Contributed articles

Commentary on Road Safety

Death and Injury in Motorcycle Accidents: The Utilisation of Technology to Reduce Risk.

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Key Findings

- A motorcyclist in the UK has around fifty times the risk of a fatal accident, compared to car driver.
- This relative risk has more than doubled over the past four decades.
- The risk could be substantially reduced by a radical re-design of the motorcycle.
- The greater application of extant technologies can reduce risk.
- The vulnerability of lower limbs, identified eighty years ago, remains.

Abstract

In the early 1970s in Great Britain, the fatality rate for motorcyclists was twenty times that for a car driver, this relative risk has widened to around fifty in modern times. Motorcycling has not become more hazardous, rather a modest decline in the fatality rate over four decades has been eclipsed by a considerably greater reduction in the rate for car drivers. Travel by car has become safer, with seatbelts, a rigid safety cell and crumple zones, airbags, head restraints, energy-absorbing steering wheels, and shatter-resistant windscreens, all contributing to risk reduction. A motorcyclist, conversely, on most modern machines, has none of these features, with the crash helmet being the only safety feature generally adopted by motorcyclists over the last half century. The risk inherent in motorcycling could be reduced to a similar level as car travel by a radical re-design of the motorcycle to include a rigid safety cell, clad in energy absorbing deformable material, coupled with a rider restraint system. Less radical technological changes that could reduce the risk of injury, or death, include fitted anti-lock braking systems, ideally with integrated stability control, and an integral impact-activated airbag may arrest the forward motion of a rider in frontal impact conditions. The relatively simple measure of increased rider and/or machine conspicuousness can reduce the risk of certain accidents.

Keywords

Motorcycle, Fatality, Accident, Airbag, Relative risk, Anti-lock braking.

Introduction

This report assesses how existing technology could be utilised to reduce the death and injury in motorcycle accidents, and thus potentially reduce the large relative risk of death of a motorcyclist, compared to that for a car driver.

Motorcycle riders in Great Britain have around fifty times the death rate in road traffic accidents, compared to car drivers, per mile travelled, based on averaging data over recent years (years 2012 to 2016, Table 1).

The absolute risk for a motorcycle rider has shown a modest reduction of around 60% over the four decades since the 1970s, with 40% of the level of risk in the 1970s persisting to modern times (Table 1). The risk of fatality in an accident for a car driver, however, has dropped *sharply* over this same time period, with the risk reduced by 84%; thus a driver has around one-sixth the risk of death on the roads, compared a driver in the 1970s (Table 1).

Table 1. The relative decline in car driver and motorcyclist fatalities over 40 years.
Annual fatality rates per billion miles; average of five years data for Great Britain.

Years	Car drivers[a,b,c]	Motorcyclists[c,d]
1972–1976	14.0	290
2012–2016	2.26	121

[a]DofT, (1977), Table 4.

[b]DfT, (2017), Table TSGB0701.

[c]DfT, (2017), RAS30013.

[d]Woodward, (1983), Table 2.

The difference in reduction of the absolute risks has led to an increase in the relative risk. Whereas there was around a twenty-fold relative risk of fatality for a motorcyclist, compared to a car driver in the 1970s, this risk has widened to more than a fifty-fold difference in modern times.

Motorcyclists and car drivers, though, have both benefitted, in terms of risk reduction, from general improvements in road safety and emergency treatment over the decades (DfT, 2015a); car drivers, and occupants, have additionally benefitted from improvements in car safety technology, including:

1. Seat belts
2. The use of a rigid passenger cell combined with deformable outer structures – ubiquitous in modern car design
3. Head restraints, shatter-resistant windscreens, deformable internal structures, and airbags.

(CDC, 1999; Sawyer, 2013).

Additionally, a range of Advanced Driver Assistance Systems (ADAS) are being introduced into more recent car designs – technologies such as electronic stability control, intelligent speed adaptation, blind spot detection, and lane keeping warning devices (EC, 2018).

Conversely, there have been no major changes to motorcycle design since the 1970s, a typical modern machine has no restraint system, nor impact-absorbing structures. The only general change, in terms of safety, has been the introduction of mandatory helmet use (1973 in Great Britain; Maartens et al, 2002).

Factors which contribute to the relatively high fatality risk for motorcyclists are discussed, followed by an appraisal of how extant technologies could be utilised to reduce risk.

Aspects of the, now obsolete, BMW C1 motorcycle are reviewed, as this provides an example of a production motorcycle, which addressed, in its design, many of the inherent vulnerabilities of powered two-wheel travel.

Motorcycling: Risk Factors

A range of factors contribute to the relatively high risk of fatal accident and injury involving motorcyclists, including, the visibility of the machine and rider (DfT, 2015b), the ways risk is perceived by riders (Musselwhite, et al., 2010), engine power (Mattsson and Summala, 2010), the role of speed (WHO, 2015), limitations of the modern helmet (Fernandes & Alves de Sousa, 2013), and lower limb vulnerabilities (NHTSA, 2008b).

Relative Lack of Conspicuousness

Motorcyclists are harder to see than larger vehicles such as cars, and motorists can fail to notice them when looking around the road, commonly referred to 'looked but failed to see' (LBFTS) in road safety literature (DfT, 2015b; Pammer et al., 2018). Motorcycle crashes, on account of another vehicle's driver LBFTS, can occur "…because motorcycles do not feature strongly in a typical driver's attentional set for driving." (Pammer et al., 2018, p. 5). In 2013 in Great Britain, an analysis showed that 47 per cent of other motor vehicles involved in accidents had failed to look properly, as well as 16 per cent of motorcyclists (DfT, 2015b).

The Perception of Risk

Although motorcycling is a statistical outlier in terms of risk of fatality, motorcyclists have reported as viewing, in general, their riding as safe; whereas other road users reported perceiving motorcyclists as being at great risk of an accident, in the results of a study of perceptions of road safety amongst a sample of adult road users in the UK (Musselwhite et al., 2010). As with some car drivers, motorcyclists have admitted to taking risks, though regarding these "…as justifiable and calculated, based on experience and conditions of the road" (Musselwhite et al., 2010, p.11). Road user behaviour is viewed to be largely "under the control of the individual" and regarded therefore as "lower risk" (Musselwhite et al., 2010, p. 8). Having control of a vehicle may lead to the *perception* of lower risk, however, fatalities amongst passengers in road accidents on public transport (buses and coaches),

Table 2. Deaths in road traffic accidents: public and personal transport.
Annual total fatalities in Great Britain; average of five years data[a]

Mode of transport	Fatalities
Bus or coach (occupants)	8
Pedal cycle	108
Motorcycle users	336
Car occupants	791

[a]DfT, (2017), RAS30001; data for years 2012–2016.

where the individual has *no control* over the vehicle, are exceptionally rare in Great Britain. There were an average of eight buses or coach occupant fatalities per year during years 2012–2016; average annual fatality data for public transport (buses and coaches), are compared with that for personal transport users (car, motorcycle and pedal cycle), in Table 2.

There were *zero* passenger fatalities due to train accidents in Great Britain in the nine (financial) years up to, and including, 2015/16 (ORR, 2017).

Engine Power

For a given engine capacity, the power of an engine can vary, and engine cubic capacity has been described as a "poor measure of power" (Langley et al., 2000, p. 659). The fatality risk in accidents was found to increase both with the power, and the power-to-weight ratio, of a motorcycle (adjusting for the estimated annual mileage of riders of different powered motorcycles), in a Finnish study, which included data from 117 fatal accidents (Mattsson & Summala, 2010). The pre-accident speed of the most powerful bikes was found to be 20 km/h, or more, over the speed limit in a large proportion of the fatal accidents (Mattsson & Summala, 2010).

Insurance data for the US has indicated that for the category of machine with the highest power-to-weight ratio ('Supersport' motorcycles), death rates per 10,000 registered motorcycles were nearly four times higher than rates for motorcyclists on all other categories of bike (IIHS, 2007).

The authors of the Finnish study had, however, noted that it is not clear whether the increase of fatalities (with both power, and the power-to-weight ratio), found in their study, was related to characteristics of the bikes, or the riding habits of motorcyclists who "choose the most powerful bikes available" (Mattsson and Summala, 2010, p. 87).

Rider Speed

For all road users, as average traffic speed increases, the risk of an accident increases, and in the event of an impact "the risk of death and serious injury is greater at higher speeds, especially for pedestrians, cyclists and motorcyclists." (WHO, p.21). Although there is a particular increased risk for motorcyclists at higher speeds, 33 per cent of the 5286 motorcyclists involved in fatal crashes in the USA in 2016 were considered to have been speeding (racing, driving too fast for conditions, or exceeding the posted speed limit), compared to 19 per cent for passenger car drivers (NHTSA, 2018). An analysis, utilising multivariate risk models, of data from the German In-Depth Accident Study (GIDAS) database for the period 1999–2017, demonstrated a "…strong and significant relationship between relative speed and injury severity in motorcycle crashes…" for helmeted riders (Ding et al., 2019).

Effectiveness, and Limitations, of Modern Helmets

The use of a helmet reduces the risk of death, or head injury, in the event of an accident; data collected in the USA indicates that helmets are about 37 per cent effective in preventing motorcycle deaths (Deutermann, 2004), and 67 per cent effective in preventing brain injuries (NHTSA, 2008a). There were broadly similar findings reported in the results of a Cochrane Collaboration systematic review, based on data from more than one country, helmets reduce the risk of death in crashes by 42 per cent, and head injury by 60 per cent (Lui et al., 2008).

In the USA, helmet law varies from state to state, with survey results indicating that the overall rate of regulatory-approved motorcycle helmet use was 65 per cent in 2016; of the 5286 motorcyclists killed in road traffic accidents in that year, 41 per cent were not helmeted, based on known helmet use (NHTSA, 2018).

Helmet wear was made mandatory for motorcyclists in Great Britain in 1973, however, contrary to what might have been expected, enactment of the Law did not lead to a reduction in total annual motorcycle fatalities in the immediate following years (Evans, 2020, p. 71, Table 3). Total motorcycle mileage increased during this period, and there had been a high level of helmet usage prior to been made mandatory, factors which could account for the increase in fatalities in the late 1970s (Evans, 2020).

Worldwide, although 169 countries (ninety four per cent) have a national law requiring the use of helmets among motorcyclists (WHO, 2015), in many countries there are legal "loopholes" that may limit the effectiveness of legislation, and so "…only 44 countries have laws that apply to all drivers and passengers, all roads and engine types, require the helmet to be fastened, and make reference to a particular helmet standard" (WHO, 2015, p. 26). The 44 countries are "disproportionately high-income countries in the European Region" (WHO, 2015, pp. 26–27); however, "approximately 80% of motorcyclists killed on European roads sustained head impacts and in half of these cases, the head injury was the most serious." (EC, 2020).

Head Injury amongst Helmeted Riders

Head injury, and death from head injury, may still occur in riders wearing helmets that meet a regulatory standard, due to (i) the nature of the impact exceeding the design limits of the helmet, and/or (ii) insecure fitting of the helmet:

(i) Impacts exceeding Design Limits of Helmets

The widely used ECE 22.05 helmet design standard testing includes a drop test with an impact speed of 5.5 – 7.5 m/s (Ghajari et al., 2008). Other standards, such as

BS 6658:1985 (UK), FMVSS 218 (USA), Snell M2005, and AS/NZS 1698, have some variation in the testing specifications, though they all include a drop test onto a flat anvil (Ghajari et al., 2008). Motorcycle helmet manufacturers design the helmets based on the velocity specified in helmet impact energy absorbing tests, in order to meet the required standard (Fernandes & Alves de Sousa, 2013).

Impacts, in reality, occur at a range of velocities, and, as the (kinetic) energy to be absorbed increases with the square of the impact speed (Fuss et al., 2014), the energy at 10.5 m/s will be approximately double that at 7.5 m/s (the maximum ECE anvil test velocity), and at 15 m/s, approximately quadruple. The deformation of a helmet can therefore reach the design limit at higher impact speeds, and an impact may potentially be "…too severe for any wearable helmet" to protect against (Fernandes & Alves de Sousa, 2013, p. 4).

Current motorcycle helmets can thus be considered effective for 'moderate' speed impacts, however at increasing speeds of impact (and therefore impact energy), a limit will be reached where the capacity for deformation (energy absorption) of the helmet material is attained (Fernandes & Alves de Sousa, 2013); the excess of energy (i.e. that not absorbed by the helmet) will be sustained by the rider.

(ii) Insecure Fitting of the Helmet

The Royal Society for the Prevention of Accidents (RoSPA) cited results, in a 2006 motorcycling safety policy paper, from an analysis of reports of fatal accidents; it had been found that the helmet came off in 20 per cent of fatal crashes; 12 per cent before the crash, and 45 per cent during the crash (Lynam et al., 2001, in RoSPA, 2006). It had been noted in the Hurt Report (USA) that if the helmet fits loosely, the crash impact may cause the helmet to rotate and slip off the head, even though the retention system is fastened, and 5.9 per cent of the helmeted riders involved in the accidents analysed, did not have the retention system fastened (Hurt et al., 1981).

Lower Limb Injuries in Motorcycle Accidents

In his first report (BMJ, 1941) of his studies on death and injury amongst motorcyclists involved in accidents, the Australian-born Oxford neurosurgeon Hugh Cairns (1896–1952) reported a greater tendency to lower limb fractures (particularly compound fractures) in motorcycle accidents, compared to other types of accident. With a view to the future, Cairns suggested that if helmets were more widely worn (thus, as he posited, saving lives), the number of "severe" lower limb fractures "requiring prolonged treatment" may increase, and that their prevention "deserves further study" (Cairns, 1941, p. 470). Walpole S. Lewin succeeded Cairns as Consultant Neurosurgeon to the Army (RCS, 2019), and in a 1956 review "Motorcyclists, crash helmets and head injuries" written with [Royal Army Medical Corps] Captain W.F.C Kennedy, suggested that the "invalidism from major leg fractures" may "be lessened by the fitting of leg-protection bars to all machines" (Lewin and Kennedy, 1956).

Since these reports (Cairns, 1941; Lewin and Kennedy, 1956), however, there has been no radical change in the design of most motorcycles in terms of leg protection, and the Royal Society for the Prevention of Accidents have reported that around 80% of motorcyclist casualties suffer leg injuries (RoSPA, 2006). Analysis of US National Trauma Data Bank-National Sample Program (NTDB-NSP) data, from 2003 to 2005, indicated that lower-extremity injuries were the most common injuries sustained by motorcyclists, with fractures of the tibia, fibula, and femur the most prevalent of these injuries (NHTSA, 2008b).

Leg protection, where it exists on a machine, might consist of fairing ('cowling') or crash bars (Haworth & Schulze, 1996). Although protective clothing can reduce the risk of less serious injuries to the lower limbs (Haworth & Schulze, 1996), crash bars are not considered effective - the reduction of injury to the ankle and foot has been found to be balanced by an increase of injury to the leg (Hurt Report, 1981). In an impact situation, as the rider on most machines is not restrained, a rider's leg may not remain in the leg space afforded by the crash bar, or fairing (Haworth & Schulze, 1996).

Reducing the Risk of Death and Injury in Motorcycle Accidents

A radically re-designed motorcycle, such as the now obsolete BMW C1, could potentially provide a level of crash protection approaching that of a small car (BMW Motorrad, 2000).

Assuming, however, motorcycle design continues along existing lines, combined Anti-Lock Braking (ABS) and stability systems, and possibly airbags, have the potential to reduce risk (NTSB, 2018, EC, 2020).

The relatively simple change of increased conspicuousness can reduce the involvement in accidents (Wells et al., 2004), and restricting novice riders to less powerful machines may reduce fatalities (Evans, 2020).

Redesigning the Motorcycle

The great increase in car use has been accompanied by considerable improvements in car safety technology. In the 1960s, cars started to be built with safety features such as head restraints, energy-absorbing steering wheels, shatter-resistant windshields, and safety belts (CDC, 1999). The rigid passenger cell/crumple zone combination, now a standard design feature of cars, was first patented by Mercedes engineer Béla Barényi in 1951; in an accident the vehicle's front and rear structures are designed to deform and progressively absorb the impact energy, reducing the risk that the occupant space (safety cell) is impinged (Sawyer, 2013).

BMW Motorcycles introduced, to commercial sale in 2000, a motorcycle (the BMW C1) that addressed most, if not all, vulnerabilities of those riding powered two-wheel machines. The machine has a roll cage, an energy absorbing crumple zone, seatbelts, and a seat that would prevent the rider from sliding under the lap belt in the event of an accident ('anti-submarining' technology) (BMW Motorrad, 2000). Notably, it was designed to provide sufficient head protection to obviate the need for use of a helmet; furthermore, head *movement* in the event of an impact would be limited by a head restraint structure. The roof and windshield, forming part of the safety cell, provided a certain degree of protection from wind and weather (BMW Motorrad, 2000).

The manufacturer claimed the C1 offered comparable accident protection to a European compact car in head-on collisions (BMW Motorrad, 2000). Frontal (head-on) impact occurred in 78% of the motorcycles involved in two-vehicle crashes in the USA in 2007; with half of all motorcyclist fatalities occurring as a result of two-vehicle crashes (NHTSA, 2008c). Many countries granted BMW's request that C1 riders be exempt from national helmet requirements, however, authorities in the UK (an important market for the company), declined to exempt C1 riders (DeAmicis, 2015).

The overall safety worthiness of the design was acknowledged in a contemporaneous review, though a concern was raised over maintaining balance at very low speed due to the rider restraint and higher centre of gravity (Ash, 2001).The reviewer was critical of the decision to not allow exemption of the rider from the requirement to wear a helmet in the UK: "The C1 was designed to be ridden without a crash helmet, and all the safety data - which shows it is much safer than a conventional scooter - was accrued without helmets." (Ash, 2001).

The machine was relatively expensive, and not a commercial success, and was discontinued after a few years (DeAmicis, 2015).

Anti-lock Braking & Stability Control Systems

Motorcycles are, by their nature, less stable than cars, and it is left to the skill of the rider to remain upright, for example, in situations involving hard braking on corners; excessive braking, with consequent loss of control, has been identified as a significant factor in accidents (Teoh, 2011). The locking-up of a wheel, due to excessive braking, can be avoided on machines fitted with an Anti-lock Braking System (ABS), which is available on some machines since being first utilised on a motorcycle by BMW in 1988 (Teoh, 2011). An analysis of data on fatal accidents involving motorcyclists riding ABS-equipped machines, compared with the same models without ABS, revealed a 37% reduction in fatalities amongst the riders of ABS-equipped bikes (period of analysis 2003–2008; Teoh, 2011).

Antilock braking systems provide maximum stopping capability when a motorcycle is in an upright position, when a rider is leaning into a curve, part of the traction needed for braking is already being used for cornering (NTSB, 2018). Stability control systems that link ABS to the lean angle of the motorcycle, provide the benefit of ABS during braking in an upright position, or while cornering, and thus could reduce single-vehicle crashes that involve loss of control and running wide on a curve (NTSB, 2018). A few motorcycle manufacturers currently offer some form of advanced stability control system, though only on specific models (NTSB, 2018).

Airbags

Airbags have been fitted to cars for over 60 years, and there is overwhelming evidence that they are effective at saving lives and preventing serious injury in car accidents, particularly if used with a well fitted three-point seat belt (Wallis & Greaves, 2002). Injuries due to the deployment of airbags in cars can occur, though most (up to 96%) are comparatively minor (Wallis & Greaves, 2002).

The provision of air bags on motorcycles is more complex than in cars, as the dynamics of a crash are more difficult to predict; early crash tests with airbags on motorcycles indicated that an airbag system could be beneficial in frontal impacts (EU, 2020). In the early 1990s, tests with different types of motorcycle fitted with an airbag, indicated that full restraint was not possible above a speed of 30 mph, though in reducing the speed of a rider trajectory, could still be beneficial (Happian-Smith & Chinn, 1990).

Since 2006, Honda Motorcycles has offered an airbag option on the Honda Goldwing model (EU, 2020), a particularly large and heavy motorcycle, currently offered with a six-cylinder engine with a displacement of 1833cc and with a kerb weight of 383 Kg (Honda UK, 2020). The airbag is positioned in front of the rider and sensors attached on the front forks detect changes in acceleration caused by frontal impacts (EU, 2020); frontal impacts are common in accidents involving a motorcyclist and another vehicle (NHTSA, 2008c).

Speed Moderation: Engine Power Restrictions

Placing restrictions on novice riders, such as the power of machine that can be ridden, can lead to a reduction in fatalities, particularly amongst younger riders. Enactment of the UK Helmet Law (1973) did not lead to a reduction in total fatalities in the immediate following years, in

1978 there were 1163 motorcyclist fatalities, a figure not exceeded in any subsequent year, and two-thirds (772) were young males (Woodward, 1983, in Evans, 2020). Implementation (1982–1983) of legislation restricting the engine size, and power, of learner machines, coupled with a new two-part test and a time-restricted provisional licence, led to a *sharp reduction* in total fatalities (Evans, 2020, p. 72, Table 4). The extent to which the restriction of power and capacity of machine that could be ridden contributed to the reduction, is difficult to assess, as there were confounding, contemporaneous, licence and training changes; however, evidence from elsewhere indicates a correlation between increasing engine power and risk of fatality (Mattsson & Summala, 2010), for all riders.

Highway speed limits can also have a direct effect on the incidence of rider fatalities; in Japan, the raising of the maximum speed limit for motorcycles traveling on national expressways from 80 km/h to 100km/h in year 2000 led a 30% increase in the incidence of serious injury or death in accidents (Sumida, 2002).

Conspicuousness

There is evidence to support the intuitive view that a motorcycle rider is more likely to be noticed by another road user if the motorcyclist is more conspicuous. A large New Zealand study, conducted 1993-1996, involving 463 cases (motorcyclists involved in crashes that led to hospital treatment with a severity score >5, or death), and 1233 randomly selected controls from the same region and time period (Wells et al., 2004). Factors were found to *reduce* the risk of crashes that would involve injury or death:

- Wearing any reflective or fluorescent clothing: Odds Ratio (OR) 0.63, 95% confidence interval (CI) 0.42–0.94
- Use of a white, rather than black, helmet: OR 0.76 (CI: 0.57–0.99)
- Headlight on in daytime: OR 0.73 (CI: 0.53–1.00)

Thus, wearing *any* reflective or fluorescent clothing led to greatest reduction in risk, with the data for having 'headlamp on' or white (versus black) helmet indicating a reduction in risk, although of borderline significance in this study.

Elsewhere, it has been reported that in Europe "motorcyclists who use daytime running lights have a crash rate that is about 10% lower than that of motorcyclists who do not." (EC, 2020).

Conclusions

Motorcycling carries the highest risk of death in an accident, in comparison with any other common form of road transport.

A modern helmet, meeting a regulatory standard, and correctly fitted, reduces substantially the risk of death, and risk of head injury; although the wearing of a helmet is mandatory, a motorcyclist in Britain is around fifty times as likely to be killed in an accident, compared to a car driver over the same distance.

The risk of lower-limb injuries, identified in the 1941 report by Cairns as deserving further study, remains largely unaddressed in current motorcycle design.

Measures, summarised in this review, which could be taken to reduce the toll of death and injury, include

1. the wider fitment to machines of:
    a. Anti-lock Braking Systems (ABS), ideally combined with an electronically-linked stability control system, and
    b. an impact-activated airbag system may arrest the forward motion of the rider in the event of a frontal impact (a relatively common accident scenario).
2. Speed moderation, including restrictions on the power of machines that can be ridden by novice riders (in countries that have not already done so).
3. Increased rider conspicuousness, for example, the use of a dipped headlamp, or daylight lights.

The application of measures (i) to (iii) could reduce the risk to motorcyclists; in order, though, to approach the level of protection afforded by a modern motor car, future designs of motorcycles would have to be redesigned around the impact protection of the rider, and thus have a restraint system, and enclose the rider within a rigid structure, clad in (impact) energy-absorbing deformable structures.

Aspects of the design (roll cage, seatbelts and deformable structures) of the, now obsolete, BMW C1, could provide a starting point for the development of inherently safer machines in the future, and, also potentially address the risk to lower limbs.

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