostly on police data records is not always the most appropriate way to analyze PTW accidents either in terms of accident frequency or severity. The reason is that many critical variables may be missing and cannot be measured at post-crash phases, for example traffic volumes, traffic density, speed, pre-crash manoeuvres, overtaking, lane changing, braking/accelerating etc. This is also mentioned in Lord and Mannering (2010). In addition, police reports may overestimate accident severity remarkably (Tsui et al., 2009). Consequently, there is need for a detailed observation of road sites constantly and for a detailed accident recording system. In this case, naturalistic data which involve accidents may be a good alternative in order solve these issues. Another approach of course is the modelling of near missing accidents (or incidents). A near missing accident or an incident that happen today, could be an accident in the future, so modelling near-misses and incidents could provide interesting information. This approach is implemented widely in aviation safety, where the small number of accidents prohibits the classic methodological approach.

In terms of methodology, it is observed that the large majority of studies in regard with every aspect of PTW safety are based upon classic statistical methods with some few exceptions which are mentioned earlier in the paper such as Neural Networks. However, rider behaviour (and of course human behaviour) is a very complex variable which is expressed via various actions while riding but even before riding (e.g. alcohol consumption). Thus, modelling human behaviour is a very challenging task and may need a different approach. For example, in transportation systems, legal and social constraints, laws and restrictions may define behaviour, in a sense that human actions and system evolution can be predicted and outcomes may be determined by system dynamics (Frazier and Kockelman, 2004). Then chaos theory may apply to model human behaviour and also to (accident generating) system outcomes. For example, do PTW accidents occur randomly? Do they occur in a designed way that could be called 'deterministic'? In the second case, knowing the initial conditions will lead to accurate forecast. Moreover, traffic may be chaotic and its effect on PTW accidents has not been investigated so far. In any case, chaos applications in regard with PTW accidents seem to be an interesting and promising approach, especially when non-linear relationships seem to exist.

When it comes to interaction, there is not much difference from behaviour in terms of methodology used so far. However, there is one point that has not been investigated sufficiently yet. In every aspect of daily life, humans have to make decisions. Some people even compare real life to chess, where players constantly make decisions and immediately face the effect of each decision. Interactions between road users take place when overtaking, lane changing, braking, giving way, approaching an intersection and so on. Many studies have focused on gap acceptance, conspicuity and errors but no studies have explored the potential strategy that each individual uses in the transport network and its effect on accidents.

In that context, every road user becomes the 'player' and every decision has its 'payoff'. A game theoretical approach to behaviour and interaction is considered by authors a fruitful direction for further research. In order to define a game it is required to identify the players, their alternative strategies and their objectives. Several questions need an answer, such as what strategy is used by car drivers when confronting PTWs and the opposite, whether riders have a strategy, whether they make the optimum decision, how their strategy evolves over time and finally how they adapt to critical situations and whether the various measures make riders to adapt their strategic interaction with other motorized traffic and pedestrians. It is important to mention that also car drivers' attitudes and perceptions towards motorcyclists are important to be further investigated given that a large proportion of motorcycle crashes result from errors made by other vehicles (Tunnincliff et al., 2012). Finally, another interesting category of games (aside from games between road users), is this which presents the interaction between road users and authorities. An authority could be for example the police. Each player has different strategies and aims. This could also be very interesting if further explored as Bjørnskau and Elvik (1992) argue. In this study, a game theoretic model was developed in order to explore if traffic law enforcement can permanently reduce accidents. It is stated that the linkage between accident rates, violation rates and police enforcement, examined via a game theoretic model has not tested so far.

Computation intelligent methods, such as artificial neural networks (ANN) have not been used widely for PTW safety analyses. Neural networks allow non-linear relationships between dependent and independent variables and require no prior assumptions. Nonetheless, the interpretability of their results is not straightforward as in traditional statistical methods of analysis which offer more interpretable results but have some drawbacks (for example they require prior assumptions to be valid and cannot handle some problems). Although ANN can overcome many problems of statistical methods they can be time-consuming. A more detailed review of neural networks in transportation research is presented in Karlaftis and Vlahogianni (2011). Other statistical methods that have been used in accident frequency analysis are Bayesian models with promising results (Chin and Quddus, 2003; Ahmed et al., 2011; Yu et al., 2013). These response models for count data are specified hierarchically in several layers and Marcov Chain Monte Carlo techniques are required in order to obtain inference (Tunaru, 2002). Consequently, it is concluded that other more intelligent computational methods are applied in PTW safety and test their results in comparison with previous research methods.

A limitation identified in PTW literature is the lack of detailed real-time traffic and weather variables. In the large majority of cases, weather variables in the time of the accident are expressed as 'good weather', 'rainy', 'snow' etc. and not in a quantitative scale. PTW riding involves more direct exposure to weather conditions such as temperature, visibility, wind direction/speed, rainfall intensity and so on. The real-time quantitative weather effects are entirely new in analyzing accident frequency with only a few studies found to have incorporated such data. On the other hand, some studies attempted to relate traffic congestion and accident occurrences (Quddus et al., 2009; Park and Abdel-Aty, 2011). In most of such studies the AADT was used. No real-time traffic data were found to have been used to analyze PTW accident occurrences and fatalities. However, some researchers attempted to incorporate such kind of data to investigate accident occurrence and severity. For example, Yu et al., (2013) analyzed freeway crash occurrences using real-time weather and traffic data prior to the accident. Vlahogianni et al. (2012a), attempted to model the effect of such variables on the risk of secondary incidents. Very few studies found to have been incorporated real-time traffic data to model accident severity (Christoforou et al., 2010; Quddus et al., 2009).

All these studies seem to regard such data as promising tools for researchers. As a result, their effect on specific PTW accident frequencies and severity is a good direction for further research. Moreover, it is possible that weather conditions may affect rider behaviour and even traffic conditions (volumes, speed etc.). Although it seems that PTW riders prefer to ride in good weather conditions, accidents in adverse weather conditions do occur. However, traffic volumes are not the same in good and adverse weather and it would be interesting to study what is the ratio of accidents to the number of PTWs. Finally, the effect of some important pre-crash variables which are mentioned earlier in this section raise the need for further research. Last but not least, the relationship between exposure and risk has been mentioned (Harrison and Christie, 2005). Of course, this presupposes large and highly detailed databases.

6. Conclusion

This paper attempted to provide a critical review of PTW safety summarizing the main research results so far, as well as to identify the research gaps and propose directions for further research. More specifically, rider behaviour, interaction with other motorized traffic, accident frequency/rates and accident severity are examined in this paper. In addition, the main contributory factors are examined separately and in conjunction with the other factors. Research gaps were identified and a broad framework for future research is proposed.

This framework for future research comprises a two level approach. Firstly, studies on PTW risk factors need to be multiplied, examining those factors together or separately, through either macroscopic or microscopic analyses. These studies should further explore available data and methodologies used, tackling as much as possible their inherent limitations and addressing in detail as many contributory factors as possible.

At a second level, there is need for a co-investigation and co-consideration of issues related to behaviour, accident frequency and accident severity, addressing properly the complexity of PTW safety. In fact, Powered-Two-Wheeler behaviour, accident frequency and accident severity interact differently in the various circumstances and there is need for research co-examining these interactions. PTW safety analysis through such an approach supposes the study of the traffic system as a whole, the investigation of the accident generation process from its beginning to its final outcome, attempting the synthesis of the joint effect of the various contributory factors to accident and injury causation.

Through this approach for future research regarding PTW safety, road user behaviour will be better associated to accident frequency and severity, and a better insight of the PTW safety phenomenon will be possible. When the interactions between behaviour, accident frequency and severity are co-considered with the various contributory factors (riders, other users, road and traffic environment, vehicles) the accident and injury causes as well as the related solutions are better identified. Special emphasis should be given to factors with increased impact, like the interaction between PTW specific behavioural patterns with the related traffic and weather characteristics.

However, this co-investigation and co-consideration of behavioural, risk and severity issues require PTW safety data which are more complete (including exposure and performance indicators) and more detailed (in depth investigation and naturalistic riding studies), as well the optimum exploitation of analysis methods as described in this paper. As PTW safety is a growing global societal problem, the benefits from this approach for future research can be substantial, as these more complete future research results will allow for more targeted and highly efficient countermeasures.

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APPENDIX A

*** Please insert Table A.1 here ***

*** Please insert Table A.2 here ***

*** Please insert Table A.3 here ***

*** Please insert Table A.4 here ***

Country	Mopeds			Motorcycles		
	Mopeds (x 1.000)	Road Fatalities	Fatalities per 10^6 mopeds	Motorcycles (x 1000)	Road Fatalities	Fatalities per 10^6 motorcycles
Austria	319	18	56	393	68	173
Czech Republic	473	4	8	430	95	221
Finland	260	9	35	227	16	70
France	1.121	248	221	1.436	704	490
Germany	2.104	74	35	3.763	635	169
Greece	1.389	36	26	1.499	372	248
Iceland	2	0	0	7	1	143
Israel	19	3	158	94	40	426
Italy	2.550	203	80	6.305	943	150
Japan	7.694	454	59	5.042	564	112
Luxemburg	26	0	0	16	1	63
Netherlands	500	44	88	623	60	96
New Zealand	27	0	0	73	50	685
Poland	922	83	90	1.013	259	256
Slovenia	41	6	146	41	17	415
Spain	2.290	100	44	2.707	386	143
Sweden	201	8	40	303	37	122
Switzerland	165	4	24	651	67	103
United Kingdom	84	10	119	1.182	403	341

Table 1: Number of PTWs, fatalities and fatality rates across European and other countries. Year 2010; Source IRTAD, 2011.

Author(s)	Year	Data						Method of analysis														Contributory risk factors
		questionnaire	simulator	experiment (virtual environment video based, field)	direct observation	interview	police records	correlation tests	descriptive statics	ANOVA, ANCOVA, MANCOVA	factor analysis (PCA, exploratory, confirmatory FA)	cluster analysis	chi square test	discrete choice (logistic, multinomial)	structural modeling analysis	survival analysis	reliability analysis	log-linear	regression (hierarchical, generalized, linear, Poisson etc	in-depth analysis	other	
Cheng et al.	2011	•	•					•		•				•								aggressive driving violations, hazard perceptions
Steg and van Brussel	2009	•									•			•			•					errors, lapses, violations, positive attitudes towards speeding
Yeh and Chang	2009	•														•						age, family motorcycle ownership
Rutter and Quine	1996	•									•		•									age,willingness to break the law and violate the rules
Di Stasi et al.	2011			•						•												training, experience
Chung and Wong	2012	•										•	•									age, gender
Broughton et al.	2009	•											•									type of area, time of day
Wong et al.	2010	•									•				•							sensation seeking, amiability, impatience
Cheng and Ng	2010	•									•					•						past history of accidents
Haque et al.	2010a	•												•				•				past history of accidents, aggression, risk-taking
Elliott et al.	2007	•									•								•			traffic errors, control errors, speed violations, performance of stunts, safety equipment, age, exposure
Mannering and Grodsky	1995	•												•								exposure, riding above the speed limit, passing vehicles on the shoulder or passing between lanes of traffic
Liu et al.	2009		•											•							•	experience
Rosenbloom et al.	2011			•						•												motorcycle licence,past history of accidents
Chorlton et al.	2012	•									•								•			past behaviour, control and behavioural beliefs, attitudes, moral norm, normative belifs, age, self-identity, anticipated regret, training status, engine size
Schwebel et al.	2006	•		•							•								•			sensation seeking, anger-hostility
Özkan	2012	•									•						•					traffic errors, control errors, speed violations, performance of stunts, safety equipment, age, exposure
Chang and Yeh	2007	•										•		•								age, gender, experience, driving skills
Chen	2009	•													•							personality traits, attitudes toward traffic safety
Maestracci et al.	2012	•					•						•									anxiety, conspiquity, ptw lane changing, other users' lane changing, skidding and failure to give way
Elliott	2010	•						•											•			affective attitude, self identity, perceived group norm, group identification, interaction between perceived group norm and group identification
Woodcock	2007				•							•									•	mistakes, violations
Di Stasi et al.	2009	•	•					•		•												risky behaviour, saccadic velocity, subjective mental workload
Dandona et al.	2006					•							•									violations
Rathinam et al.	2007	•												•								experience, learning source of riding, speed, riding frequency and distance, aggressive behaviour, encounter with the police
Chen and Chen	2011	•									•				•							perceived enjoyment, concentration, sensation seeking, experience
Reeder et al.	1996	•											•									licence, convictions, exposure, alcohol
Hosking et al.	2010		•							•												experience, hazard response times
Tunnicliff et al.	2012	•						•											•			theory of planned behavior variables, perceived behavioural control, attitudes, sensation seeking
Brandau et al.	2011	•										•										neuroticism, risking personality, risking driving style, inatention, impulsivity
Creaser et al.	2009			•																	•	alcohol, task demand, time pressure, tolerance
Goldenbeld et al.	2004	•									•						•		•			training, experience
Walton and Buchanan	2012				•				•				•									speed, presence of car at t-intersection, free headway, location

Table A.1: Overview of PTW behaviour in terms of data, method of analysis and contributory risk factors

Author(s)	Year	Data								Method of analysis										Contributory risk factors
		questionnaire	simulator	experiment (video based, picture-based, field	police records	hospital records	national accident database	other database	road site observation	correlation tests	chi square	descriptive statics	ANOVA, ANCOVA, MANCOVA	factor analysis (PCA, exploratory, confirmatory FA)	regression (hierarchical, generalized, linear, Poisson etc.)	discrete choice (logistic, multinomial)	survival analysis	log-linear	in-depth	
Shahar et al.	2011	●											●		●					empathic/perceptual factors, spatial factors
Pai et al.	2009						●									●				type of area, lighting, age, gender
Gershon et al.	2012			●											●					type of area, PTW rider's outfit
Crundall et al.	2008a	●											●	●						gender, experience, negative attitudes, empathic attitudes, awareness of perceptual problems, spatial understanding
Horswill and Helman	2003	●		●					●							●				speed, hazard perception, sensation seeking, attitudes to riding/driving
Li et al.	2009				●	●		●								●	●			type of area, road type, location, speed
Haque et al.	2012				●													●		nightime riding, wet road surface, failure of drivers to notice ptws, failure to judge correctly the speed/distance, stop/waiting vehicles, location, interaction with opposing traffic
Shahar et al.	2010	●	●																	type of vehicle, age, experience, driving/riding skills, mindset
Clarke et al.	2007				●						●	●								age, experience, collision type, ptw type, loss of control, curvature, conspicuity
Crundall et al.	2012			●									●							dual drivers, experience, eye movements
Clabaux et al.	2012						●												●	location, area type
Crundall et al.	2008b	●		●									●							junction, distance, appraisal and perceptual errors
Cavallo and Pinto	2012			●									●							daytime running lights, distance
Gould et al.	2012		●										●							time of day, vehicle type, tri-headlight configuration
Radin Umar et al.	1996				●										●					week of the year, running headlights, fasting in Ramadhan, Balik Kampong culture
Williams and Hoffmann	1979				●							●								collision type, maneuver type, inadequate motorcycle visibililty, conspiquity
Ragot-Court et al.	2012	●									●	●								car driver's behaviour in events/type of driving/detection problems/internal condition
Horswill et al.	2005			●									●							vehicle type, speed, viewing times

Table A.2: Overview of PTW interaction with other motorized traffic in terms of data, method of analysis and contributory risk factors

Author(s)	Year	Data							Method of analysis									Contributory risk factors
		questionnaire	interview	direct observations	police records	national accident database	other databases	hospital data	descriptive statistic	regression (hierarchical, generalized, linear, Poisson etc.)	discrete choice (logistic, multinomial)	ARIMAmodels	survival analysis	chi square	cluster analysis	other	in-depth	
Lin et al.	2003	●														●		age, past crash history, exposure, risk-taking level, alcohol consumption, traffic violations
Preusser et al.	1995				●	●			●									speed, alcohol, collision type
Haque et al.	2010b				●					●								type of intersection, road type, red light cameras, exposure
Teoh	2011				●	●			●									age, speed, alcohol, antilock brake system
Wanvik	2009					●			●									road lighting, weather conditions, road surface conditions
Harrison and Christie	2005	●													●	●		age, gender, riding patterns, exposure, skills
Paulozzi et al.	2005						●			●								gross national income per capita
Law et al.	2009					●				●								per capita GDP, infant mortality rate, medical care, political factors, helmet laws, motorcycles per capita, changes in road infrastructure and vehicle design
Hyatt et al.	2009					●	●					●						gasoline price, age of motorcycle, age of occupants, gender
Harnen et al.	2003						●			●								intersection, approach traffic flow, approach speed, lane width, number of lanes, shoulder width, land use
Moskal et al.	2012				●						●							age, gender, helmet, alcohol, leisure travel, licence
Teoh and Campell	2010				●	●				●	●							ptw type, speed, alcohol, age, gender
Paulozzi	2005				●				●									motorcycle age
Haque et al.	2009				●					●								time of day, wet road surface, location, road type, number of lanes, speed limit, number of occupants, engine capacity, age
Oluwadiyaa et al.	2009		●						●									risky behavior, chaotic traffic, road design faults
Ahlm et al.	2009							●			●					●		alcohol, pharmaceuticals, drugs, day of the week
Houston	2007				●	●				●								helmet laws, age, speed limit, alcohol limit, alcohol consumption, income per capita, motorcycles per capita
Morris	2006				●	●				●								seasonality, climate measures, helmet laws
Ichikawa et al.	2003							●	●									sex, age and occupational, time of crash, helmet act
Supramaniam et al.	1984				●					●								state, year,helmet laws
Kyrychenko and Mc Cartt	2006				●						●							helmet laws, age, gender
Branas and Knudson	2001				●	●				●								helmet laws, population density and temperature
Ouellet and Kasantikul	2006						●		●					●				helmet use
Dee	2009				●	●										●		helmet laws, population,state, time of day
Houston and Richardson	2008				●	●				●								helmet laws, population/density, speed limit, climate measures, per capita alcohol consumption, income per capita, motorcycles per 1000 people, age, education
Huang and Lai	2011				●	●							●					alcohol, age, crashing in fixed object, time of day, curvature, area type
Mayrose	2008				●				●									helmet laws, helmet use, gender, state, age
Kasantikul et al.	2005				●				●					●				alcohol, location, type of collision, gender, error, collision type, curves
French et al.	2009									●								helmet laws, education, speed limit, administrative license revocation
Keall and Newstead	2012					●					●							area of residence, age, protection aids, exposure, vehicle age
Daniello and Gabler	2011				●				●									collision with roadside fixed objects
Schneider IV et al.	2012				●	●					●							age, alcohol, riding without insurance, helmet, education, risk behaviour
Abdul Manan and Várhelyi	2012				●	●			●									area type, road type, age, gender, licence, collision type, helmet, time of day
Xuequn et al.	2011			●							●							helmet, road type, number of passengers, registration status, gender, weather
Bjørnskau et al.	2012	●									●			●				motorcycle type, age, engine size, speed, experience, risky behaviour, unsafe attitudes

Table A.3: Overview of PTW accident frequency/rates in terms of data, method of analysis and contributory risk factors

Author(s)	Year	Data						Method of analysis										Contributory risk factors
		police records	national accident database	hospital data	local and state databases	interview	surveillance data	ordered response (logit, pro etc.)	multinomial	nested logit	logistic regression	poisson regression	log-linear	classification trees	bayesian method	chi square	non parametric tests	
Quddus et al.	2002	●						●										nationality, engine size, time of day, headlight, collisions pedestrians and stationary objects
Yannis et al.	2005	●											●					age, engine size
Pai	2009	●	●								●							age, engine size, collision partner, number of vehicles involved, weather, time of day, day of the week, speed limit, right-of-way violation, motorcycle manoeuvre
Majdzadeh et al.	2008	●				●					●						●	fire, cost of damage, collision type, weather conditions, gender, safety equipment
Zambon and Hasselberg	2006	●		●							●							age, socioeconomic status
Rifaat et al.	2012				●			●										street type, manoeuver type, truck, speed, alcohol
Pai and Saleh	2008a	●	●					●										age, gender, manoeuver type, engize size, exposure, control, number of invovled vehicles, type of collision, time of day, day of the week, month, weather, lighting, road type
Pai and Saleh	2008b	●	●					●										age, gender, engine size, collision type, crash partner, exposure, speed limit, control, lighting, weather, overtaking or changing lanes
Savolainen and Mannering	2007	●							●	●								alcohol, helmet, speed, collision type, roadway characteristics
de Lapparent	2006	●													●			gender, age, collision type, weather, helmet, engine size, time of day, intersection
Shankar and Mannering	1996	●							●									environmental factors, rider attributes, roadway conditions, vehicle characteristics
Montella et al.	2012	●	●											●				collision type, pavement conditions, surface level, weather, intersection, road alignment, curvature, area type, road type
Donate-López et al.	2010	●										●						age, gender, helmet use
Shaheed et al.	2011				●				●									crash type, lighting, failure to yield right-of-way
Langley et al.	2000			●		●					●							engine size, licence
Albalate and Fernández-Villadangos	2010	●						●										gender, speed, road width, alcohol, congestion
Zambon and Hasselberg	2007	●	●								●							alcohol, traffic environment, speed limit, type of crash, area type
Keng	2005	●									●							helmet, vehicle type, age, gender, time of day, area type, speed limit, weather, head/neck injuries
Gabella et al.	1995	●					●				●							helmet, age, alcohol, time of day, motorcycle damage, risky behaviour
Nakahara et al.	2005			●												●		helmet, age, alcohol, time of day

Table A.4: Overview of PTW severity in terms of data, method of analysis and contributory risk factors