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Who, where, when: the demographic and geographic distribution of bicycle crashes in West Yorkshire

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Abstract

Factors associated with cycle safety, including international differences in injury and mortality rates, protective equipment and bicycle training, have been subject to increasing academic interest. Environmental variables associated with cycle safety have also been scrutinised, but few studies have focussed on geographical factors at the local level. This paper addresses this research gap by analysing a geo-referenced dataset of road traffic incidents, taken from the UK's STATS19 dataset (2005 - 2012). We investigate incidents involving cyclists within West Yorkshire. This is an interesting case study area as it has an historically low cycling rate but very ambitions cycling plans following investment from the Department of Transport. West Yorkshire is found to be an unusually risky area for cyclists, with an estimated 53 deaths and 1372 serious injuries per billion kilometres cycled, based on census commuting statistics. This is roughly double the national average. This riskiness varies spatially and temporally, broadly in line with expectations from the previous literature. An unexpected result was that cycling seems to be disproportionately risky for young people in West Yorkshire compared with young people nationally. The case study raises the issue of potential negative health impacts of promoting cycling amongst vulnerable groups in dangerous areas. We conclude by highlighting opportunities for increasing cycling uptake via measures designed primarily to improve safety. The analysis underlying this research is reproducible, based on code stored at github.com/Robinlovelace/bikeR.

Introduction

In the recent Annual Report of the UK's Chief Medical Officer, Dame Sally Davies, emphasised the need to promote active travel from a health perspective: "encouraging more people to engage in active travel, such as walking and cycling, is crucial to improving the health of the nation" (Davies, 2014, p.16). A recent systematic review of 16 cycling-specific studies concluded there was moderate evidence for a reduction in cardiovascular risk factors, and strong evidence for fitness benefits (Oja et al., 2011). Research strongly suggests that the health benefits of modal shift to cycling greatly outweigh the risks, with health benefit to cost ratios estimated to be 7:1 in the Netherlands (de Hartog et al., 2010), 20:1 in the UK (Hillman, 1993) and more than 70:1 at the city level in Barcelona (Rojas-Rueda et al., 2011).

Despite this cycling for everyday trips remains low in most high income nations. In the UK, the number of miles cycled per person appears to have increased in recent years - from 37 to 53 miles (DfT, 2013) — perhaps partly due to a boom in leisure cycling. However, cycling still accounts for only 1.7% (up from 1.4% in 2007) of all journeys in Great Britain and 0.8% of all distance travelled (ibid., Tables NTS0301 to NTS305). This is despite the fact that roughly two-thirds of all trips were within easy cycling distance (between 0 and 5 miles) in 2012 (ibid, Table NTS0307).[1] In terms of commuting, for which the best data are available, the proportion of people using a bicycle as their primary mode of transport has remained steady at just over 3% across England (Goodman, 2013). This masks substantial geographical variation: outside London, bicycle commuting in England has actually declined, from 3.2% in 2001 to 2.9% in 2011.

[1] Also, 38% of all trips were between 0 and 2 miles, easily accessible for cyclists of all abilities (DfT, Table NTS0307). It is interesting to note that the proportion of trips made for short journeys (less than 5 miles) has declined over the past two decades, from 69.8% in 1995/7 to 65.8% in 2012. The time series data suggests this trend has stopped since the recession (with a minimum of 65.2% reached in 2007)

Fear of injury caused by motorised traffic is a major barrier to cycling (Fishman et al., 2012; Lorenc et al., 2008). This may be justified in some contexts. Whilst the balance between the risks and reward from cycling are strongly positive overall, there are factors which alter this balance. It has been estimated that switching from car to bicycle use will result in 3-14 months of additional life from the increase in physical activity compared with just 5-9 days lost from traffic collisions in the Netherlands (de Hartog et al., 2010). However, the societal benefits depended on who switches mode: because of their increased propensity to crash cars, young people taking up cycling was found to be particularly beneficial. In the UK, the risk of death from travelling one kilometre on foot or by bicycle is more than 17 times higher than by car, (Davies, 2014).

A recent comparison of hospital and police records of casualties from cycling in Ireland suggests that under-reporting may lead to underestimates of the true risks of cycling (Short and Caulfield, 2014). This issue is especially pertinent to the present paper, which uses the publicly available STATS19 dataset, collated by the police. Official documents suggest that only casualties classed as fatal and to a lesser extent serious can be relied upon from STATS19 (as opposed to 'slight' injuries, which are likely to be greatly under-reported) (Keep, 2013). This is an issue as it means the nature of the data is selective, insofar as incidents are more likely to be recorded the more severe they are (Langley et al., 2003). Furthermore there is no legal obligation for those injured to report the collision to the police. Moreover, if there is no injury, the incident is not deemed 'reportable' (DfT, 2013). For these reasons we focus on serious and fatal injuries in the exposure-normalised risk estimates for comparison with national figures. 'Slight' incidents account for 80% of the records, however, so these are used unless otherwise stated.

The geographical and demographic distribution of factors linked to cycling uptake has powerful policy implications, yet has received little academic attention (Fraser and Lock, 2011). Indeed, whilst promoting cycling results in relatively unambiguous benefits in some contexts, as is the case for the cycle hire scheme in Barcelona (Rojas-Rueda et al., 2011), in other cases the balance is not so clear. In the London cycle hire scheme, for example, the health benefits were found to be positive overall but marginal for young women, for whom the harms from road casualties may outweigh the benefits from physical activity (Woodcock et al., 2014). As such, a focus on particular contexts that are subject to cycling promotion is warranted.

The case study area

West Yorkshire is a metropolitan county with a population of 2.2 million (2011 Census), occupying an area of 2,030 km^2. It thus has a relatively high population density of 1,084 people per km^2 (compared with 420 across England) who are unevenly distributed between the 5 Local Authorities of Leeds, Bradford, Wakefield, Calderdale and Kirklees. The Local Authorities run most local services such as schools and housing, whilst the West Yorkshire Combined Authority manages transport, economic development and regeneration in the region. The vast majority of the population is urban, although West Yorkshire also contains tracts of countryside, with the Yorkshire Dales to the North and the majority of Calderdale and Kirklees to the West (Fig. 1). Although the Yorkshire cities of York and Hull (outside the study area to the East) have traditionally high rates of cycling, the county's major cities, Leeds and Bradford, have historically low levels of active travel and heavily car orientated urban plans. Sport cycling is popular in some parts of West Yorkshire[2] yet the county overall lacks a visible utility cycling culture (West Yorkshire Metro, 2013). At 1.3% (see Table 3, below), the rate of cycling to work in West Yorkshire (a reasonable proxy for cycling overall) is less than half the national average of 3.2% (Goodman, 2013).

In recent years there have been efforts to amend this situation, and even calls for Leeds (historically known as the 'Motorway city of the Seventies')[3] to become a 'cycling city'. A spend of £30 million on cycling between 2014 and 2017 is planned, including £18 million from the Department for Transport (DfT) through the Cycle City Ambition Grant (CCAG) to construct a 23 km cycle superhighway between West Yorkshire's largest cities: Leeds and Bradford.

The West Yorkshire Integrated Transport Authority (WYITA) is committed to raising expenditure on cycling from its previous value of £1.30 per person per year to £5 starting now and running until 2026. The

[2] The settlements of Ilkley and Otley, for example, are home to two of the largest cycling clubs in the country.
[3] See http://gu.com/p/3zkyz/sbl .

associated behavioural target is for a 300% increase in the rate of cycling and for no growth in car use over the same period (West Yorkshire Public Transport Executive, 2014).

These figures are highly relevant in the national context: the All Party Parliamentary Cycling Group (APPCG) recommends spending of *at least* £10 per person per year on cycling nationwide, with a target for 10% of all trips to be by bicycle by 2025 (Goodwin, 2013). Given the current all-purpose share of 1.7% (DfT, 2013, Table NTS0301), this accounts for roughly a *600%* increase nationwide, far more ambitious than West Yorkshire's target.

The strategic case for this investment has been made predominantly on the basis of the need to generate a legacy from 2014 Grand Depart, the beginning of the Tour de France, which was awarded to the county (WYITA, 2013). There is local ambition to maximise the long-term benefit from what was the largest free sporting event in the region's history. It has been suggested that the investment will capitalise on West Yorkshire's "increasing appetite for the cycling" associated with the Tour (p.24 WYITA, 2013). This ambition received a boost in Leeds with the publication of 2011 census data, which showed growth in cycle commuting, from 1.4% in 2001 to 1.9% in 2011 across the city. To put this growth in the national context, Leeds ranks 34th out of all 324 English Local Authorities in terms of absolute growth in cycling, and 13th excluding London. In terms of northern English cities, Leeds has seen the fourth greatest shift to cycling, trailing only Newcastle, Manchester and Sheffield. Cycling has declined in the other Local Authorities within West Yorkshire, leading to a highly uneven spatial distribution of cycling across the county (Fig. 1). The WYITA (2013) revealed a 0.8% increase in the proportion of travel to work by bicycle for Leeds between the 2001 and 2011 censuses, from 1.1% to 1.9%. No change was recorded in Bradford, remaining at 0.8%. The report also states 4.4% of respondents took up to cycling in 2012.

10% of respondents in West Yorkshire report safety as the most important barrier to cycling (WYITA, 2013), which is surprisingly low given the findings of Fishman et al. (2012) and Pooley et al. (2011). The latter paper reports that "poor safety was one of the key reasons for not cycling expressed by approximately 80% of respondents" in a survey of 619 people across four English towns, including in Leeds (Pooley et al., 2011). Further research in England suggests that motorised road traffic is the "greatest perceived danger" for cyclists, with "busy rush hour conditions" being particularly off-putting (Pooley et al., p. 69 - 70).

Satisfaction with cycling infrastructure in the area is limited. A survey of cycling infrastructure and cycle commuting suggests a link between the two variables locally, finding that the costs bicycle crashes in West Yorkshire amount to roughly £2 million (WYITA, 2013, p.63). The investment in infrastructure is expected to reduce the number of reported cyclists injured or killed by traffic casualties each year by 10% on completion (end of 2016) with estimated economic savings of around £200,000 (ibid.).

Whilst there has been much work on the factors associated with bicycle use (see Buehler, 2012), less has been written on the issue of barriers. Safety concerns have been found to be the most important barrier to cycling uptake in several contexts (Fishman et al, 2012; Reynolds et al., 2009; Lorenc et al., 2008). Furthermore, Davies (2014) argues that "in order to improve uptake, we need to improve safety. The relative risk associated with journeys by active travel methods are unacceptably high and must be reduced ... An improved understanding of methods to improve road safety for all modes of transport and how these can be applied to the road system in England would be beneficial." (Davies, 2014; p16-17). Analyses of factors associated with harm must therefore be understood if the potential benefits of cycling are to be shared equitably (Mullen et al., 2014). This paper builds on this observation and seeks to provide evidence towards greater understanding of the risks of active travel in the local context.

Hypotheses

The hypotheses tested in this project were based on the literature on cyclist safety and fall into three broad categories: who, where and when.

1. Who is most at risk?

1.1. Young adults (below 20) will be more likely to be involved in crashes than the rest of the population (Martinez-Ruiz et al., 2014).

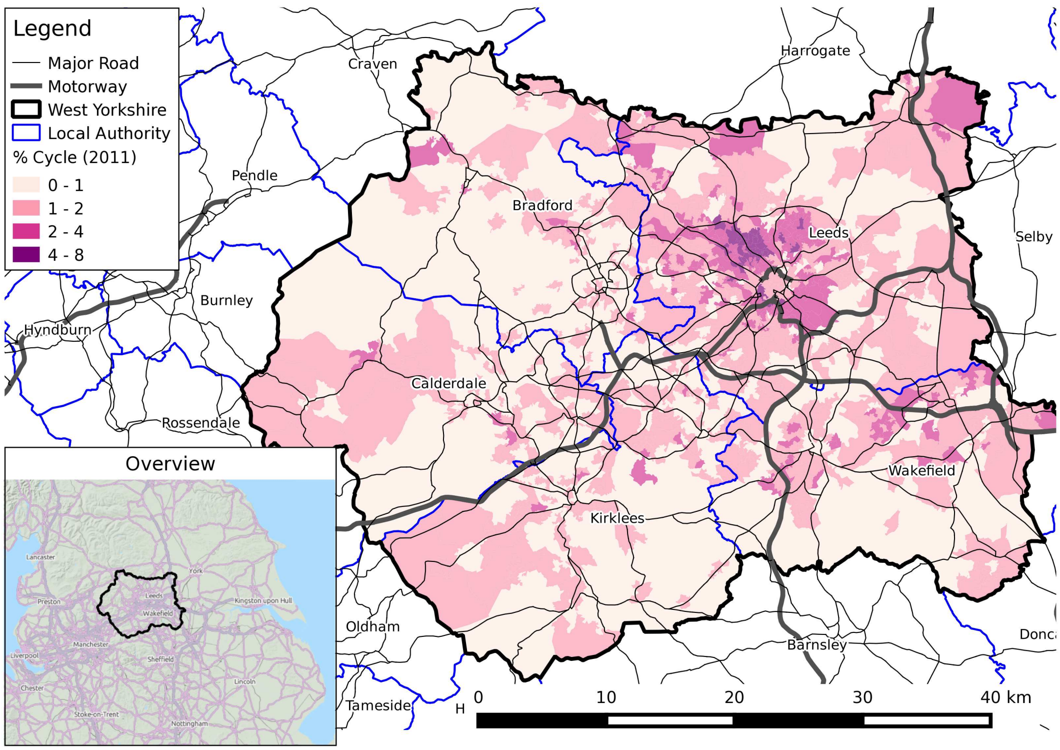

Figure 1: Overview of the study area

1.2. We expected this trend to be stronger in more challenging cycling environments, for example on large roads.

2. Where are crashes most likely to happen?

2.1. Areas with the highest rates of cycling were expected to have the lowest injury rate per unit exposure. This is based on the 'strength in numbers' hypothesis that it will be relatively safer to cycle in areas with a large number of commuters. This hypothesis has received empirical support from the geographical literature on the subject (Vandenbulcke et al., 2009).

2.2. We expected unusual and challenging features of urban infrastructure to be associated with higher than average rate of cycling than the rest of the road network. Following (Vandenbulcke et al., 2014), we specifically expected clusters of collisions near junctions and roundabouts. Also based on this work, we expected cycle infrastructure to reduce risk.

3. When are bicycle crashes most likely?

3.1. We expected absolute levels of cycling injuries to have increased over time, in line with estimates on the growing distance cycled per year nationwide.

3.2. The diurnal and seasonal distribution of incidents was expected to be different for cyclists than for other road users (Twisk and Reurings, 2013; Thornley et al., 2008).

Data

The main input data source for this study is the National STATS19 dataset on road traffic incidents.[4] The data used in this paper includes all police-recorded road crashes that took place between the 1st January 2005 and the 31st December 2012, providing 8 years of uninterrupted records. The structure of the raw dataset is itself quite complicated, divided into three main files:

- Accidents0512.csv, a 178 Mb file containing 1.3 million rows of data on the key attributes of each incident, including time and data, location (Easting and Northing is provided in OSGB1936 coordinates to the nearest 1 m, but rounded to the nearest 10 m in most cases), road type and other contextual variables such as weather.
- Casualty0512.csv, a 74 Mb file containing 1.8 million rows on the attributes of casualties from the incidents. These include reference to the vehicle, "accident" and socio-demographic information about those injured.
- Vehicles0512.csv, a 142 Mb file containing 2.5 million rows of data about the registered vehicles involved in the incidents. Variables include vehicle type and other vehicle attributes plus demographic details of the driver.

In terms of geographic data, the bulk of the analysis was conducted only on crashes that occurred within the case study region of West Yorkshire (Fig. 1).

Method

The analysis strategy was based on consideration of the data and the hypotheses we were aiming to test.

[4]The full dataset can be downloaded from data.gov.uk/dataset/road-accidents-safety-data. Note that we follow the advice of road safety charities in its avoiding the term "accident", which implies that the collision had no cause and removes culpability from the the person who was culpable. See http://www.roadpeace.org/resources/Crash_Not_Accident_April_2007.pdf for further information.

Estimating exposure

A major methodological challenge faced by anyone trying to draw conclusions from road incident data is that the underlying level of exposure is usually unknown. Therefore, researchers can rarely tell if increases in crashes are due to change in the riskiness of an activity or whether simple increases in exposure - in this case an increase in cycle use in particular areas - is to blame.

The method used to estimate exposure varied depending on the hypothesis being tested. In terms of where people cycle, the best small-area data available is from census data on mode of travel to work. Because of the finding that commute modal share for cycling is highly correlated with modal share for all trips (r = 77%) (Goodman, 2013), commuting can be used as a proxy for the rate of cycling overall. Based on this insight, we can take commuter data and develop a simple formula to estimate the distance cycled across all trips in each geographic zone, for the wider cyclist community (Equation 1):

$$d_T = \frac{n \times f \times \bar{d}}{p}$$

where d_T is the total distance cycled per year in each zone, n is the number of bicycle commuters, f is the frequency $\bar{d}$ is the average distance of each bicycle trip (which we assume to be the same for commuting and non-commuting trips) and p is the proportion of bicycle trips made for commuting purposes. To convert the number of people cycling to work into an estimate of total distance cycled per year, the following assumptions were made:

- 400 one-way trips are made each year per commuter (Hall et al., 2011).
- The average length of bicycle trips is 4.5 km (DfT, 2013, Table NTS0306; see Fig. 2).
- Cycle commuting accounts for 1/3 of all bicycle trips (DfT, 2013, Table NTS0409).[5]

The average trip length of bicycle trips from 2005 to 2012 was 2.8 miles or 4.5 km (Keep, 2013), a distance the author notes is increasing. To explore this further, we analysed the recently released National Travel Survey (2002-2012). It was found that bicycle trips did indeed show an upward trend in average distance when they were aggregated by year. Cross tabulating the results by binary mode (bicycle/non-bicycle trips) and purpose (commuting/other) showed that commuting trips are on average further than trips for other purposes although the difference is smaller for bicycle trips. The average trip distance has surprisingly passed 5 km for cyclists. The identical result was found when *stages* were used as the unit of analysis. The subsequent analysis should be seen within the context of this national tendency towards longer-distance bicycle trips, perhaps along faster roads (Fig. 2).

These assumptions imply that every bicycle commuter, as recorded in the 2011 Census, results in 5,400 km of total distance cycled for *all people, for all purposes.*

In this way we have built an equation in which we can take the number of bicycle commuters and estimate the rate of cycling for all purposes, following NTS data which shows 1/3 of bicycle trips are due to commuting. Note that an important distinction between *cycle commuter*, as defined by the 2011 census, and commuting by bicycle should be made here. Because the census asks only for the dominant mode of travel to work while cycling is often a 'backup' or secondary mode, we should not assume that all bicycle commuting trips are made by respondents of the 2011 census who say they cycle to work.

The true relationship between the number of people who cycle to work from the census and distance cycled overall will clearly be more complex and will vary depending on average distance of commuter and other bicycle trips. The values resulting from Equation 1 should be seen as a first approximation of geographical variation in exposure to risk. Refining the estimate based on data on distance bands of travel to work by mode would be possible, but for the purposes of this study, the average value of 5,400 km/yr for all modes and all people per cycle commuter will be used. Further work investigating the link between cycle commuting and cycling overall is needed, to better infer the latter from the former for small areas (Goodman, 2013).

[5] British citizens make on average 15.6 bicycle trips per year, of which an average of 5.4 are for commuting.

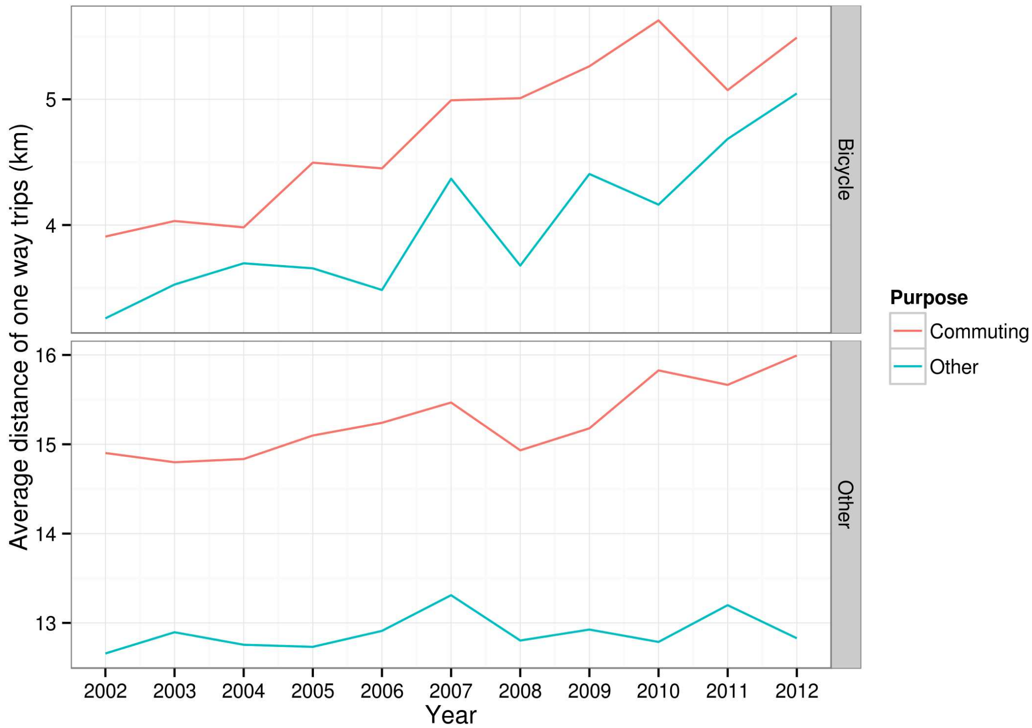

Figure 2: Average distance travelled by mode and purpose (source: National Travel Survey, 2002:2012)

Results

Prevalence of incidents involving cyclists in West Yorkshire

Over the entire study period the proportion of incidents involving cyclists was 8.1%, which is below the national average of 10.4%. Given that only 1.3% of commutes in the area are by bicycle, less than half the national average of 3.2% (Goodman, 2013), the incident rate is disproportionately high.

Furthermore the proportion of incidents involving cyclists in West Yorkshire has been increasing over time (Fig. 3). The proportion of reports involving cyclists has increased from 6.4% in 2005 to 10.5% of in 2012, a 65% increase in 8 years and a growth rate of 0.5 percentage points per year. This follows a national trend in the increase of reported incidents. This may be accounted for by increased distance cycled compared with stagnating or declining distance travelled by other modes. The proportion of distance travelled nationwide increased by 57% (from 0.50% to 0.79%) over the same period according to the National Travel Survey, so increased exposure to risk only explains part of the increase in casualties. Another possible explanation is that the number of incidents that go unreported is decreasing, although this is difficult to verify.

There was a clear seasonal pattern in the data, with a predominance of cycling injuries during the summer months. Dividing the year into 4 quarters, it was found that the summer months (from April until September) were associated with a relatively high proportion of incidents involving cyclists (10.1% on average), compared with the colder half of the year (6.4%). This can be explained by reduced cycling during cold, wet and dark conditions, while other modes of transport are relatively unaffected by adverse weather.

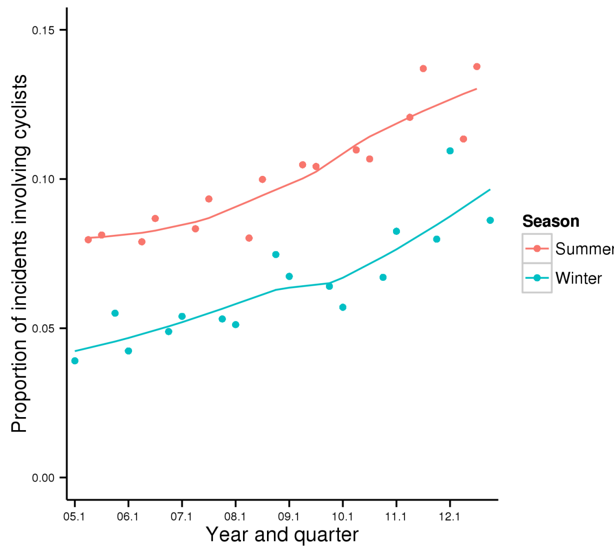

Figure 3: Increases in the proportion of incidents that involve cyclists in West Yorkshire, from Q1 2005 to Q4 2012 by season

Who is most at risk?

Age

The age distribution of cyclist road casualties in West Yorkshire is compared with that of pedestrians and other road users in Fig. 3. The age distribution of cyclist casualties in West Yorkshire is anomalous compared with that of the UK: 45% are 25 years old and below, compared with 38% nationally, a 6% point anomaly (accounting for rounding) (Fig. 5). This cannot be explained by age structure alone (although the proportion of young citizens in the region, 33%, is 2% above the national average). No such anomaly was found for incidents involving only motorised vehicles, although a disproportionate proportion of pedestrian casualties in West Yorkshire were young (57% against 51% nationally). This provides some evidence to suggest that West Yorkshire is an especially unsafe place to be a young cyclist or pedestrian, raising the question: why?

The 2002 - 2008 National Travel Survey provides individual-level data on mode of travel by age, geocoded to the coarse level of Government Office Regions. Yorkshire and the Humber (which contains West Yorkshire) was used as a proxy for the cycling rate by age and the absolute rate was normalised by the ratio between the proportion cycle commuting in West Yorkshire (1.3%) and the region as a whole (2.6%). Thus the proportion of trips made by bicycle for each age group was used as a measure of exposure. The resulting odds ratios for West Yorkshire and nationally are presented in Tables 1 and 2.

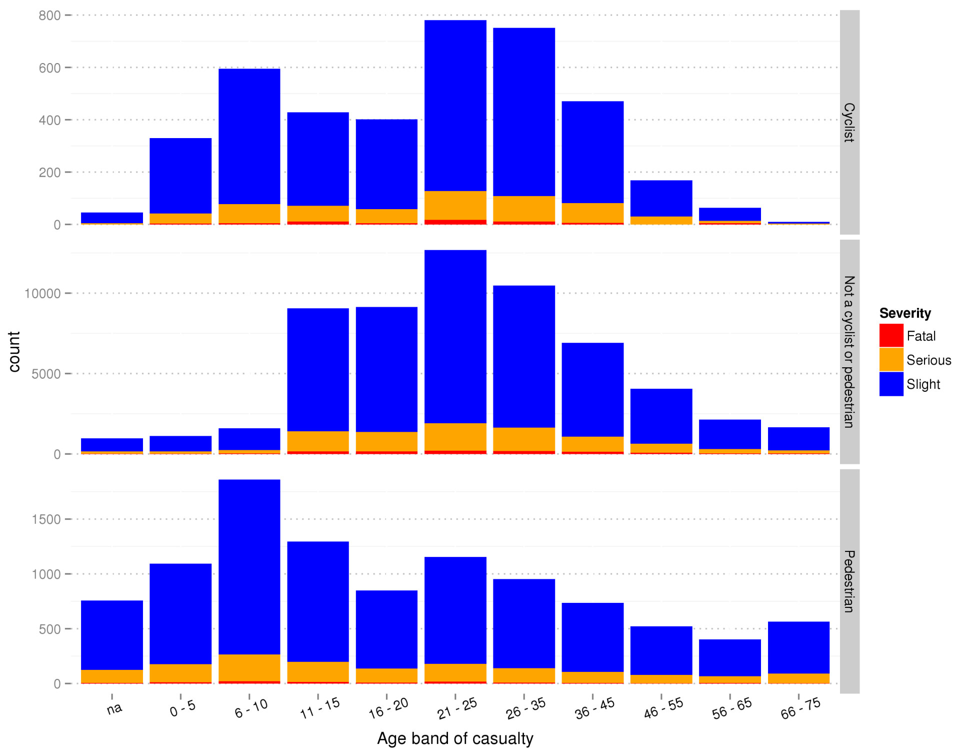

Figure 4: Cyclist and non-cyclist casualties from road traffic incidents, 2005 - 2012 in West Yorkshire, by age and severity. Note the variably sized age bins, which down-play the relative risks of road crashes for young people

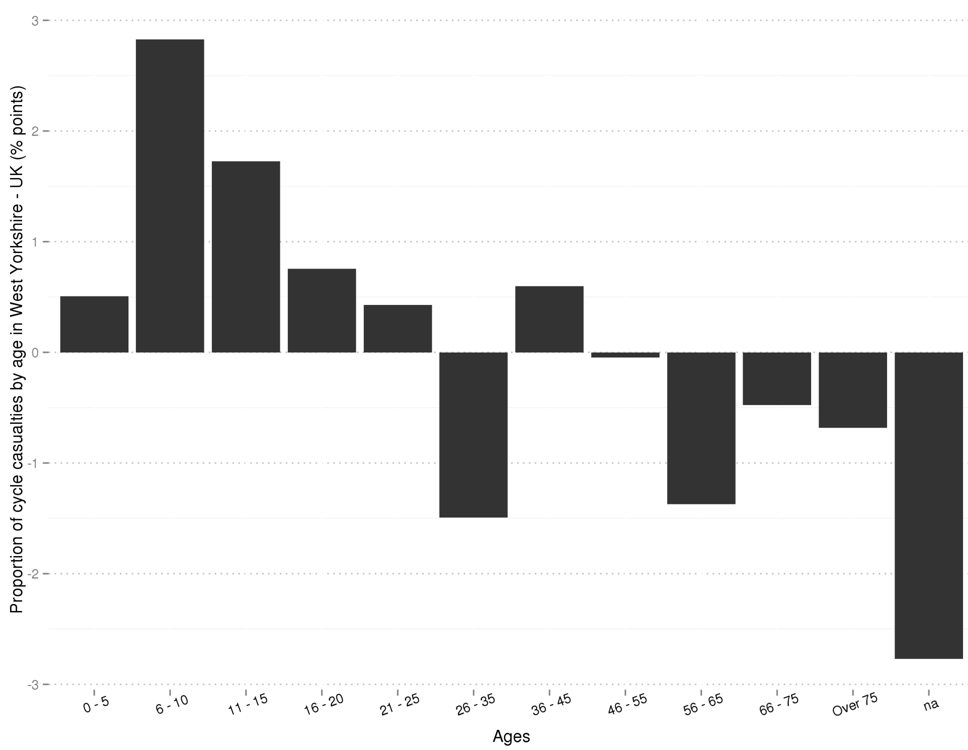

Figure 5: Anomaly in the age distribution of cyclist casualties in West Yorkshire, compared with the UK

Table 1: Odds ratios for different age bands in in West Yorkshire. Note, the proportion of trips by bicycle by age groups are for Yorkshire and the Humber as no estimates for West Yorkshire are available.

Age band	% trips by bicycle	% casualties cyclists	Odds ratio
0 - 10	2.7	15.5	11.97
11 - 20	4.1	18.7	9.24
21 - 45	6.7	21.2	6.46
56 +	2.8	6.0	4.34

Table 2: Odds ratios for different age bands in Great Britain.

Age band	% trips by bicycle	% casualties cyclists	Odds ratio
0 - 10	3.0	16.40	5.56
11 - 20	4.4	24.63	5.54
21 - 45	7.1	29.94	4.22
56 +	2.3	9.97	4.39

These tables suggest that the risks of cycling are disproportionately greater for young people in West Yorkshire compared with the nation as a whole. More localised age-specific exposure data are needed to verify this result. In combination with the corroborating findings presented in Fig. 4, the calculated odds ratios suggest a worrying pattern of risk for young people in the West Yorkshire. The odds ratios also drop for older cyclists across Great Britain but far less than in West Yorkshire, suggesting environmental or social factors in the area make cycling particularly risky for children.

An unexpected age-related finding was that the proportion of cyclist casualties in the middle aged group of 46–55 is growing much faster than any other group, a trend that differs remarkably from the national trend (Fig. 6). At the national level the proportion of cyclist road casualties in this age group has increased slightly faster than cyclists overall, a 2.5 fold increase relative to 2005 compared with a doubling for the closest groups. West Yorkshire far surpasses this, with the proportion of all road traffic casualties who are cyclists in this age group increasing more than 4 fold in 7 years.

In the absence of localised cycling data we can only hypothesise the reasons for this anomaly. The growth of local cycling clubs has arguably strengthened the phenomenon of 'mamils' (middle-aged men in lycra) (Aldred, 2013) in West Yorkshire. Starting from a very low baseline also helps explain why casualties in this group grew fastest. We speculate that part of this growth can be attributed to the excitement surrounding the Tour de France, which appeals to an older audience. While further research is needed to fully explain the growth in middle aged bicycle casualties, the results point to a much stronger wider point: that localised analyses of national road traffic casualty statistics can uncover unexpected findings. We conclude by discussing the policy and academic implications of the research.

Gender

The 2011 Census indicates 6 times more men than women regularly cycle to work (10,697 males compared with 1,785 females), demonstrating the highly gendered nature of cycling. The gender ratio may be higher still when considering the distance cycled, especially when sport cycling, a male dominated activity, is included.[6]

Table 3 shows there were 8 times more male cyclist casualties than female cyclist casualties in West Yorkshire, a high ratio found in other gendered modes of transport, such as the motorbike (Table 3). Given the gender difference in cycling to work, this does not necessarily mean that female cyclists are safer, there are simply

[6] There is no evidence for this male dominance in cycling in Yorkshire and the Humber from the National Travel Survey, however: only 55% of all 8,615 bicycle trips reported in West Yorkshire were made by males, far lower than the proportion of male cycle commutersin the county (86%).

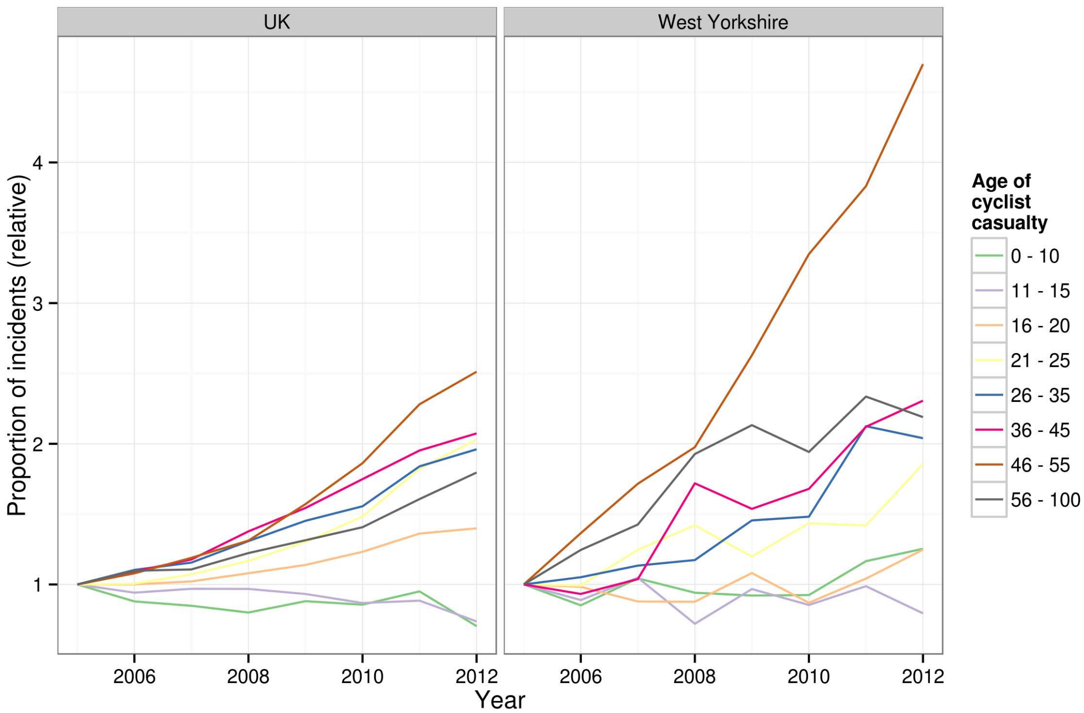

Figure 6: Growth in cyclist casualties as proportion of all road traffic casualties by age band in the UK and West Yorkshire, relative to 2005 values.

fewer on the road. We do not have sufficient data to assess whether *relative* risk is greater for males or females.

Table 3: Ratio of male to female road casualties in West Yorkshire by mode.

Mode of transport	N. casualties	% Male	% Female
Pedestrian	10190	57.3	42.7
Cyclist	4046	88.8	11.2
Motorcycle 125cc	581	90.2	9.8
Car occupant	47239	54.0	46.0
Heavy (> 3.5 T) lorry	363	93.9	6.1

Where are crashes most likely to happen?

The overall spatial distribution of incidents involving cyclists follows the road network, as do incidents with no cyclist casualties (Fig. 7). The relative density of cyclist crashes is clearly higher in urban centres, however, and is clearly absent from the motorway network. The extent to which bicycle crashes are concentrated in urban areas, and especially Leeds, becomes clear when Kernel Density Estimate (KDE) levels are used to avoid the information loss associated with 'overplotting' (Wickham, 2011). This is presented in Fig. 8, which shows the extent of the clustering of incidents involving cyclists. Of course, this pattern likely reflects the high rate of cycling and around Leeds city centre (see Fig. 1). This pattern sets the scene for the geographically aggregated statistics presented below, which normalise the number of incidents involving cyclists in each area by estimated exposure.

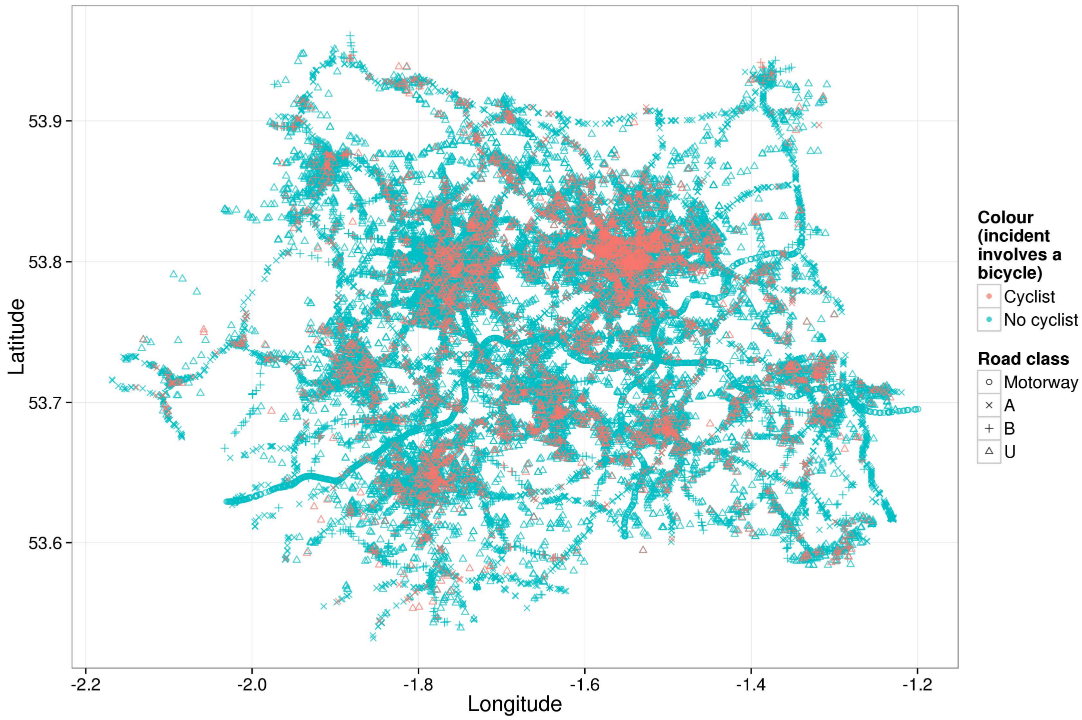

Figure 7: Overview of the spatial distribution of road traffic incidents with cyclists and no cyclists involved

Normalised risk

The total distance cycled in West Yorkshire was estimated to be 69 million km, based on the fact that there were 12,706 cycle commuters recorded in the 2011 Census and Equation 1. To corroborate this estimate, the same method was used at the national level, resulting in an estimate of 4.0 billion vehicle kilometres (bkm) across England (there are 742,675 cycle commuters nationwide): it is reassuring to note that the DfT's official estimate of total distance cycled nationally is of the same order - 3.1 billion miles (5.0 bkm) (Keep, 2013).[7] In terms of risk, our estimate of 621 serious injuries per bkm cycled per year (S/bkm/yr) is also close to the official estimate of 623 S/bkm/yr, presented as 1005 injuries per billion vehicle *miles* in Keep (2013).

Based on the census data and geographically aggregated statistics on serious cyclist injuries and fatalities, the relative risk of cycling was calculated for West Yorkshire's 5 Local Authorities (Table 4).

Table 4: Summary statistics on cycle commuting, serious and fatal incidents involving cyclists and inferred risk in deaths and serious injuries per billion kilometres cycled (D/bkm/yr and S/bkm/yr respectively).

NAME	N. Cycle	% Cycle	N. Serious	N. Death	mkm/yr	D/bkm/yr	S/bkm/yr
Bradford	1715	0.8	136	6	9.2	81	1835
Calderdale	903	1.0	81	3	4.9	77	2076
Kirklees	1829	1.8	123	3	9.9	38	1556
Leeds	6352	1.9	297	8	34.3	29	1082
Wakefield	1907	1.3	116	7	10.3	85	1408
West Yorkshire	*12706*	*1.3*	*753*	*27*	*68.6*	*53*	*1372*
England	*742675*	*3.1*	*19924*	*919*	*4,010*	*29*	*621*

[7] Note the official estimate is for Great Britain, whose population is 12% greater than that of England. This implies the result for England, assuming equal rates of cycling across the countries, would be 2.7 billion miles or 4.4 bkm.

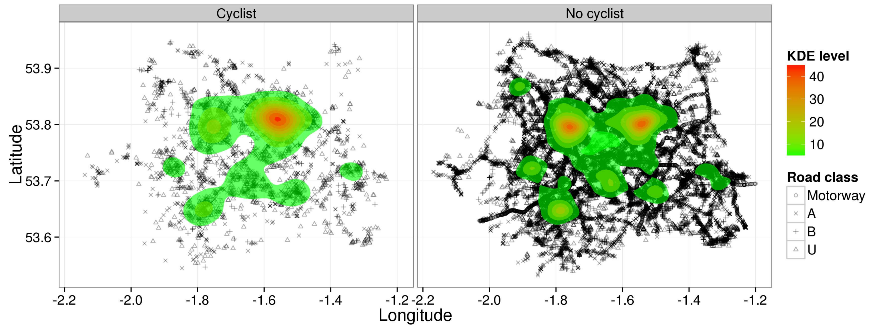

Figure 8: Kernel Density Estimates for incidents involving cyclists (left) and no cyclists (right)

Although Leeds has the highest number overall cyclist casualties (and second highest number of casualties per capita), the results suggest this is due to heightened exposure: central Leeds seems a comparatively safe place to cycle within West Yorkshire. Each of the Local Authorities in the table are more risky than the national average in terms of serious injury rates per estimated distance cycled. Calderdale, the Local Authority with the worst yearly serious injury rate (11.2 serious injuries per 1000 cycle commuters) is more than 3 times worse than the national average in this metric.

The same method was used to estimate relative risk at lower geographic levels (Fig. 9). Because of the relative sparseness of the point data, it was found that there were many `NA` values for small zones. Census wards (with a mean population of just over 25,000) were therefore used to map estimated risk: with 124 wards in West Yorkshire and 753 serious injuries in the region over 8 years, there were only 6.2 serious injuries to cyclist per ward.

It is interesting to note that the spatial distribution of estimated *risk* presented in Fig. 9 is very different from the distribution of crashes overall (Fig. 8). This emphasises the importance of normalising for exposure, in this case estimated at the small area level from mode of commute data.

The use of 'serious' and 'fatal' incidents as the numerator of risk was to allow for direct comparability between our analysis at high spatial resolution and official estimates of cyclist risk, which are generally coarser. Incidents classified as 'slight' "are more likely to be under reported than more serious casualties" (Keep, 2013, p. 3) so were not used to estimate exposure-normalised risk. Still, the statistics on slight injuries constitute 81% of incidents involving cyclists and, depending on police reporting practices and therefore constitute a very useful source of information on the relative risk of cycling in different areas. The high correlation between the estimated risk of 'slight' and 'serious' incidents (r = 0.62 at the ward level, r = 0.63 at the Local Authority level) suggests that riskiness is to some degree geographically determined, regardless of exposure levels and type of casualty.

Our findings provide some support for 'strength in numbers' (hypothesis 2.1): the number of people cycling to work (and hence our estimate of exposure) in each zone is negatively correlated to risk per bkm (r = 0.39 and r = 0.95 at ward and Local Authority levels respectively)

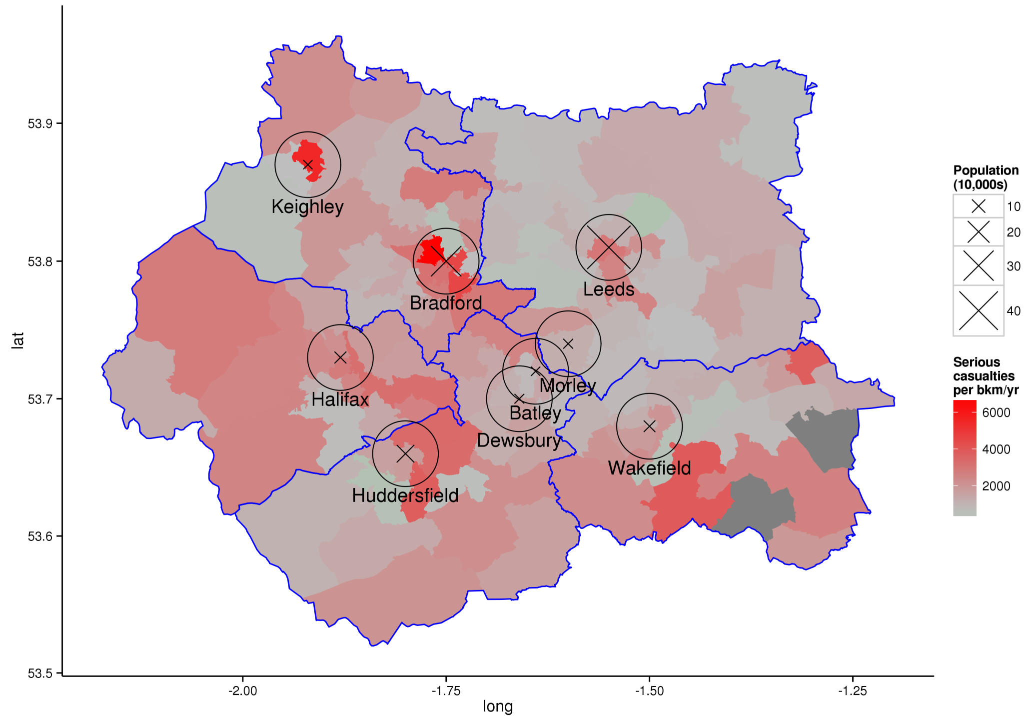

Figure 9: Risk of cycling per billion kilometres across West Yorkshire. The circles represent 5 km bands from the city centres which are deemed cyclable by the majority of the population

Road type

The relative proportions of road traffic incidents are roughly the same across A, B and U (Unclassified) roads between those that involve cyclists and those that do not (Fig. 10). The exception to this is the number of incidents occurring on the motorway, which is to be expected as cycling on motorways is not permitted. Of note was the high proportion of cycling injuries happening on (fast) A roads (42.3%), greater than the proportion of other incidents happening on these roads (41.0%). Given that that A roads constitute only a fraction of all roads and the tendency of cyclists to avoid busy roads, this finding suggests that cycling on A roads in West Yorkshire is a disproportionately risky compared with other places: Assuming that 30% of on-road cycling takes place on A-roads, this would imply that cyclists are 37% more likely to be involved in a crash on A roads than on other types of road. (Local survey data on the types of road where people cycle by distance would be needed to verify the 30% figure: if cyclists heavily avoid A roads, as can be expected, the relative risk could be much higher in West Yorkshire.) Indeed, this finding is supported by national statistics showing that the *serious* injury rate for cyclists on A roads (2,407 per billion miles cycled) is more than double the rate for cycling on all road types (1,005) (Keep, 2013).

Junctions and roundabouts seem to be disproportionately risky for cyclists in West Yorkshire, coinciding with the existing literature (e.g. Reynolds et al., 2009). An interesting trend in the data, not shown in Table 5, is that the increased riskiness of junctions for cyclists dissipates as the severity the injury increases: 30% of serious cyclist injuries and 44% of all cyclist deaths happened away from junctions. This implies that although cyclists are proportionally more likely to be hit near junctions than other road users, when collisions do happen on (presumably fast) open roads, they tend to be severe for cyclists.

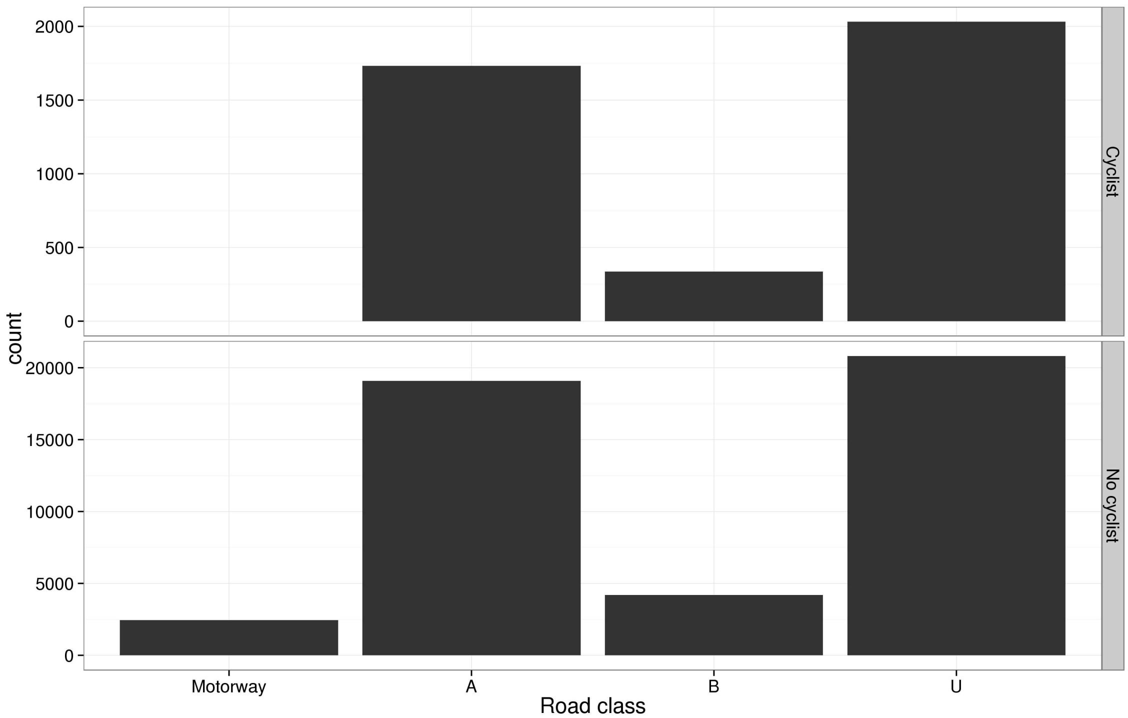

Figure 10: Number of road incidents in West Yorkshire with cyclists (top) and no cyclists (bottom) involved by road class

Table 5: The proportion of incidents involving cyclists (n = 4,101) and no cyclists (n = 46,555) within 10 m of different types of junction.

Junction type	Cyclist	No cyclist
Not at junction	27.1	39.4
Roundabout	7.0	5.7
Mini-roundabout	0.7	0.6
T junction	46.4	33.7
Slip road	0.7	1.8
Crossroads	10.0	11.2
Multi-junction	1.7	2.6
Private drive	2.9	1.5
Other junction	3.6	3.5

When are bicycle crashes most likely?

Time of day

The distribution of cyclist casualties across the day is similar to that of road traffic incidents overall. However, crashes involving cyclists have a much 'peakier' distribution than that all other road traffic incidents, with the incident density during the afternoon rush hour almost 50% higher for cyclists than non-cyclists (Fig. 11).

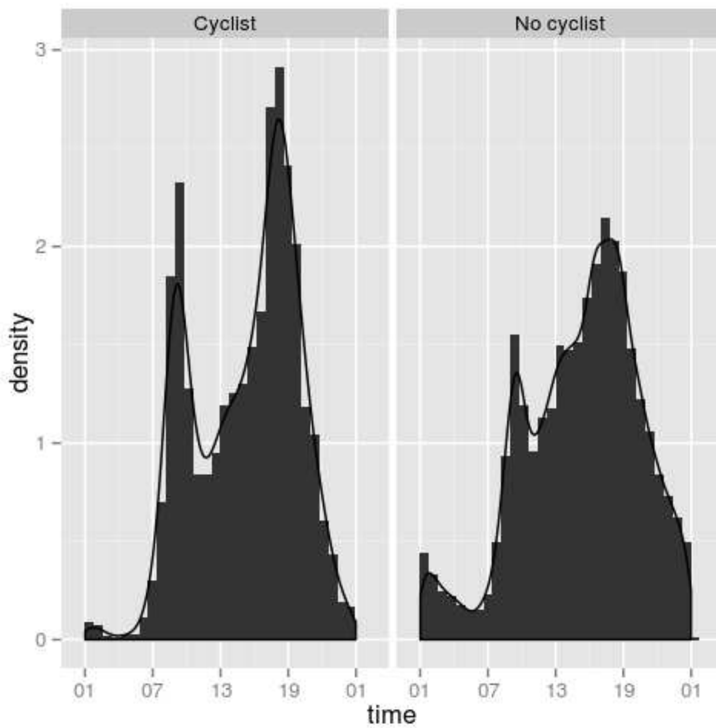

Figure 11: Time of day distribution of cyclist road traffic casualties relative non-cyclists.

Light conditions

We found no evidence in the data to support the hypothesis that cyclists are disproportionately more at risk during night time. The proportion of bicycle crashes that took place in daylight (79%) was higher than the proportion of all incidents (71%) and the difference grew with increased injury severity: 81% of cyclist deaths occurred during daylight, whereas only 53% of other deaths did, implying that cyclists' aversion to cycling at night may explain relatively low incident rates at night for cyclists overall. Other factors must be used to explain why this tendency grows stronger for more severe injuries. These could include cyclist and driver behaviour (who are perhaps more cautious in the dark), lower traffic volumes leading to fewer multi-vehicle incidents (which tend to be more severe) and the increased long-range visibility of cyclists who have lights. More evidence would be needed to test these potential causes.

The interaction between age and time of day

To further explore the reasons behind the finding of increased risk amongst young people, we analysed the time of day during which incidents happened, disaggregated by age group. Cyclists seem disproportionately at risk during the rush hour (i.e. on the way to work). Subsequently, we explored whether the bimodal distribution displayed in Fig. 11 may vary with age. This does indeed seem to be the case: the timing of cycle crashes shifts from a unimodal distribution for the lowest age groups to a fully bimodal distribution for young adults. This time evolution is not as pronounced for other types of road traffic incidents (Fig. 12). This pattern continues until retirement age (not shown).

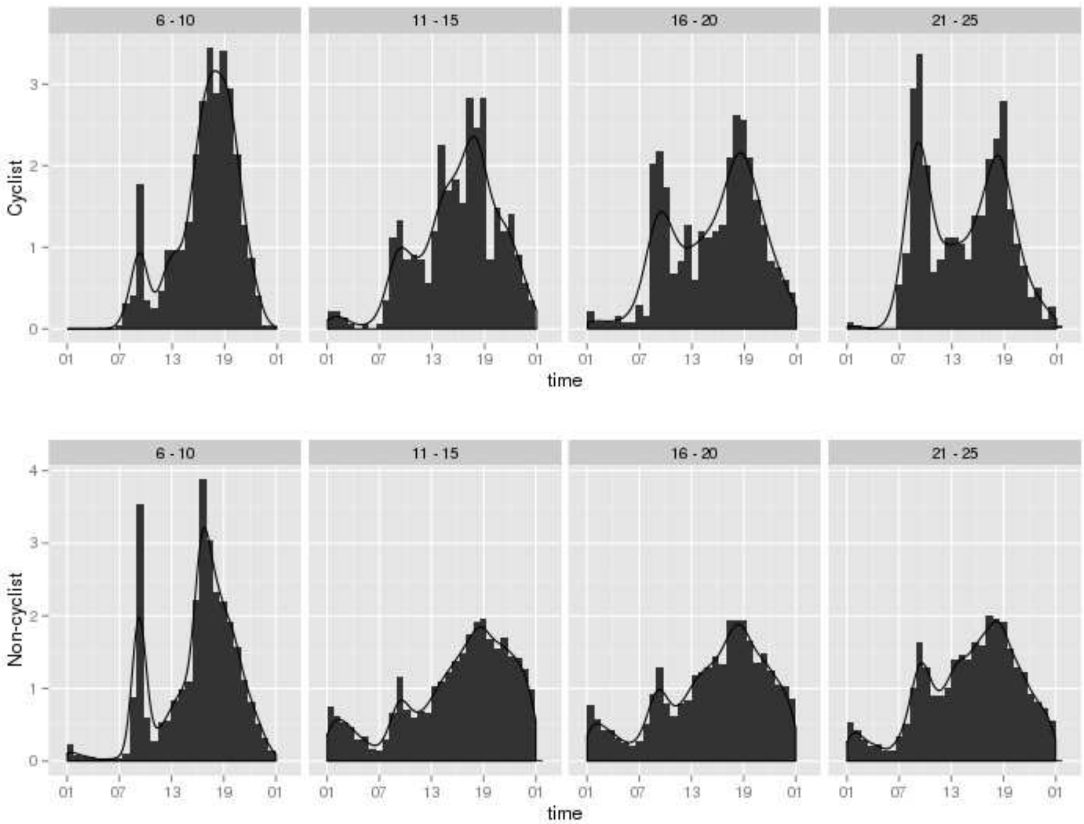

Figure 12: Time of incident for cyclist and non-cyclist casualties by age band

Discussion and conclusions

This paper explores the social and spatial characteristics of cyclist casualties in West Yorkshire. Our findings are particularly relevant for future policies as the region historically has a low cycling rate, and has recently committed to investing in local cycling infrastructure and promotion. We designed a set of hypotheses around three broad research questions: who is most at risk, where are the crashes most likely to happen and when are bicycle crashes most likely? Our findings for each will be discussed here in turn within the wider context of the relevant literature.

Who is most at risk?

Our findings support the hypothesis that young cyclists are at greater risk from road traffic than adults. West Yorkshire appears to be especially risky for young cyclists, both compared with other forms of transport in the area and compared with the age distribution of risk nationwide. This agrees with the conclusions of Martinez-Ruiz et al. (2014), who found people under age 30 were more at risk when cycling compared to older age brackets. This should be a cause for concern given the behaviour of young people today will have effects long into the future and the disproportionate impact on disability adjusted life years (DALYs) of young casualties (Woodcock et al., 2014). We did not find any evidence that cycling is riskier for older people than the population at large overall. However, the *rate* of increase in casualties in the middle-aged 'mamil' group is new and unexpected. We hypothesise that this can be explained by growth in leisure cycling, reflecting the increased danger to sports cyclists on fast roads relative to utility cycling.

Our second hypothesis within this question was that risk to vulnerable groups would be higher on larger, faster roads. Although we found evidence that faster A roads were more dangerous overall for cyclists (in-line with national-level analyses), we did not find evidence of vulnerable groups being *disproportionately* at risk in these environments.

Where are crashes most likely to happen?

Our finding that the number of people cycling to work in each zone is negatively correlated to risk per bkm supports the idea that the more cycling there is in a particular area, the safer cycling becomes. This aligns with the 'strength in numbers' hypothesis (Jacobsen, 2003) and is an indication that promoting uptake may lead to a virtuous circle, whereby increased numbers address safety directly, and subsequently indirectly through reduced safety concerns. On the other hand there is evidence that measures targeting safety specifically improve perceptions of safety (El-Basyounya and El-Bassiouni, 2013), thereby indirectly increasing uptake. Future studies should explore the presence of such 'positive feedbacks' and the importance of perceived risk of injury for cycling uptake. However, our local exposure estimates are based solely on cycle commuting, so this finding requires further research to be corroborated.

Secondly, we found evidence to support the hypothesis that cyclists were disproportionately at risk on high traffic roads, junctions and roundabouts than other road users. This is in line with several studies that demonstrate junctions and roundabouts are the main hazard for cyclists on cycle lanes (see Krizek and Roland, 2005; Watchel and Lewison, 1994). In their analysis of STATS19 data from 1990-1999, Stone and Broughton (2003) similarly found over 70% of incidents occurred at or within 20m of a junction. When these incidents were disaggregated by severity, however, this effect dropped for more serious injuries.

Cyclists were found to be disproportionately at risk on the largest roads (A roads), compared with other modes of travel, highlighting cyclists' vulnerability to high traffic speeds and volumes. This trend was not found for B or Unclassified roads, suggesting that safe cycling infrastructure could have a substantial role in reducing risk along heavily used roads. This finding is supported by national statistics showing that the serious injury rate for cyclists on A roads (2,407 per billion miles cycled) is more than double the rate for cycling on all other road types (1,005) (Keep, 2013). We have also seen the propensity for increased risk on faster roads at a more local scale in London, where over half of all bicycle crashes (52.2%) from 2005-2007 occurred on A roads (Singleton and Lewis, 2011). It is worth nothing, however, that research has shown crash circumstances are unevenly distributed also by the road type, so that collisions with motor vehicles are found to be over-represented on major roads with parked cars, whereas collisions more often involve infrastructure on multi-use paths and bike paths (Teschke, 2014). Therefore appropriate safe cycling infrastructure may vary by road type.

When are bicycle crashes most likely?

The proportion of incidents involving cyclists has indeed increased over time, which supports the hypothesis we put forward. But, because the increase happened faster than growth in the proportion of all distance travelled by bicycle nationwide, this additionally implies cycling in West Yorkshire has become more dangerous over time. This follows the same nationwide pattern reported by the Department for Transport (DfT), who, in their Road Casualties Annual Report, stated the number of killed or seriously injured casualties had been rising steadily since 2004, insofar as in 2012 the number was 32% higher than the 2005-2009 average. This was accompanied by an estimated 12% increase in cycle traffic (DfT, 2012b).

In terms of the distribution over time, bicycle crashes were found to be different from the national average, with a 'peaky' bimodal distribution. This implies that cyclists are disproportionately affected by the heavy traffic conditions of the 'rush hour'. This can be associated with more motorised vehicles on the road allowing for increased risk of a collision, and has been evidenced in literature (e.g. Kim et al., 2007). In terms of the effect of light conditions, we found no evidence to support the hypothesis that cyclists are disproportionately more at risk during night time. Interestingly this goes against much research which finds an increased risk of cycling in the dark, which decreases visibility and therefore slows reaction times (Rodgers, 1995). Further research is needed to more fully understand this, which may be related simply to fewer cycle trips taking place at night or behavioural factors of drivers and cyclists, obedience of road signs, wearing of bright-coloured clothes and the display of lights.

Overall we have found evidence that agrees with some of our proposed hypotheses whilst others received limited support. There is great potential for further research to validate our speculative interpretations and bring about firm conclusions. In addition, there were methodological issues encountered which may have influenced our results.

This study was reliant on census commuting data to estimate the *denominator* of risk: relative exposure in different zones. This is problematic in two ways. First, cycling rates amongst zone inhabitants may not always relate to the amount of cycling passing through a particular area (e.g. if a zone is particularly popular for recreational cycling). Second, cycling to work is an imperfect proxy for cycling overall (Goodman, 2013). It is conceivable that in some areas there is very little cycling to work (e.g. due to lack of nearby jobs) but many leisure trips amongst inhabitants. Conversely, in areas where it is less pleasant to cycle but where many residents cycle to work, our methodology will overestimate cycling. Still, census data on travel to work provides the most comprehensive and highest resolution data on cycling available, allowing estimation of risk at an unusually high level of spatial resolution. The paper therefore highlights the importance of local survey data for corroborating estimates of exposure and the methodological opportunities for improving small-area estimates of cycling (e.g. based demographic and geographical factors associated with high rates of non-work cycling, not considered in the analysis).

Another methodological issue raised by this research relates to the *numerator* of risk: number of cyclist casualties. The uncertainty surrounding police records for non-fatal casualties has already been mentioned with respect to police under-reporting in Ireland (Short and Caulfield, 2014). A wider issue is whether riskiness is well measured by the number of incidents that result in police reports or hospitalisations at all. For every incident reported in STATS19, there may be many 'close calls' in which cyclists narrowly avoid harm. Indeed, Kroon (cited in Schepers, 2013) found in the Netherlands that the rate of reporting by the police is much higher when a bicycle crashes with a motor vehicle as opposed to when no other vehicles are involved. Although hospital episode statistics collate more bicycle crash records than police data, again it is argued they systematically fail to note how an incident occurred (instead focused on collecting age, gender and injury data) (Benington, 2012).

Methodological opportunities are highlighted by the research. The use of new 'naturalistic' monitoring technologies and innovative methods of analysis has been used recently to estimate the factors associated with risk at the local level (Dozza and Werneke, 2014). We believe this methodology, and the simpler approach of asking participants where they feel most in danger (Chataway et al., 2014), has great potential for improving understanding of the social and geographical factors associated with both perceived risk and risk inadequately indexed by STATS19.[8] Additionally, Van der Horst (2014) has found behavioural observation through video capture was a successful technique for data collection on cyclist risk, as it allowed repeated review and judgment of different aspects of the situation. Stevenson (2014) also uses cameras attached to participants' bikes, allowing for naturalistic data from an objective point of view. In this sense qualitative research may offer much by way of answering several questions that have arisen during our data analysis.

There is great potential to increase the geographical resolution and accuracy of risk estimates presented in this paper. Using geographically aggregated bicycle commuter counts is only a rough proxy for the cycling rate in an administrative zone overall, let alone along specific paths. Fortunately, new datasets will soon become available to overcome this limitation. These include 'volunteered geographic information' (Goodchild, 2007), for example from GPS-enabled smartphone applications such as Strava[9]. Companies such as Google already collect vast quantities of geographically coded data, creating the potential for corporations to share data with government for social benefit. Another option is the uptake of apps developed by government and researchers. Finally, passively collected data from mobile phone service providers have a huge potential to inform policy makers about where and how people travel (e.g. Bonnel and Hombourger, 2014). These

[8] 'The Near Miss Project' is an example of new approaches to identifying where bicycle crashes have almost happened and has already recorded more than 1,000 incidents. See http://nearmiss.bike/ for more information.

[9] See http://labs.strava.com/heatmap/ for an insight into the coverage of this dataset.

emerging datasets and the new methodologies they will require will play a large role in future cycling risk studies.

The resulting insights have the potential to influence policy. The interventions to improve cyclist safety resulting from this research should include reduced speed limits (Bunn et al., 2003), off-road paths along fast roads (Vandenbulcke et al., 2014) and better enforcement of road regulations (Wegman et al., 2012). More radical approaches include steps to normalise cycling, restrict car use and the modification of road markings to encourage safer driving (Shackel and Parkin, 2014). These changes have the potential to simultaneously improve the health benefits of cycling while lowering one of the most important barriers to cycling: fear of injury.

The most important empirical contribution of this paper is the finding that risks to cyclists are context-specific and geographically variable. The work indicates that different types of cyclists have different risk profiles in different places, implying cycle safety policy should be more targeted to local needs. Given that health benefits of cycling are generally not geographically dependent - with the notable exception of air pollution (de Hartog et al., 2010) - it is risk of injury, the major health cost of cycling uptake, that will determine the geographical distribution of health benefit: cost ratios in most contexts. It is conceivable, for example, that there are locations in which the costs outweigh the benefits for especially vulnerable groups (e.g. teenagers with little cycling experience or training).

Identification of such 'danger hotspots', using the methods presented in this paper alongside localised data collection and emerging 'big' datasets, will help prioritise funding and inform transport policies in other area.[10] Localised analysis of STATS19 data can provide a fast and inexpensive insight for local authorities tasked with improving cycling provision and the desirability of cycling, for example to comply with new regulation.[11] Further work in this area is especially needed in areas where ambitious targets and large funding grants for increased cycling have been allocated. This will ensure that the wide-ranging health benefits of cycling can be enjoyed everywhere in safety.

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[10] The methods of this research are reproducible, allowing others to re-use the code used to analyse STATS19 and other datasets for their own purposes. We encourage the re-use of the R code stored at github.com/Robinlovelace/bikeR for further work in other areas, with due acknowledgement to this paper.

[11] The the recently passed Active Travel (Wales) Act provides an example of new regulation on cycling. This legally binding legislation was passed by the National Assembly for Wales and requires "highway authorities to have regard in the construction and improvement of highways to the desirability of enhancing provision for cycling and walking". Source: http://www.senedd.assembly.wales/mgIssueHistoryHome.aspx?IId=5750.

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