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PLEASE CITE THE PUBLISHED VERSION

<https://doi.org/10.1016/j.aap.2020.105548>

PUBLISHER

Elsevier

VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

This paper was accepted for publication in the journal Accident Analysis and Prevention and the definitive published version is available at <https://doi.org/10.1016/j.aap.2020.105548>.

LICENCE

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REPOSITORY RECORD

Murphy, Peter, and Andrew Morris. 2020. "Quantifying Accident Risk and Severity Due to Speed from the Reaction Point to the Critical Conflict in Fatal Motorcycle Accidents". Loughborough University.
<https://hdl.handle.net/2134/12156480.v1>.

**Quantifying Accident Risk and Severity due to Speed from the Reaction Point to the
Critical Conflict
in
Fatal Motorcycle Accidents**

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Abstract

In fatal road vehicle accidents motorcycles are overrepresented per vehicle kilometre travelled. Fatal accidents involving motorcycles contain mode specific characteristics, and in common with fatal accidents involving all road users, speed typically presents as a significant contributory factor. The aim of the present study is to provide quantitative estimates for the contribution of speed in situations commencing from the reaction location to the safety critical event involving a motorcyclist and resulting in a fatal accident. The contribution of speed to the resulting accident risk and accident severity is considered from this reaction point. A speed-squared versus stopping distance domain, termed the severity-risk space, is examined to determine the accident measures. The defined accident measures, namely, accident risk, accident severity and accident severity risk are calculated for sixteen fatal accidents from a police dataset of recent UK motorcycle accidents. The estimates of the defined measures are provided in terms relative to values estimated for the

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vehicle travelling at the speed limit at the safety critical event. The relative accident risk in response to a safety critical situation shows a partial speed dependent reaction phase and a speed-squared dependent braking phase and ranges from 1.3 to 2.8. The speed-squared dependent accident severity measure ranges from 1.4 to 7.3 at pre-impact speeds. The relative accident severity risk shows speed squared to speed cubed dependency components during the reaction phase and a speed to the power of four dependent braking phase and ranges from 2.3 to 22.8. In eight cases the collision would have been avoided had the motorcyclist been travelling at the speed limit at the critical point and in the other eight cases the relative accident severity at impact ranged from 1.4 to 17.2. The speed-squared versus stopping distance domain provides an informative parameter space for considering the accident risk and accident severity dimensions of road user accidents.

Keywords

motorcycle accident, speed, kinetic energy, stopping distance, accident risk, accident severity

1. Introduction

Road safety remains a major societal issue within the European Union. In 2016 25,600 people died on the roads in Europe (ERSO Report, 2018). Road fatalities have generally been falling within the EU in recent times, although there are variations between Member States. Over the past 25 years, most Member States have achieved an overall reduction, some more than 50% (Morris et al., 2018). During this period, research on road safety and accident prevention has predominantly focused on protecting car occupants, with significant results. However, at the

same time the number of fatalities and injuries amongst other categories of road users has not fallen to the same extent, indeed, in some cases, they have risen. Vulnerable road users (VRUs) are a priority and represent a real challenge for researchers working on accident prevention. Accidents involving VRUs comprised approximately 48% of all fatalities in the EU during 2016, with motorcyclists comprising 14% of all fatalities (3644 fatalities, ERSO Report, 2018). Motorcycle accidents with fatal outcomes are the focus of the present study.

Motorcycles are appealing to road users for a variety of reasons and their use has continued to increase over the years. One of the reasons for their appeal, in terms of mobility, is their compact size which permits them to park in small spaces. Their size also aids motorcycle riders to easily move in and out of traffic. Motorcycles have low mass and aerodynamic drag compared to cars, involve low CO₂ emissions, and are therefore a fuel efficient modal choice. They are attractive for leisure trips and many returning or new users with disposable income are (re-)discovering this activity (Stutts, et al., 2004; Dischinger, et al. 2006).

However, there are disadvantages; e.g. they move in traffic environments (including high speed limit environments) predominately populated with larger mass vehicles without the protective structure and devices of car drivers. Having two wheels means that motorcycle riders can lose control more easily than car users; control can be lost due to uneven road surfaces, an object in the road or inadequately placed street furniture (Van Elslande and Elvik, 2012). Therefore, motorcycle riders are very vulnerable road users and road accidents involving injuries to them remain a major concern. It is recognised that a concerted effort is required to understand and further improve the safety of motorcyclists (e.g. Morris et al., 2018; <https://safe2wheelers.eu>).

At present, the fatality, serious, and slight, injury risks for motorcyclists are far above the same risks for car users (Nazemetz et al., 2019; MAIDS, 2007; Silla et al., 2018; McCarthy et al., 2005; ERSO Report, 2018). The US study by Nazemetz et al., 2019 reports that motorcycle accident fatalities more than doubled from approximately two thousand per annum in 1996 to about four

and a half thousand per annum in the US in 2014. While during the same time period all traffic fatalities fell from forty thousand to the low thirty thousands per annum. The European report (MAIDS, 2004) involved the collection of motorcycle accident data for five European countries; France, Spain, Germany, Italy and the Netherlands and highlights main accident configurations such as intersections (35% of accidents). The UK study by McCarthy et al. (2005) reports that motorcycle accidents include ‘right of way’ accidents, accidents involving loss of control on bends, and accidents caused by motorcyclists using the more frequent overtaking and passing opportunities. Following up on these studies which identify high risk situations for motorcyclists the present study examines the effect of speed on outcome once these safety critical encounters involving a motorcycle have taken place.

Many studies underline the relationship between speed and road accidents, highlighting issues such as the individual casualty risk of travelling at a certain speed (Kloeden et al., 2002) to accident sensitivity to speed limit changes (Nilsson, 2004; Elvik et al., 2004). These authors indicate that physical principles underlie the speed dependencies observed in their controlled data analyses and resulting models. Nilsson (2004), in describing the power law model relating speed and accident risk and severity refers to the importance of kinetic energy, energy of impact and stopping distance are referred to in Kloeden et al. (2002), and kinetic energy is considered in Elvik et al. (2004) and estimates of stopping distances for different speeds are also provided to compare accident risk. The consequence of speed in an accident has been quantified in terms of vehicle damage energy (e.g. Campbell, 1974; Vangi, 2009); specifically for motorcycles in Vangi and Cialdai (2014), and in powered-two-wheeler/car accident reconstruction in Pierini (2016). Numerous studies also relate speed and injury risk (e.g. Mackay, 2007; Otte et al., 2012; Wisch et al., 2017) and in the context of motorcycle accidents relative speed has been shown to correlate well with injury (Otte et al., 2006; Dinga et al., 2019).

In the present study the contribution of speed in situations, commencing from the reaction location to the safety critical event involving a motorcyclist and resulting in a fatal accident, is considered. The effect of speed on defined accident risk and severity is examined. From the reaction point accident risk is quantified in terms of stopping distance and accident severity is quantified in terms of speed squared. A novel display/parameter space is introduced indicating the variation of speed-squared versus stopping distance from the reaction point to the rest position of the vehicle following braking. The vertical axis represents accident severity (proportional to speed-squared) and the horizontal axis represents accident risk (proportional to stopping distance). The integral of the speed-squared versus stopping distance graph (the area under the speed-squared line is shown to represent overall severity risk – the accident risk weighted by the severity of accident. The methodology allows the accident risk and accident severity dimensions to be analysed and quantified in a direct and unified manner.

2. Material and methods

A police database of fifty-one powered two-wheeler (motorcycles and mopeds) accidents which took place between 2010 and 2016 in the West Midlands, UK, is examined. The UK police force completes a collision investigation report for every road traffic accident that involves fatal or life-changing consequences. A formal collision investigation is typically undertaken by a highly trained collision investigator and a subsequent report is completed. Each report includes detailed information regarding the collision location, the circumstances surrounding the collision, witness statements, vehicle defects and contributory factors which lead to the accident taking place. The police also carry out a series of tests in order to determine the main causes of the accident and which party is believed to be at fault. From the dataset of fifty-one accidents sixteen cases (all involving a motorcycle) are available where the pre-impact vehicle speeds could reasonably be

estimated using a variety of methods (other than through witness statements) for accidents involving motorcyclists and fatal outcomes; these are the data selected for further analysis.

The sixteen cases with fatal outcomes and estimated speed data comprise a variety of accident configurations summarised in the list below. In all but one accident a motorcyclist was killed. In one case (case 14) a pillion passenger only was fatally injured and, in another case (case 9), a pillion passenger and motorcyclist were fatally injured. The main accident configurations are illustrated in Fig. 1 with accompanying summary descriptions of the configurations provided in Table 1. Each of the sixteen accidents is indexed according to the descriptions in Table 1.

1. Car moves from lane 2 to lane 3. Motorcycle moves rapidly (above the speed limit) from lanes 1 to 2 to 3. Vehicles simultaneously move into lane 3 resulting in a collision. (Oth – motorcycle weaving in traffic)
2. Car intends to turn right from side road into main road, edging out slowly, motorcycle coming from left brakes heavily and loses control, impacting kerb, sliding along pavement into tree. No actual contact between vehicles. (T11, Oth – loss of control, off roadway to left)
3. The car turns right out of side road into path of motorcycle approaching from the right. Motorcycle moving above speed limit. Car stopped while other vehicles pass. Motorcycle travels 2.7 seconds behind another vehicle prior to collision. (Oth - Opponent vehicle turning to the right, crossing the [straight] motorcycle path. Motorcycle is travelling straight, coming from the right side of the opponent vehicle.)
4. Car in filter lane, turns right into side road, impacted by motorcycle travelling above speed limit in the opposite direction. (T8)
5. Van stationary at T junction, intending to turn right out of side road onto main road. Van commences turn, collides with motorcycle coming (above the speed limit) from

the right. Motorcycle attempted emergency braking, was upright when colliding with van. (Oth - Opponent vehicle turning to the right, crossing the [straight] motorcycle path. Motorcycle is travelling straight, coming from the right side of the opponent vehicle.)

6. Motorcycle loses control navigating a left-hand bend (travelling above the speed limit), collides head on with slowed car travelling in the opposite direction. Skid marks start at centreline and move to opposing carriageway. (LoCC, Oth – head on collision)

7. Car turns right into driveway across path of motorcycle. Motorcycle travelling above speed limit attempts emergency braking. Motorcycle falls to side and motorcycle and rider slide along carriageway into kerb then car. (T8, Oth – loss of control on roadway)

8. Motorcycle travelling above the speed limit towards junction (along the 'stick' of the T) when the rider loses control, motorcycle slides across the junction and collides with the opposite kerb. No other vehicle. (Oth – missed intersection/end of road, Oth – loss of control on roadway)

9. Other vehicle turning right into side road, motorcyclist travelling in opposite direction. Motorcyclist emergency brakes, skids and slides into the other vehicle. Rider and pillion passenger thrown from motorcycle. (T8)

10. Motorcycle approaches crossroads intending to turn right, waits for light to turn green. Car travelling (above the speed limit) in opposite direction intending to go straight on approaches junction when lights have turned green, goes through without slowing. When lights turned motorcycle had started to turn right, across path of car. (T8)

11. Car turning right into side junction, impacted by motorcycle travelling (above the speed limit) in the opposite direction. Motorcycle overtaking cars. (T8)

12. Car turning right into premises, struck on offside by motorcycle that was overtaking it. Motorcycle travelling above the speed limit. (Oth - Opponent vehicle turning to the right, crossing the [straight] motorcycle path. Motorcycle is travelling straight in the same direction as the heading of the opponent vehicle and overtaking it.)
13. Car turns right out of side road (performing a U-turn using the side street) into path of motorcycle travelling above the speed limit along the carriageway. Car stationary in side road before pulling out. (Oth – manoeuvring - opponent vehicle is U-turning from the right to the left at side street/carriageway intersection. Motorcycle traveling from right on carriageway)
14. Motorcycle accelerates and pillion passenger falls. No other vehicle. (Oth - fall from moving vehicle)
15. Car turned right across the path of a motorcycle. Motorcycle collides with the nearside of the vehicle. Poor weather conditions. Motorcycle moving above the speed limit, car turns across the path of the motorcycle at close range. (T8)
16. The motorcycle travels straight ahead. The car travels in the opposite direction, and makes a right turn manoeuvre. As the car performed this manoeuvre, the rider of the motorcycle applies the brakes and induces a skid. The motorcycle falls to its nearside and slides along the road, before colliding with the front of the car. The rider is thrown clear, colliding with street furniture. (T8, Oth – loss of control on roadway – straight road)

Fig. 1 Accident configuration for motorcycle and opponent vehicle (Morris et al., 2018)

C1	<ul style="list-style-type: none"> Motorcycle travelling straight Opponent vehicle crossing the motorcycle path from the right side
C2	<ul style="list-style-type: none"> Motorcycle travelling straight Opponent vehicle crossing the Motorcycle path from the left side
T5	<ul style="list-style-type: none"> Motorcycle turning to the left, crossing the (straight) opponent vehicle path Opponent vehicle is travelling straight in the same direction as the heading of the motorcycle before turning
T7	<ul style="list-style-type: none"> Opponent vehicle turning to the left, crossing the (straight) motorcycle path Motorcycle coming from the opposite direction, travelling straight
T8	<ul style="list-style-type: none"> Opponent vehicle turning to the right, crossing the (straight) motorcycle path Motorcycle coming from the opposite direction, travelling straight
T10	<ul style="list-style-type: none"> Opponent vehicle turning to the left, crossing the (straight) motorcycle path Motorcycle is travelling straight, coming from the left side of the opponent vehicle
T11	<ul style="list-style-type: none"> Opponent vehicle turning to the right, crossing the (straight) motorcycle path Motorcycle is travelling straight, coming from the left side of the opponent vehicle
T13	<ul style="list-style-type: none"> Opponent vehicle turning to the left, crossing the (straight) motorcycle path Motorcycle is travelling straight in the same direction as the heading of the opponent vehicle before turning
L1	<ul style="list-style-type: none"> Opponent vehicle and Motorcycle travelling in the same direction Motorcycle is travelling straight and hit by the opponent vehicle (going straight) from the rear
L2	<ul style="list-style-type: none"> Opponent vehicle and Motorcycle travelling in the same direction Opponent vehicle is swerving to the left in front of the Motorcycle and hit by the motorcycle
L6	<ul style="list-style-type: none"> Opponent vehicle and motorcycle travelling in the same direction Motorcycle is travelling straight and hit by the opponent vehicle (turning left) from the rear
L7	<ul style="list-style-type: none"> Opponent vehicle and motorcycle travelling in the same direction Opponent vehicle is swerving to the right in front of the Motorcycle and hit by the motorcycle
L8	<ul style="list-style-type: none"> Opponent vehicle and motorcycle travelling in the same direction Opponent vehicle is u-turning from the right to the left in front of the Motorcycle and hit by the motorcycle
LoCC	<ul style="list-style-type: none"> The driver of the motorcycle loses the control of his vehicle, in a curve, and crashes into an opponent vehicle

Oth	• All other scenarios that are not covered by any of the previously described scenarios.
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Table 1 Summary descriptions of accident configurations (adapted from Morris et al., 2018)

2.1 Parameter Estimation

The key parameters estimated are friction coefficients, vehicle stopping distance and pre-impact speed and distance to collision. The road/tyre friction coefficients are estimated using dedicated accelerometer equipment during re-enactments/tests performed under emergency braking. Friction coefficients for the road/motorcycle on its side during sliding are also estimated through re-enactment testing and/or through comparison with values stated in the literature for a particular motorcycle model. The stopping distance is comprised of the distance travelled during the braking response time to an incident and the braking distance, and/or sliding distance, if present. The braking and sliding distances, are estimated from the tyre and slide (motorcycle on its side, and/or motorcyclist clothing) marks on the road, respectively. The braking response distances are estimated taking into consideration results from recent studies (Jurecki and Stańczyk, 2009; Jurecki and Stańczyk, 2014). The distance to collision (d_{tc}) is the distance from the reaction point to the safety critical incident to the impact point. It is typically estimated through calculating the braking distances up to impact and calculating the reaction distance (d_r) at the estimated speed. The d_{tc} is then the sum of the braking distance up to impact and the reaction distance. The d_{tc} can be different if the unexpected event occurs at a location other than the eventual impact location e.g. a car edging out from an intersection initiates an emergency response on the behalf of the motorcyclist. In this case the d_{tc} is the distance from the reaction point (which is located by working back from the beginning of the braking skid mark) to the intersection. As motorcycle crashes have particular characteristics pre-impact speed may be estimated via a variety of methods. Speed estimates are obtained from

- (i) Closed circuit television (CCTV) security camera evidence,
- (ii) tyre marks due to braking,
- (iii) motorcycle slide marks, (Hague, 2004)
- (iv) motorcyclist slide marks, and
- (v) pedestrian throw calculations (Otte, 2004; Searle and Searle, 1983).

Analysis of vehicle damage can also be informative regarding pre-impact speeds but is more challenging than speed estimation for car to car impacts due to the typically large mass ratio between a motorcycle and other vehicle and the resulting collision dynamics which may redistribute the incoming translational kinetic energy into translational, rotational and projectile components in addition to vehicle damage. Pre-impact speeds are not estimated via damage analysis (as per the method of Vangi and Cialdi, 2016, for example, because the speeds/damage is typically too great) but the damage is recorded in detail in the form of photographic evidence and noted together with other corroborative evidence such as witness statements, when estimating speed.

2.1.1 Closed Circuit television CCTV security camera

The motorcycle travels past two reference positions (where the distance between the two reference positions is measured at the scene) between (in this case) the recorded times of 15 s and 17 s. The motorcycle travels the reference distance in 21 frames of the CCTV footage as illustrated below; counting the number of frames provides an estimate of the time taken (t_{est}) to travel the distance d_{ref} between two reference points, e.g. in Fig. 2 $t_{est} = 21 \text{ frames} / 25 \text{ frames/s} = 0.84 \text{ seconds}$.

$$d_{ref} = \text{position 2} - \text{position 1} = 45.4 \text{ m} - 27.9 \text{ m} = 17.5 \text{ m}$$

$$v_{est} = d_{ref} / t_{est} = 17.5 \text{ m} / 0.84 \text{ s} = 20.8 \text{ m/s} \text{ (63 km/h, 39.4 mph)}$$

Fig. 2 Speed estimation using closed circuit television (CCTV) security camera

2.1.2 Tyre Marks

For a motorcycle skidding to a stop under steady braking (constant negative acceleration)

$$v_d^2 = v_0^2 - 2\mu g d \quad (1)$$

v_0 = initial speed

v_d = speed at distance d

μ = coefficient of friction

g = acceleration due to gravity

the final velocity (v_{df}) is zero;

$$v_{df}^2 = v_0^2 - 2\mu g d \quad (2)$$

Re-arranging Eq. (1) for (v_0) gives:

$$v_0 = \sqrt{2\mu_{skidding} g d} \quad (3)$$

2.1.3 Motorcycle slide marks

$$v_0 = \sqrt{2\mu_{sliding}gd} \quad (4)$$

2.1.4 Pillion passenger slide

A method for estimating the speed at which a pillion passenger strikes the road when falling off a motorcycle (as the motorcycle accelerates forward), is derived from a pedestrian slide calculation. The estimation is based upon the vertical distance from where the pillion passenger falls from the rear of the motorcycle to the road surface, and the horizontal distance he or she slides along the road surface to a stop (Hague, 2004).

$$v_0 = \sqrt{2\mu_pgd} + \mu_p\sqrt{2gh} \quad (5)$$

where: v_0 = initial velocity that the pillion passenger strikes the ground

μ_p = coefficient of friction applicable to the pillion passenger

h = height of centre of gravity that pillion passenger falls from

and d = pillion passenger slide displacement

2.1.5 Motorcycle Throw Distance (Searle and Searle, 1983)

d_{th} = motorcyclist throw displacement

$$v_{\max} = \sqrt{v^2 + 2\mu gd_{th}} \quad (6)$$

In the cases examined the speed is estimated by one or more of the various methods above adapted to the specific conditions e.g. friction coefficient for a faired/unfaired motorcycle, gradient etc. The multiple methodologies occasionally revealed valuable additional information e.g. CCTV security camera showing braking lights on over a section of road before tyre skid marks are produced. The methods are combined to provide the most accurate estimates of the speed at the reaction point to the safety critical event.

2.2 Method

The method used follows from the theory given in section 3 and is summarized presently. Stopping distances are estimated based on the pre- incident speed and ignoring the collision position (if any) – i.e. from the reaction point to the safety critical incident to the position the motorcycle would stop if the speed is brought to zero through braking and/or sliding. The stopping distances for the accidents are compared with the stopping distances that would have occurred if the motorcycle was travelling at the speed limit. The stopping distance comparison is considered in the context of the accident risk dimension – the greater the stopping distance (with its starting point measured from the reaction location) the greater the likelihood of an accident occurring. The speed estimate is squared providing a representation of the kinetic energy prior to impact and this is used as an indicator of severity of impact. These estimates are compared to the speed limit squared values which give an indication of the severity of impact if the collision occurred when the motorcycle is travelling at the speed limit. The estimated speed squared values are plotted versus the stopping distances. The area under the curve represents the severity risk (i.e. the sum or integral of the chances of an accident occurring at a given distance from the reaction location multiplied by the severity estimate at that distance). The speed limit values squared are also plotted versus their stopping distances. The area under this curve represents the

severity risk (i.e. the sum or integral of the chances of an accident occurring at a given instance multiplied by the severity estimate for that instance) if the motorcycle is travelling at the speed limit when the incident response is initiated. Relative severity risks are obtained by calculating the ratio of the areas of the accident estimates to the speed limit estimates.

Case Number	Estimated Speed, v mph, km/h Method	Speed Limit, v_L mph, km/h, m/s	Friction Coefficient μ (N/m)	Measured Braking Distance (d_b) Motorcycle Sliding Distance (d_{sl}) and Throw Distance (d_{th}) (m)	Braking Distance (d_b) at Speed Limit (m)
1	47, 75.2 20.9 CCTV camera	40, 64 17.8	0.80 ABS (not used) 0.79 grass/clothing	30.0 d_{th}	n/a
2	47, 75.2 20.9 tyre and motorcycle body marks	30, 48 13.3	0.68 non-ABS 0.35 faired motorcycle sliding	26.4 d_b 11.9 d_{sl} Total distance from beginning of braking to collision with tree 50.7 m	13.3
3	50, 80 22.4 CCTV camera	30, 48 13.3	0.74 de-activated ABS for test	1.5 d_b	12.
4	81, 129.6 36 CCTV camera	40, 64 17.8	estimated as 0.76 de-activated ABS for test	24.1 d_b	21.2
5	55, 88 24.4 tyre marks	30, 48 13.3	0.81	37.7 d_b	11.1
6	56, 89.6 24.9 CCTV camera	30, 48 13.3	0.68 0.35 fully faired motorcycle sliding	10.0 d_b 22.5 d_{sl}	13.3
7	70, 112 31.1 tyre and motorcycle body marks	30, 48 13.3	0.69 0.36 sliding	15 d_b 17.5 d_{sl}	13.1
8	50, 80 22.2 tyre marks	30, 48 13.3	0.77	19.6 d_b 7 d_{sl}	11.7
9	45, 72 20 CCTV camera	30, 48 13.3	0.79	12.9 d_b	11.5
10	50, 80 22.2 (car) CCTV slide marks	30, 48 13.3	0.75 car 0.39 sliding	30.8 d_{th} 45 d_{sl}	n/a
11	80, 128 35.8 CCTV camera	30, 48 13.3	0.74 0.30 sliding	3.8 d_b gap 4.2 25.0 d_{sl}	12.2

12	60, 96 26.7 CCTV camera re-enactment	30, 48 13.3	0.75	1.6 d_b	12.0
13	min. 42, 67.2 18.7 slide displacement	30, 48 13.3	0.84	17.8 d_b gap 6.8 (to impact)	10.7
14	66, 105.6 29.5 slide displacement	30, 48 13.3	0.66 coarse tarmac/nylon clothing	54.6*	n/a
15	45, 72 20 tyre marks	30, 48 13.3	0.79	25.7 d_b	11.5 d_b
16	36, 57.6 16.1 tyre marks and slide displacement	20, 32 8.89	0.73 0.27 sliding	7.2 d_b gap 3.7 14.0 d_{sl}	5.5 d_b

Table 2 speed and distance estimates: friction coefficients and distances *distance of pedestrian slide (pillion passenger fall)
(n/a – not applicable)

3 Theory

As a guide to safe road use the Highway Code - UK, 2017 provides a set of typical stopping distances similar to the stopping distances shown as a function of designated speed limits (20, 30, 40, 50, 60 and 70 mph) in Fig. 3. The stopping distance comprises the distance travelled during the braking reaction time and the braking distance.

Fig. 3 Motorcyclist stopping distances at the designated UK speed limits of 20, 30, 40, 50, 60 and 70 mph (32, 48, 64, 80, 96 and 112 km/h in m/s of 8.9, 13.3, 17.8, 22.2, 26.7 and 30.1)

A commonly employed temporal metric for assessing collision risk is *time to collision*, *ttc* - the time required for two vehicles to collide if they continue at their present speed and on the same path (Hou et al., 2014). Comprehensive studies (Jurecki and Stańczyk, 2009; Jurecki and Stańczyk, 2014) show that the braking response time can be written in terms of the *ttc* as

$$t_r = 0.4 \times ttc + 0.3 \quad (7)$$

t_r = reaction time, ttc = time to collision

The expression is also consistent with recent findings from a naturalistic study (Markkula et al., 2016) indicating that cognitive load comprises a base processing component and a component dependent on the urgency of the impending critical situation. The immediacy of the situation is determined via visual looming which can be related to *ttc* (Lee, 1976).

The reaction distance (dark gray) in Fig. 3 depends on the *ttc* [Eq. (1)] and the speed as follows:

$$d_r = v \times t_r \quad (8)$$

$$= v \times (0.4 \times ttc + 0.3)$$

$$= v \times (0.4 \times \frac{d_{tc}}{v} + 0.3)$$

$$= 0.4d_{tc} + 0.3v \quad (9)$$

For the purpose of the graph the reaction time (to an emergency situation/traffic event) is estimated at 0.7s ($t_r = 0.4 \times ttc + 0.3$) with a constant $ttc = 1$ s ($= \frac{d_{tc}}{v}$), so the distance to the safety critical event increases linearly in direct proportion to the speed.

e.g. A motorcyclist travelling at 20 mph encounters a conflict situation that necessitates emergency braking

The speed in SI units (m/s) is

$$1 \text{ mph} \rightarrow \frac{1.6 \text{ km}}{1 \text{ h}} \rightarrow \frac{1.6}{3600} \times \frac{1000 \text{ m}}{1 \text{ s}} \rightarrow 0.444 \frac{\text{m}}{\text{s}}$$

$$\text{initial speed } v_0 = 20 \text{ mph} \rightarrow 20 \times 0.444 \frac{\text{m}}{\text{s}} = 8.9 \frac{\text{m}}{\text{s}}$$

The reaction distance (d_r) is

$$d_r = v_0 \times t_r = 8.9 \frac{\text{m}}{\text{s}} \times 0.7 \text{ s} = 6.2 \text{ m}$$

This is indicated in dark gray in the bottom panel of Fig. 3.

The kinematic equation relating speed under constant negative acceleration due to braking is

$$v^2 = v_0^2 - 2\mu g d \quad (10)$$

where d = distance travelled under constant braking from initial point of braking, v = speed at distance d , v_0 = initial speed, μ = tyre-road surface friction coefficient, g = acceleration due to gravity

As the distance travelled under constant negative acceleration (uniform braking) increases linearly (i.e. as d increases linearly) speed-squared ($v_0^2 - v^2$) decreases linearly from an initial value of v_0^2 .

Rearranging Eq. (2) in term of distance from the initial point of braking, d gives

$$d = (v_0^2 - v^2)/2\mu g \quad (11)$$

From Eq. (3) it can be seen, if the (initial) speed (v_0) is doubled, the braking distance increases four-fold in bringing the vehicle to rest ($v = 0$).

e.g. A motorcyclist travelling at 20 mph commences full emergency braking

The braking distance (i.e. the distance moved through in reducing the speed from an initial value $v_0 = 8.9$ m/s to a final value $v = 0$ under constant negative acceleration due to braking is, from Eq. (3),

$$d = [(8.9)^2 - 0^2]/(2 \times 0.76 \times 9.81) = 5.3 \text{ m}$$

This is indicated in light gray in the bottom panel of Fig. 3.

e.g. A motorcyclist travelling at 40 mph commences full emergency braking

The braking distance is

$$d = [(17.8)^2 - 0^2]/(2 \times 0.76 \times 9.81) = 21.2 \text{ m}$$

This is indicated in light gray in the panel third from bottom of Fig. 3.

In the event of a conflict that initiates a full braking response the likelihood of collision is proportional to the stopping distance (which is comprised of the speed dependent reaction distance and the speed-squared dependent braking distance as illustrated in Fig. 3). Therefore, stopping distance is interpreted in terms of the accident risk dimension. The arrow at the bottom of Fig. 3 signifies the location of an unexpected event e.g. a car turning across the path of the motorcyclist at close range. If the motorcyclist is travelling at 20 mph at the reaction point the collision is avoided (the vertical line with the arrow does not pass through the stopping distance indicated for 20 mph – bottom panel). If the motorcyclist's speed is 40 mph a collision occurs (the line with the arrow intersects the stopping distance shown for 40 mph – third panel from bottom). Because an unexpected event can occur at any location beyond the reaction point the relative likelihood of a collision occurring is dependent on the ratio of the stopping distances between the two speeds. The stopping distances themselves change slightly if the distance to the unexpected event changes as the *ttc* changes.

Eq. (10) can also be interpreted in terms of the magnitude of impact should a collision occur. Multiplying eqn.10 by $\frac{1}{2} m$ and rearranging speeds on the left-hand side gives the work-kinetic energy theorem [Eq. (12)]

$$\frac{1}{2}mv_0^2 - \frac{1}{2}mv^2 = m\mu g d \quad (12)$$

from which the kinetic energy ($\frac{1}{2} \times \text{mass} \times \text{speed-squared}$) is specified as a function of braking distance

$$\Delta K = K_i - K(d) = W_f \quad (13)$$

The change in kinetic energy (ΔK) = initial kinetic energy (K_i) minus the kinetic energy at distance d = work done by the frictional force W_f in reducing the speed from v_0 to v .

As speed-squared is directly related to the kinetic energy, which is indicative of the magnitude of impact, it (i.e. speed-squared) is considered in terms of the severity dimension (vertical axis, Fig. 4). Speed-squared is constant throughout the reaction distance and decreases linearly with braking. The arrow in Fig. 4 indicates the location of the unexpected event (the same event as in Fig. 3). The x -axis of Fig. 3 contains the same information as Fig. 2; at 20 mph (bottom panel – panel 1) a collision does not occur but at 40 mph a collision does occur – following a line vertically upwards from the arrow – it does not intersect panel one but does intersect panel 3. Additionally, in this representation following the line vertically upwards from the arrow it intersects panel 3 (Fig. 4) during the linearly decreasing section. The speed-squared value at this intersection can then be read from the vertical axis, giving an indication of kinetic energy and hence severity of impact. The relative severity at a different speed is determined by comparing its speed-squared value at its point of intersection with the vertical line.

Speed Squared (m^2/s^2) versus Stopping Distance (m) at the Designated Speed Limits (m/s)

Fig. 4 Speed-squared versus braking distance d_b at the designated UK speed limits of 20, 30, 40, 50, 60 and 70 mph (32, 48, 64, 80, 96 and 112 km/h in m/s of 8.9, 13.3, 17.8, 22.2, 26.7 and 30.1)

In summary, Fig. 3 or correspondingly the x -axis of Fig. 4 can be used to determine the relative likelihood of a collision occurring at different speeds. Additionally, the vertical axis of Fig. 4 can be used to indicate the severity dimension of impact should a collision occur. Through combining these two dimensions the concept of severity risk is introduced. This is the likelihood of a collision occurring at a given braking distance weighted by the magnitude of the impact should a collision occur at that point. The accident severity risk (ASR) can be estimated from the area under the curve of the speed-squared versus stopping distance graph. It is the sum of the products of severity (the speed-squared magnitude indicated on the vertical-axis) at each location [i.e. $v_0^2(d) - v^2(d)$] multiplied by a measure which is an indicator of the risk of accident – (the stopping distance) at that point (d). The relative accident severity risk (RASR) is the ratio between the areas of speed-squared versus stopping distance for the two different initial speeds. The two

particular speeds of interest are the estimated speed at the estimated reaction location and the speed limit at this location.

3.1 Calculation

The following parameters are initially estimated for the critical traffic safety incident:

- (i) Braking distance up to impact (d_{bi}), gap, commencement of sliding or coming to a stop
- (ii) Distance to collision (d_{tc})
- (iii) Reaction distance (d_r)
- (iv) Total stopping distance (d_s) from reaction point to coming to a stop (ignoring impact)
- (v) Speed squared at each distance d during reaction and braking distance phases
- (vi) Estimates for (i), (iii), (iv), and (v) at the speed limit keeping the d_{tc} constant

And the following final comparison and estimates are made:

- (vii) Compare stopping distance at estimated speed, d_s , stopping distance at the speed limit, d_{sL} with d_{tc} . (When estimating the stopping distance at the speed limit sliding is assumed not to have occurred.)
- (viii) Compare v_i^2 , $v_{L,i}^2$
- (ix) Estimate RAR = stopping distance at estimated speed divided by the stopping distance at the speed limit
- (x) Estimate RAS = estimated speed squared divided by the speed limit squared

- (xi) Estimate ASR = area under the estimated speed-squared versus stopping distance graph
- (xii) Repeat ASR estimate at the speed limit
- (xiii) Estimate RASR = area under the estimated speed-squared versus stopping distance graph divided by the area under the speed limit-squared versus stopping distance graph

A sample calculation illustrates the technique; in this case the motorcycle is travelling straight ahead (green arrow) from the right in the figure and has right of way (ROW) and a car (blue arrow) is making a right turn across the carriageway, to travel in the opposite direction (Fig. 5).

Fig. 5 Accident configuration: Car turning right (blue arrow) and motorcycle going straight ahead (green arrow)

The movement of the road users (manoeuvre of the car, travel of the motorcycle) occurs in a timeframe which gives rise to a critical road safety conflict initiating an emergency braking response on behalf of the motorcyclist. The motorcyclist's pre-braking speed (v_0) is estimated via CCTV at 75 km/h (47 mph, 20.9 m/s). His braking distance from initiation of braking up to impact with the car is measured from the tyre skid marks on the road to be $d_{bi} = 7.5$ m. The impact speed is estimated from Eq. (1) as

$$v_i = \sqrt{v_0^2 - 2\mu_{skidding}gd_{bi}} = \sqrt{20.9^2 - 2(0.68)(9.81)(7.5)}$$

$$= 18.4 \text{ m/s}$$

$$(\text{and } v_i^2 = 338.6 \text{ m}^2/\text{s}^2)$$

Fig. 6 Distance to collision (d_{tc}) and braking distance to collision (d_{bi}) and braking reaction distance (d_r)

To estimate the distance to collision, d_{tc} , the braking reaction response distance is added to the braking distance to collision (Fig. 6) :

$$d_{tc} = d_{bi} + d_r \quad (14)$$

From Eq. (9) $d_r = 0.4d_{tc} + 0.3v$, hence

$$d_{tc} = d_{bi} + 0.4d_{tc} + 0.3v$$

$$0.6 \times d_{tc} = d_{bi} + 0.3v$$

$$d_{tc} = 1.67d_{bi} + 0.5v = 23.0 \text{ m}$$

giving a reaction distance

$$d_r = 0.4d_{tc} + 0.3v$$

$$= 0.4[1.67d_{bi} + 0.5v] + 0.3v$$

$$d_r = 0.67d_{bi} + 0.5v = 0.67 \times 7.5 + 0.5 \times 20.9$$

$$= 15.5 \text{ m}$$

If the impact had not occurred and the motorcycle came to rest from braking the total braking distance would have been 32.7 m giving a total stopping distance of $d_s = d_r + d_b = 15.5 \text{ m} + 37.5 \text{ m} = 53 \text{ m}$. The traffic safety conflict is again considered with the vehicles at the same initial positions (the d_{tc} is the same) but this time the speed of the motorcycle is the speed limit $v_L = 13.3 \text{ m/s}$. The above calculations for the speed limit give the values shown in row 3 of Table 3 with row 4 displaying the ratio between all measures at the estimated speed compared to the speed limit.

	d_{bi} (m)	d_{tc} (m)	d_r (m)	d_b (m)	d_s (m)	v_0 (m/s)	v_0^2 (m ² /s ²)	v_i (m/s)	v_i^2 (m ² /s ²)	ASR (m ³ /s ²)
Estimated Speed	7.5	23	15.5	37.5	53	20.9	436.8	18.4	338.6	14960.4
Speed Limit	9.8	23	13.2	13.3	26.5	13.3	176.9	5.1	26.1	3246.0
Ratio	0.77	1	1.3	3.2	2.1	1.6	2.5	3.6	13.0	4.6

Table 3 Distances, speeds, speed squared values and accident severity risk (ASR) at the estimated speed and at the speed limit and their ratios

In Table 3 the ratio in row 4 under stopping distance $= d_s/d_{sL} = \text{RAR}$ and the ratio in row 4 under ASR is the RASR.

All estimates are shown on the graph of the severity risk space in Fig. 7. The immediate observation can be made that the d_{sL} is not less than the d_{tc} . Hence the collision would have occurred even had the motorcycle been travelling at the speed limit. At the d_{tc} (reading the graph from left to right) the v_i^2 and v_{iL}^2 values can be read from the graph (vertical arrow at distance

23m on the x -axis) and correspond with the values for v_i^2 in Table 3. Although the collision was unavoidable at the speed limit the resulting impact would have had thirteen times less in magnitude.

Fig. 7 v -squared versus braking distance d_b when at the speed limit (dark gray) and at twice the speed limit (light gray)

In terms of the general accident risk dimension – the stopping distance is 2.1 times greater and hence there is a 2.1-fold increase in the risk of an impact (x -axis) with any object along the stopping distance to the initial unexpected event at the *dte*. In terms of the general severity dimension – a measure of the magnitude of impact (in this case the kinetic energy related measure speed-squared) – there is also a 2.5-fold increase (y -axis). The accident severity risk (ASR) presented i.e. the product of severity (speed-squared magnitude) at each point multiplied by a measure which is an indicator of the risk of accident – (in this case the stopping distance) at that point, is 4.6 times greater at the higher speed.

4 Results

The reaction, braking (and gap and sliding if applicable) and stopping distances are estimated via the technique shown in the sample calculation. The stopping distances at the estimated speeds and at the speed limits are shown in the right-hand columns of Table 4. An immediate consideration in term of distances is whether the stopping distance at the speed limit (d_{sL}) is less than the calculated distance to collision, d_{tc} i.e. would the collision have been avoidable? Comparing the second from right column of Table 4 with the second from left column from Table 5 it can be seen that in eight cases the $d_{sL} < d_{tc}$ and the collision is avoided. The more general comparison metric – the ratio of stopping distances (RAR) - ranges from 1.3 to 2.8.

Case Number	Reaction Distance at Estimated Speed d_r (m)	Reaction Distance at Speed Limit d_{rL} (m)	Total Braking and/or Gap and/or Sliding Distance at Estimated Speed d_t (m)	Braking Distance at Speed Limit d_{bL} (m)	Stopping Distance at Estimated Speed d_s (m)	Stopping Distance at Speed Limit d_{sL} (m)	Relative Accident Risk RAR = d_s/d_{sL}
1	0	0	0	0	0	0	0
2	25.9	23.5	50.7	13.3	76.6	36.8	2.1
3	12.2	9.5	34.6	12.2	46.8	21.7	2.2
4	34.1	28.6	86.9	21.2	121.0	49.8	2.4
5	37.5	34.1	37.5	11.1	75.0	45.2	1.7
6	34.2	30.7	46.5	13.3	80.7	44.0	1.8
7	37.4	31.9	72.4	13.1	109.7	45.0	2.4
8	28.9	26.2	32.6	11.7	61.5	37.9	1.6
9	18.6	16.6	25.8	11.5	44.4	28.1	1.6
10	0	0	33.5	n/a	33.5	0	n/a
11	40.0	33.2	88.3	12.2	128.3	45.4	2.8
12	14.4	10.4	48.4	12.0	62.8	22.4	2.8
13	25.8	24.2	21.2	10.7	47.0	34.9	1.3
14	14.8	9.9	0	n/a	14.8	0	0
15	28.4	26.4	56.1	11.5	84.5	37.9	2.2
16	24.7	22.5	18.1	5.5	42.8	28.0	1.5

Table 4 Distances at the estimated speed and the speed limit and the relative accident risk (RAR)

(n/a – not applicable)

A second consideration of immediate concern is if the $d_{sL} > d_{tc}$ what is the resulting impact severity if the motorcycle was travelling at the speed limit compared to the severity of the

documented collision. Table 5 shows that the relative accident severity at impact $RAS_i (v_i^2 / v_{L,i}^2)$ varies from 1.4 to 17.2 (for corresponding speed ratios from 1.2 to 2.3). A more general pre-collision measure of severity is obtained from the Relative Accident Severity $RAS = v^2 / v_L^2$. Combining the risk factor – stopping distance and the severity factor – speed squared – gives the relative severity risk measure – the area under the speed squared versus stopping distance graph - which ranges in value from 2.3 to 22.8 for all cases. The severity risk graphs for cases 2 to 9 and 11 to 6 are shown in Fig. 8 (cases 1 and 10 had no reaction or braking distances for the motorcyclist). The mode specific vulnerabilities of falling and sliding are readily evident in the graph showing how they give rise to large ASR (area under the curve) and RASR values (when estimating ASR at the speed limit sliding is considered not to have taken place). Large stopping distances of the order of 100 m to over 230 m are observed if full sliding takes place. Four out of five of the longer stopping distances involve a prolonged sliding phase. The arrows with numbers indicate the case numbers and their positions signify their impact distances. Fig. 9 illustrates the lower stopping distances, zooming in on cases 2 to 9, 12, 13 and 15. Again sliding, with its lower friction coefficient, typically around 0.3 as compared to 0.75 for normal skidding during braking shows a less steep line and hence a greater ASR (area under the curve). In Fig. 10 the initial speed-squared values are set equal to the same value to allow for a direct comparison of the effect that different friction coefficients (ranging from 0.68 to 0.84) have on d_s , v^2 and ASR. The effect on d_s , v^2 and ASR are modest but can be critical.

Case Number	Distance from Reaction Point to Initial Impact (d _{tc}) (m)	Braking Distance up to Impact at Speed Limit d _{bl,i} (m)	Speed Squared at Initial Impact if Initially Moving at the Estimated Speed v _i ² (m ² /s ²)	Speed at Initial Impact if Initially Moving at the Estimated Speed v _i (mph, km/h m/s)	Speed Squared at Initial Impact if Initially Moving at the Speed Limit v _{i,L} ² (m ² /s ²)	Speed at Initial Impact if Initially Moving at the Speed Limit v _{i,L} (m/s)	Relative Accident Severity v _i ² / v _{i,L} ² at Impact	Estimated Speed to Speed Limit Ratio v / v _L	Relative Accident Severity v ² / v _L ²
1	0	0	436.8	47.0, 75.2 20.9	316.8	40, 64 17.8	1.4	1.2	1.4
2	66.2	42.7	2.9	33.8, 54.0	0	0	n/a	1.6	2.5

				15					
3	8.8	0	480.0	48.6, 77.8 21.6	177.8	30, 48 13.3	2.6	1.7	2.8
4	44.5	15.9	236.0	69.1, 110.5 30.7	79.8	20, 32 8.9	3.0	2.0	4.0
5[#]	n/a	0	0	0	0	0	n/a	1.8	3.3
6	42.6	11.9	327.7	37.6, 60.1 16.7	19.0	10, 16 4.4	17.2	1.9	3.5
7	40.4	8.5	640.5	60.1, 96.1 26.7	62.7	18, 29 7.9	10.2	2.3	5.4
8	41.1	14.9	148.6	26.6, 42.5 11.8	0	0	n/a	1.7	2.8
9	24.1	7.5	200.1	31.8, 50.8 14.1	0	0	n/a	1.5	2.2
10*	0	0	492.8	49.9, 79.9 22.2	177.8	30, 48 13.3	2.8	1.7	2.8
11	57.1	23.9	1065.1	72.9, 116.6 32.4	0	0	n/a	2.7	7.3
12	10.3	0	689.4	59.2, 94.7 26.3	94.5	22, 35 9.7	7.3	2.0	4.0
13	51.9	27.7	56.3	17.1, 27.4 7.6	0	0	n/a	1.4	2.0
14	0	0	870.3	66.4, 106.2 29.5	177.8	30, 48 13.3	4.9	2.2	4.8
15	42	15.6	1.7	2.9, 4.7 1.3	0	0	n/a	1.5	2.2
16	39.7	17.2	757.3	19.4, 31.0 8.6	0	0	n/a	1.8	3.3

Table 5 distances, speeds, and speed ratios related to impact #comes to a stop after braking then sliding without hitting another vehicle or object *car speed (n/a – not applicable)

Case Number	Estimated Speed Squared v^2 (m ² /s ²)	Speed Limit Squared v_L^2 (m ² /s ²)	Accident Severity Risk at the Estimated Speed ASR (m ³ /s ²)	Accident Severity Risk at the Speed Limit ASR _L (m ³ /s ²)	Relative Accident Severity Risk RASR = ASR/ASR _L
1	436.4	316.8	0	0	n/a
2	436.8	177.8	22987.9	6549.1	3.5
3	501.8	177.8	14805.6	3853.3	3.8
4	1296.0	316.8	100565.7	15788.9	6.4
5	595.4	177.8	33466.8	8028.3	4.2
6	620.0	177.8	43879.5	7819.6	5.6
7	967.2	177.8	89003.6	8004.6	11.1
8	492.8	177.8	28393.1	6738.4	4.2

9	400.0	177.8	12617.2	4997.5	2.5
10	492.8	177.8	8254.4	0	n/a
11	1267.4	177.8	183833.8	8071.1	22.8
12	712.9	177.8	27533.6	3982.5	6.9
13	349.7	177.8	16493.0	6198.6	2.7
14	256.0	79.2	0	783.3	0
15	400.0	177.8	225900	6731.5	3.4
16	860.4	177.8	11293.1	4982.0	2.3

Table 6 speed-squared and accident severity risk (ASR) estimates
ASR = area under the curve of the v^2 versus stopping distance
graph (n/a- not applicable)

Fig. 8 v -squared versus stopping distance d_s for different friction coefficients for cases 2 to 9 and 11 to 16, arrows indicate the impact location for case 4, 7 and 11 (the other impact locations are shown, zoomed in, in Fig. 9)

Fig. 9 (Zoomed in section of Fig. 8) v -squared versus stopping distance d_s for different friction coefficients for cases 2 to 9, 12, 13 and 15, arrows indicate impact locations in the cases when they occurred

v -squared vs stopping distance for different friction coefficients

Fig. 10 v -squared versus braking distance d_s for different friction coefficients

5 Discussion

Determining the contribution of speed in a road accident, in this case an accident with a fatal outcome involving a motorcycle, is a complex process and involves different stages of consideration. In the present study the accident is analysed from the critical reaction point forward. It does not consider the contribution of speed or other factors in leading to this safety critical situation in the first instance. However, in the process of affording full accountability for speed and other factors in severe and fatal accidents it can be helpful to break the problem down into stages to allow for quantitative analysis. The significance of the theory, analysis and results detailed herein is the provision of quantitative estimates specifying the responsibility of speed in terms of accident risk and accident severity from the critical accident point forward. This allows for the comparison, not of speed values (estimated pre-impact speed and speed limit) but of the physical and physiological consequences of speed values (kinetic energy, braking, sliding and reaction distances), which have speed raised to a power, dependencies. These dependencies are displayed in an easy to interpret space, the severity/risk space, with speed squared plotted on the vertical axis and stopping distance plotted on the horizontal axis. Relative accident risk, severity and severity risk can be read directly from the graph or following basic calculations based on the graph.

When comparing an actual documented collision with a fatal outcome with a re-enactment scenario at the speed limit - typically the incidents involve one slowly manoeuvring vehicle and one faster moving vehicle (in all cases but one here the motorcycle is the faster moving vehicle) coming into conflict – an issue of immediate concern is whether the accident would have taken place had the faster moving vehicle been travelling at the speed limit i.e. whether the stopping distance d_{SL} is less than the d_{tc} . Therefore, no matter what factors are contributing to the occurrence of the conflict in the first place the contribution of speed to the risk of accident can

be quantified relative to travelling at the speed limit. The link between stopping distance and speed quantifies the risk of the accident taking place from the reaction point to the safety critical event forwards. The relative accident risk in response to a safety critical situation shows a partial speed dependent reaction phase ($0.4d_{tc}+0.3v_0$) and a speed-squared dependent braking phase ($v_0^2/2\mu g$) and ranges from 1.3 to 2.8 times greater. Comparing d_{sL} in column 7, Table 4 with d_{tc} in column 2, Table 5, it is observed that eight of the accidents would have been avoided had the motorcycle been travelling at the speed limit. Furthermore, in the event that the accident occurs even if the faster moving vehicle was travelling at the speed limit, the difference in impact severity can be compared. Table 5 column shows the Relative Accident Severity at impact $v_i^2 / v_{L,i}^2$ ranges from 1.4 to 17.2. There are other kinematic or dynamics variables that could be used for the vertical axis of the *S-R* graph – the indicator of accident severity. Kinetic energy ($\frac{1}{2}mv^2$) is the dynamics parameter that most directly informs about vehicle crush (x) and damage energy ($\frac{1}{2}kx^2$, where k is the vehicle structural stiffness); e.g. doubling the speed-squared value for a vehicle of mass m will double the vehicle damage energy in a head on or fixed barrier collision. Damage energy/crash severity can, in turn, be correlated with biomechanical injury/accident injury severity (MacKay, 2007; Hayes et al., 2018). Injury risk is proportional to accident severity as expressed via the speed-squared measure. Speed squared presents as a convenient parameter for interpreting what the road user is guided by on the one hand – speed signs and speedometer dial, and the consequences of speed in terms of d_s (v and v -squared dependency) and kinetic energy (v -squared dependency), on the other hand. Given these power dependencies, and consequences, of speed, it is pertinent to ask are speed indicators the best guides to safety, at least as currently presented? In Table 5 v -squared is converted back to speed for convenience because this is the parameter that road users are familiar with and are presented with in the car (speedometer) and on the road (road speed signs). Similarly, no matter what factors lead to the traffic safety conflict in the first instance the contribution of speed to impact magnitude can be

quantified and compared to travelling at the speed limit. The significance of this is underlined by the following consideration; even if the evidence clearly points to a right of way (ROW) violation (for example) by a vehicle moving from a stationary position (as in Fig. 5) leading to an accident the additional contribution of the impact magnitude due to travelling above the speed limit can be quantified for the ROW vehicle. This affords full responsibility for all road users up to the speed limit and full responsibility for travelling over the speed limit. A related scenario for the same road configuration is when the accident would not have taken place if the faster moving vehicle had been travelling at the speed limit at the time of the manoeuvre of the other vehicle (OV). Acknowledging that the manoeuvring vehicle is responsible up to the speed limit of the OV (ROW exists up to the speed limit at best) and that the OV is responsible for its own speed above the speed limit ensures not compensating for speed or underestimating its consequences in such cases.

The risk and severity dimensions of accidents can be explored further through the severity-risk space. RASR, combining accident risk and accident severity provides arguably the clearest overall representative indicator of relative road traffic safety due to speed in response to a critical traffic safety conflict. The severity risk graph (Fig. 4 v^2 vs d_s) provides a space to examine, quantify and compare factors that affect accident risk and severity, whether human, environmental or technological. It has a relatively simple form (e.g. compared to v vs d_b for example) with a constant straight line of v_0^2 during the braking reaction response distance and interpretation and a linear response ($v_0^2 - 2\mu g d_b$) during the braking phase.

The *S-R* curve indicates the primacy of response distances – response times reported in recent literature are lower than previously reported, but human response times are slow in terms of the ideal response required for such safety critical incidents. Autonomous vehicles (AV) can provide for much faster response times and it is then expedient to study how the vehicle occupants will react to the quicker vehicle response.

The S - R graph may also contribute towards providing a safety indicator assessment framework for considering technological advances in road user safety; tyre, road surface, ABS, MAEB (Savino et al., 2013) etc. For example, at a given speed, variation in ASR with friction coefficients is shown in Fig. 10; although these changes in ASR are relatively modest (compared to changes in ASR with speed) they may bring crucial benefits. Also, the large increase in S - R space due to sliding (Fig. 8 and Fig. 9) suggests the potential benefits of technology to maintain stability when braking to prevent falling and sliding. The relative benefits of safety technologies can be assessed and prioritised. The space facilitates severity risk assessment of a given variable or attribute while also helping to provide an understanding of the compounding effect of excess speed. There is also complementarity between the present study and studies of forward collision warning (e.g. Li et al., 2018; Tak et al., 2018) : investigation and development of the S - R space in the context of collision warning would benefit from considering the asymmetry of the braking response when accelerating/decelerating (Tak et al., 2018) and the robust assessment (simulated re-enactment) and validation (field operational trials) protocols of Li et al., 2018.

For the cases analysed the typical scenario is a stationary or slowly manoeuvring more massive vehicle (mass of other vehicle M , speed of other vehicle $v_{ov} \approx 0$) and a motorcycle plus rider (mass m) travelling at speed v . In these cases the relative velocity between the vehicles ($v_{rel} = v - v_{ov}$) and velocity as measured from the ground, i.e. absolute velocity ($v_{absolute}$), are equal or approximately equal. In other cases, where there is a non-zero relative, or closing, speed, the following expression

$$\frac{1}{2}\mu_r(v^2 - v_{ov}^2) \quad (15)$$

where μ_r is the reduced mass $= Mm/(M+m)$,

can be used to estimate the damage energy between the vehicles (Schmidt et al., 1998). Case one in the present study involves a situation where a car and motorcycle simultaneously move laterally into the same lane and collide. The resulting vehicle damage is not excessive, but the

motorcycle rider is dislodged and projected forward eventually dissipating his kinetic energy in a resulting collision with street furniture. In all cases studied the collisions involve the motorcyclist coming to a stop (zero kinetic energy) in a short time interval. From this point of view, it is expedient to consider absolute kinetic energy as measured with respect to a ground observer as well as noting the energy as per Eq. (15) when the initial impact occurs at a relative velocity. Eq. (15) does not indicate in what proportion the damage energy is shared between the vehicles.

The S - R curves are fully valid for the moment of reaction to the conflict at distance d_{tc} i.e. the response at any distance d is as shown on the graph for an unexpected event at distance d_{tc1} . However, using the same graph if the d_{tc} is shifted to d_{tc2} (say to the right by an amount Δd), the reaction distance changes by an amount $0.4 \times \Delta d$ also and hence d_s increases by $0.4 \times \Delta d$ and ASR increases by $0.4 \times \Delta d \times v^2$. The v -squared response at any distance d can be estimated from the original graph (for d_{tc1}) but now reading the speed-squared value for distance d at the value $d - 0.4 \times \Delta d$.

The speed-squared dependent accident severity measures range from 1.4 to 7.1 pre-impact and from at impact. The relative accident severity risk shows speed squared to speed cubed dependency components during the reaction phase and a speed to the power of four dependent braking phase and ranges from 2.3 to 22.8 times greater. The measures provide comparative values that reflect relative accident, risk, severity and severity risk for travelling at a given speed compared to travelling at the speed limit i.e. compared to the maximum allowed value for the road section. As it is also important for road users to exercise caution the speed limits are only guides towards safe speeds under certain conditions. It can also be beneficial to specify limits when conditions deteriorate to maintain an equal severity risk. The severity-risk space can be examined to quantify the variable conditions e.g. change in weather - friction coefficient changes

due to rain, ice (change in slope of braking portion of graph), and consequent stopping distance change.

The development and application of the methodology supports the power model (Nilsson, 2004; Elvik et al., 2004) relating average speed of traffic to road accident occurrence and severity. It suggests, together with the original studies (Nilsson, 2004; Elvik et al., 2004), that there is a strong physical basis for the power model. Because the power model is based on analysis of data for average traffic speeds (e.g. when two different speed limits have been in place on the same road section) the resulting power exponents also include what effect speed may have in leading to safety critical conflicts in the first instance and what effect it may have on modifications in traffic flow. Comparison of purely physically based approaches complements the use of the power model, and when used in conjunction with the power model, has potential to provide further insight into conflict occurrence and traffic flow effects.

Future work will examine the collision process in more detail, considering vector and momentum aspects to trace how the initial kinetic energy (and hence speed) of each vehicle contributes to the eventual outcomes for each road user. Methods to further quantify the braking response and other emergency manoeuvres will be considered together with studies of correlations between injury severity and accident severity.

10 Conclusions

- A framework for analysing the accident risk and severity dimensions of road user accidents at the reaction point to the critical road safety conflict is established.
- A speed-squared (severity dimension) versus stopping distance (risk dimension) parameter space is introduced. Accident severity risk is defined as the integral of speed-

squared over the stopping distance providing an indication of accident risk weighted by the severity of that risk.

- The accident risk (stopping distance) comprises a speed independent reaction phase component and a speed (to the power of one) reaction phase dependent component followed by a speed-squared dependent braking phase component.
- The accident severity risk which indicates accident risk (stopping distance) weighted or multiplied by severity (speed-squared) is hence comprised of speed to the power of, two, three and four, components.
- The defined accident measures, accident risk, accident severity and accident severity risk are provided in terms relative to values estimated for a vehicle travelling at the speed limit at the safety critical event. The measures are estimated for sixteen fatal accidents from a police dataset of UK motorcycle accidents.
- The vehicle speeds at the critical incident are calculated to be from 1.3 to 2.7 times the speed limit and the values of the corresponding relative accident risks, relative accident severities and relative accident severity risks are estimated to range from 1.3 to 2.8, 1.4 to 7.3, and 2.3 to 22.8, respectively.
- The speed-squared versus stopping distance domain is shown to be convenient for interpreting and quantifying accident risk and severity, highlighting the acute consequence of speed on the risk of severe accident.

Acknowledgement

The data used in this study were collected as part of a study funded by the European Commission.

The full study report can be found at the following; <https://op.europa.eu/s/nqp8>

The information and views set out in this study are those of the authors and do not necessarily reflect the official opinion of the Commission. The Commission does not guarantee the accuracy

of the data included in this study. Neither the Commission nor any person acting on the Commission's behalf may be held responsible for the use which may be made of the information contained therein.

The first author has benefited from participation in the EU COST ACTION TU1407 (<https://safe2wheelers.eu>) between 2015 and 2019.

Declaration of Interest

'Declarations of interest: none'

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Peter Murphy: Conceptualization, Methodology, Formal Analysis, Writing- Original draft preparation, Writing- Reviewing and Editing

Andrew Morris: Resources, Data Curation, Writing- Reviewing and Editing