Long term bicycle related head injury trends for New South Wales, Australia following mandatory helmet legislation

Author:
Olivier, Jake; Walter, Scott; Grzebieta, Raphael

Publication details:
Accident Analysis and Prevention
0001-4575 (ISSN)

Publication Date:
2012

Accident Analysis and Prevention xxx (2012) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Long term bicycle related head injury trends for New South Wales, Australia following mandatory helmet legislation

Jake Olivier[a,*], Scott R. Walter[b], Raphael H. Grzebieta[c]

[a] School of Mathematics and Statistics, University of New South Wales, Sydney, Australia
[b] Centre for Health Systems and Safety Research, Australian Institute of Health Innovation, University of New South Wales, Sydney, Australia
[c] Transport and Road Safety (TARS) Research, University of New South Wales, Sydney, Australia

ARTICLE INFO

Article history:
Received 12 March 2012
Received in revised form 1 July 2012
Accepted 4 September 2012

Keywords:
Bicycle helmet legislation
Australia
Long term trends
Risk compensation
Bicycle infrastructure

ABSTRACT

Since the 1991 enactment of mandatory helmet legislation (MHL) for cyclists in New South Wales (NSW), Australia, there has been extensive debate as to its effect on head injury rates at a population level. Many previous studies have focused on the impact of MHL around the time of enactment, while little has been done to examine the ongoing effects. We aimed to extend prior work by investigating long-term trends in cyclist head and arm injuries over the period 1991–2010. The counts of cyclists hospitalised with head or arm injuries were jointly modelled with log-linear regression. The simultaneous modelling of related injury mechanisms avoids the need for actual exposure data and accounts for the effects of changes in the cycling environment, cycling behaviour and general safety improvements. Models were run separately with population counts, bicycle imports, the average weekday counts of cyclists in Sydney CBD and cycling estimates from survey data as proxy exposures. Overall, arm injuries were higher than head injuries throughout the study period, consistent with previous post-MHL observations. The trends in the two injury groups also significantly diverged, such that the gap between rates increased with time. The results suggest that the initial observed benefit of MHL has been maintained over the ensuing decades. There is a notable additional safety benefit after 2006 that is associated with an increase in cycling infrastructure spending. This implies that the effect of MHL is ongoing and progress in cycling safety in NSW has and will continue to benefit from focusing on broader issues such as increasing cycling infrastructure.

1. Introduction

Mandatory bicycle helmet legislation (MHL) came into effect in New South Wales on 1 January 1991 for adults (16 years of age or older) and 1 July 1991 for children. Around that time, helmet wearing rose rapidly from about 10% and 25% for children and adults in 1990, respectively, to around 80% for both by 1992. This level was maintained the following year (Walker, 1990, 1991, 1992; Smith and Milthorpe, 1993). No published estimates of helmet wearing in NSW exist past that date.

Systematic reviews of reports on the effectiveness of helmet wearing on mitigating bicycle related head injuries have shown a positive effect (Thompson and Patterson, 1998; Attewell et al., 2001; Thompson et al., 2004); however, a recent meta-analysis suggested the effectiveness of helmets may be overstated (Elvik, 2011). Results from meta-analyses should be interpreted with caution since ultimately, they are analyses of statistical studies rather than a large statistical study in itself and sample bias will always be present regardless of who is carrying out the analysis, particularly when it is related to a political agenda or legislation (Roseman et al., 2011; Hunter and Schmidt, 1990; Slavin, 1986; Rosenthal, 1979). Research into the effectiveness of MHL in Australia, New Zealand, the US and Canada has demonstrated a positive effect in lowering bicycle related head injuries after enacting a version of MHL (Cameron et al., 1994; Walter et al., 2011; Scuffham et al., 2000; Povey et al., 1999; Rivara et al., 1994; Macpherson et al., 2002). Moreover, when considering the biomechanical helmet padding system protecting the head, Newtonian laws of physics dictate that an impact force via the helmet to the head during a reasonable velocity crash (50–60 km/h or less) must reduce the magnitude of the blunt force imposed onto the rider's head, and thus the severity of the head injury. This is a given physical fact that can be readily proven both experimentally and from in-depth real world crash investigations (Dorsch et al., 1987; Benz et al., 1993;

* Corresponding author at: Department of Statistics, School of Mathematics and Statistics, University of New South Wales, Sydney, NSW 2052, Australia.
Tel.: +61 2 9385 6656.
E-mail address: j.olivier@unsw.edu.au (J. Olivier).

0001-4575/$ – see front matter. Crown Copyright © 2012 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.aap.2012.09.003

McIntosh et al., 1998, 2010; Pang et al., 2009; Haworth et al., 2010; McIntosh and Patton, 2012). Thus, given that helmets dampen the impact force and subsequent injury severity, it is expected that evidence of helmets reducing head injuries would be evident in hospital admissions data and bicycle population surveys.

Research critical of the NSW legislation noted a decline in ridership (Robinson, 1996) among some age groups, although survey results indicated no overall change in cyclist numbers (Smith and Milthorpe, 1993). A review of Australian and international literature suggests cycling rates are increasing overall in jurisdictions with mandatory helmet laws (Haworth et al., 2010). A recent survey by the Cycling Promotion Fund (2011) cited that unsafe road condition, speed/volume of traffic, lack of bicycle lanes or safety as key reasons for not cycling. Helmets were ranked 10th on the list as a reason for not cycling more among those who had cycled in the past month and ranked 13th among non-cyclists. Further, it has been hypothesised through risk compensation, i.e., a cyclist exhibits riskier behaviour when wearing a helmet, that helmet wearing leads to more bicycle related injuries (Lardelli-Claret et al., 2003). In an effort to account for unmeasured fluctations in the cycling environment (frequency and cycling distance) and cyclist behaviour (risk compensation), Walter et al. (2011) compared the change in head injuries with limb injuries and found an approximate 29% reduction in bicycle related hospitalisations due to head injury over and above any changes to limb injuries when comparing the 18 month periods before and after MHL.

It is now over 20 years since mandatory helmet laws were enacted in Australia and little is known about its long term effects. This manuscript extends previous research by Walter et al. (2011) by modelling long term hospitalisations due to bicycle related head and arm injuries. These trends will then be compared with imports of bicycles into Australia, the average number of weekday bicycle movements on major routes to and from Sydney's CBD and estimates of cycling rates in NSW as proxies for the number of active cyclists.

2. Methods

Hospitalisations due to bicycle related head and arm injuries in NSW were identified from the Admitted Patients Data Collection (APDC) for years 1991–2010. The electronic collection of hospital data in NSW began in July 1988 with diagnoses classified using the International Classification of Diseases, 9th Revision, Clinical Modification (ICD-9-CM) system up to June 2000. The use of ICD-10-AM (Australian modification) was phased in two years prior to the dissolution of ICD-9-CM for classifying diagnoses. Additionally, hospitalisations were categorised as to whether the individual was involved in a motor vehicle collision (MVC) and age categories relevant to the two helmet laws (i.e., $\leq$15 and >15 years of age). For the purposes of our analyses, Table 1 lists the ICD-9-CM and ICD-10-AM codes used to identify bicycle related head and arm injuries in the APDC. It should be noted that there are some ICD-9-CM codes that combine head and neck injuries while there is a clear distinction between these injury locations in ICD-10-AM. As noted previously, injuries coded this way are rare with about 10 total cases per year (Walter et al., 2011). Due to the slight coding inaccuracy for identifying head injuries, ICD-10-AM was used during the overlapping period. It is important to note that the APDC does not collect information on helmet use.

2.1. Measures of exposure

Four measures of exposure are used for our analyses. Mid-year NSW population estimates were used to account for changes in population size (Australian Bureau of Statistics, 2008). As little is known about actual cycling rates in NSW, the number of bicycles imported into Australia is used as a proxy measure of the number of active cyclists (Cycling Promotion Fund, 2010). This data is only available for years 2000–2009, so our analysis using imported bicycles will be limited to the years it overlaps with hospitalisation data. During this 10 year period, bicycle imports outnumbered car sales each year for an overall difference of approximately 2 million units.

Since 2002, the NSW Roads and Maritime Services have counted the number of bicycle movements at three primary locations that feed into cycleways within the Sydney CBD (Sydney Harbour Bridge, Anzac Bridge and Anzac Parade). These counts have been aggregated by year and weekday counts have been averaged to estimate the number of daily commuting cyclists in the Sydney CBD (Table 2). Annually since 2001, the Australian Sports Commission has conducted the Exercise, Recreation and Sport Survey (ERASS) in an effort to collect information on physical activity including types of activities (Australian Sports Commission, 2010). After stratification by state/territory, participants aged 15 years or older were randomly selected for a telephone interview (Australian Sports Commission, 2010). Estimates of NSW residents aged 15 years or older who had cycled in the past 12 months for years 2001–2010 are given in Table 2.

The use of arm injuries as a comparison for head injuries is known as a dependent non-equivalent no-treatment control group (Shadish et al., 2002). As noted in previous research, unmeasured changes in the cycling environment, safety improvements and the behaviours of cyclists (e.g., cycling rate and distance cycled) would affect head and arm injuries similarly with the exception of interventions directed at one and not the other (Povey et al., 1999; Walter et al., 2011). Any deviations from the comparison of head and arm injuries over time would indicate the effects of such differentially targeted interventions. The use of cyclist arm injuries as a comparison to account for threats to internal validity is superior to other mechanisms such as pedestrian or motor vehicle related injuries (Shadish et al., 2002).

2.2. Statistical analysis

Log-linear regression was used to estimate the trend in head and arm injuries from the beginning of the first MHL in NSW (i.e., January 1991) up to 2010 which is the most recently available hospitalisation records. This approach models the counts of head and arm injuries with the independent variables *TIME*, *INJURY* and $TIME \times INJURY$. The trend variable *TIME* represents the number of years since MHL so that 1991 corresponds to $TIME = 0$ while *INJURY* is an indicator variable that takes on the values 0 for arm injuries and 1 for head injuries. Generalised estimating equations (GEE) were used to account for within-year variability between head and arm injuries (Dobson and Barnett, 2008). Our analytic model thus takes the following form.

$$\log(count) = \beta_0 + \beta_1 TIME + \beta_2 INJURY + \beta_2 TIME \times INJURY + \log(exposure)$$

Due to the reference coding described above, the term *TIME* describes the yearly rate of change in arm injuries and the statistical test associated with the $TIME \times INJURY$ term is a measure of how the yearly change in head injuries differs from arm injuries. Since tests of interaction are less powerful than main effects, interaction p-values larger than 0.05 but less than 0.20 will be assessed by their effect size (Marshall, 2007).

Table 1
ICD-9-CM and ICD-10-AM codes used for case selection.

	ICD 9-CM code range	5th character	ICD 10-AM
Cyclists	E800–E807 E810–E825 E826, E829	3 6 1	V10–V19
Head injury	800–804, 850–854 870–873, 830, 910, 918, 920, 921, 925.1, 930–932, 950, 951, 957.0, 959.0		S00–S09
Arm injury	810–819, 831–834 840–842, 880–887 912–915, 903, 923, 927, 955, 959.2–959.5		S40–S69
Cyclist MV collision	E810–E819	6	V12–V14 V19.0–V19.2 V19.4–V19.6
Cyclist non-MV collision	E800–E807 E820–E825 E826, E829	3 6 1	V10–V11 V15–V18 V19.3, V19.8, V19.9

Table 2
Bicycle related head injury and arm injuries hospitalisations in New South Wales for 1991–2010.

Year	Head injuries	Arm injuries	NSW population	Bicycle imports	Sydney CBD cycling counts	ERASS
1991	590	660	5,898,731			
1992	648	760	5,962,569			
1993	635	839	6,004,880			
1994	634	882	6,060,190			
1995	667	964	6,126,981			
1996	732	1114	6,204,728			
1997	745	1058	6,276,961			
1998	750	1144	6,339,071			
1999	756	1115	6,411,370			
2000	828	1334	6,486,213	926,924		
2001	715	1171	6,575,217	774,938		400,800
2002	795	1241	6,628,951	1,109,736	1552	429,100
2003	806	1390	6,672,577	1,003,844	1693	404,300
2004	882	1457	6,707,189	1,247,991	1870	481,700
2005	847	1583	6,756,457	1,168,601	2251	474,200
2006	1004	1622	6,816,087	1,199,854	2622	468,300
2007	878	1576	6,904,942	1,427,738	2958	447,400
2008	840	1623	7,014,887	1,203,628	3121	539,600
2009	769	1619	7,127,168	1,154,077	3915	503,600
2010	706	1620	7,221,536		3974	603,500

Sources: Admitted Patients Data Collection (HOIST), NSW Ministry of Health; Cycling Promotion Fund. CPF Annual Report 2009/10. Canberra (AUST): CPF; NSW Roads and Maritime Services; Exercise, Recreation and Sport Survey (ERASS), Australian Sports Commission (2010).

3. Results

The number of bicycle related head and arm injury hospitalisations in NSW from 1991 to 2010 is presented in Table 2. Fig. 1 shows an increasing trend in counts of hospitalisations for head and arm injuries across the study period. Head injury counts are considerably lower than arm injury counts and are increasing at a much slower rate (0.5% vs. 3.3% per year). The results of fitting the model described above with population size and bicycle imports as proxy exposure measures are shown in Table 3. Where population was used as the exposure, both injury groups increased over the period with arm injuries increasing at a significantly faster rate than head injuries. Head and arm injuries within the same year exhibited strong correlation ($\widehat{\phi} = 0.89$). The model based on bicycle imports as the exposure showed a downward trend in both groups with a rate of divergence similar to the population based model. Potentially due to few time points, the use of bicycle imports as exposure led to a non-estimable Hessian matrix in the generalised estimating equations framework. Model estimates were then obtained under an assumption of within-year independence which is a conservative approach (i.e., inflated *p*-values). Both models found a large gap between injury groups at *TIME* = 0, which increased over time.

The analysis was repeated separately for each combination of children/adults and MVC/non-MVC with the results presented in Table 4. Since Australian bicycle import data is not broken down into age categories, the NSW population is used as the offset for each model. Further, the Sydney CBD cycling count and ERASS data

Table 3
Untransformed log-linear model estimates for bicycle related head and arm hospitalisations using population size (1991–2010) and bicycle imports (2000–2009) as the offset.

Variable	Population size			Bicycle imports		
	Estimate	95% CI	*p*-Value	Estimate	95% CI	*p*-Value
TIME	0.032	0.026, 0.038	<0.001	−0.006	−0.026, 0.014	0.535
INJURY	−0.205	−0.252, −0.157	<0.001	−0.217	−0.611, 0.177	0.281
TIME × INJURY	−0.027	−0.032, −0.022	<0.001	−0.025	−0.054, 0.003	0.083

Table 4
(a) Untransformed log-linear model estimates for bicycle related head and arm hospitalisations by age group and crash type using population size (1991–2010) as the offset. (b) Untransformed log-linear model estimates for bicycle related head and arm hospitalisations for adults by crash type using cycling counts (2002–2010) and ERASS (2001–2010) as the offset.

(a)	Variable	Motor vehicle collisions			Non-motor vehicle collisions		
		Estimate	95% CI	*p*-Value	Estimate	95% CI	*p*-Value
Children	TIME	−0.011	−0.026, 0.005	0.188	0.005	−0.008, 0.018	0.420
	INJURY	0.625	0.449, 0.801	<0.001	−0.350	−0.548, 0.152	0.001
	TIME × INJURY	−0.021	−0.035, −0.007	0.003	−0.017	−0.035, 0.001	0.060
Adults	TIME	0.062	0.051, 0.073	<0.001	0.073	0.068, 0.077	<0.001
	INJURY	0.038	−0.077, 0.152	0.519	−0.187	−0.262, −0.112	<0.001
	TIME × INJURY	−0.031	−0.041, −0.022	<0.001	−0.035	−0.041, −0.029	<0.001
(b)							
Cycling Counts	TIME	−0.047	−0.073, −0.021	<0.001	−0.046	−0.055, −0.037	<0.001
	INJURY	0.367	−0.093, 0.827	0.118	0.007	−0.180, 0.195	0.939
	TIME × INJURY	−0.051	−0.081, −0.022	<0.001	−0.047	−0.058, −0.036	<0.001
ERASS	TIME	0.044	0.030, 0.058	<0.001	0.042	0.023, 0.061	<0.001
	INJURY	0.166	−0.247, 0.549	0.395	−0.100	−0.596, 0.396	0.693
	TIME × INJURY	−0.039	−0.064, −0.014	0.002	−0.040	−0.073, −0.008	0.016

are unlikely to contain information on child cycling rates, so these proxy exposures will only be used for the analysis of adult injuries. Arm injuries are significantly increasing for adults in both models while there is no significant trend for children. The results from each model show a significant divergence in head and arm injuries in the post-MHL period. The rate of divergence is more pronounced for adults (3.1% and 3.4% per year for MVC and non-MVC respectively) than children (2.1% and 1.7% per year). This divergent pattern is echoed, though more pronounced, when Sydney CBD cycling counts (5.0% and 4.6% per year) and the ERASS cycling participation estimates (3.8% and 3.9% per year) are used as the offset.

For direct comparison, bicycle imports, Sydney CBD cycling counts, ERASS cycling participation estimates and hospitalisations were standardised to mean 0 and standard deviation 1. Fig. 2 is a plot of these standardised values over time. The increase in arm injuries appears to mimic the increase in bicycle imports. Using Pearson's correlation coefficient, the trend in bicycle imports was highly associated with arm injuries ($r = 0.73$, $p = 0.016$) while the associations with Sydney CBD cycling counts and ERASS cycling participation estimates were marginally insignificant ($r = 0.575$, $p = 0.105$ and $r = 0.577$, $p = 0.081$ respectively). None of the proxy measure trends were significantly associated with the trend in head injuries. However, there appears to be an association between both head and arm injuries and bicycle imports, Sydney CBD cycling counts and ERASS cycling participation estimates up to 2006. A clear divergence between the three cycling exposure proxies and head injuries occurs post 2006. This is discussed further below.

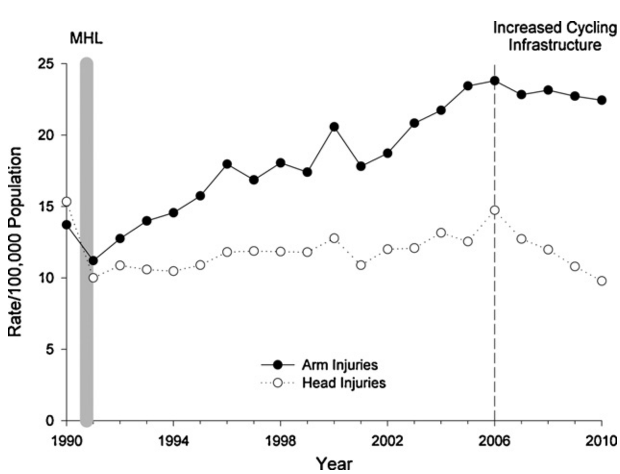

Fig. 1. Rates per 100,000 population of bicycle related head and arm hospitalisations in New South Wales by year (1991–2010).
Source: Admitted Patients Data Collection (HOIST), NSW Ministry of Health.

4. Discussion

Little is known regarding the long term effects of mandatory helmet legislation in NSW and, as a result, this study set out to estimate trends in bicycle related head injury hospitalisations from the enactment of MHL to the most recently available data. Our results suggest the immediate drop in head injuries in addition to any changes in arm injuries after MHL, as observed in Walter et al. (2011), has clearly been maintained over a long period. Each model estimated a growing divergence between head and arm injuries since MHL. Although head injury rates prior to MHL were greater than arm injury rates (Walter et al., 2011), the steady divergence post-MHL has led to a 46% drop in head injuries compared to arm injuries up to 2006 and a 51% drop by 2010.

The increase in the rate of arm injuries is consistent with risk compensation theory; however, this increase is more likely due to increases in cycling since it mimics the trends in bicycles imported into Australia, the counts of cyclists commuting into the Sydney

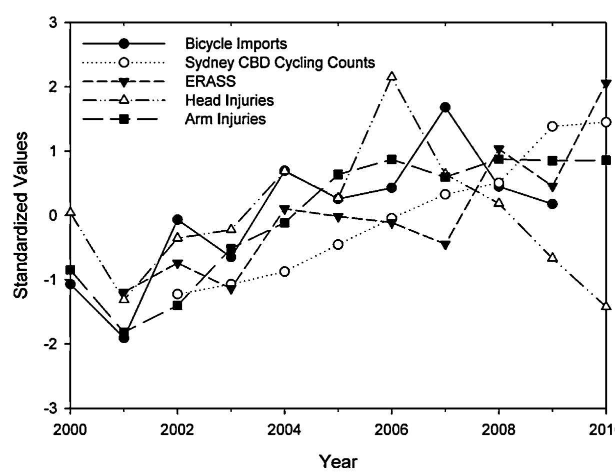

Fig. 2. Standardized bicycles imported into Australia, cycling counts in Sydney CBD, NSW cycling participation estimates (ERASS) and bicycle related head and arm hospitalisations by year (2000–2010).
Sources: Admitted Patients Data Collection (HOIST), NSW Ministry of Health; Cycling Promotion Fund. CPF Annual Report 2009/10. Canberra (AUST): CPF; NSW Roads and Maritime Services; Exercise, Recreation and Sport Survey (ERASS), Australian Sports Commission, 2010).

Please cite this article in press as: Olivier, J., et al., Long term bicycle related head injury trends for New South Wales, Australia following mandatory helmet legislation. Accid. Anal. Prev. (2012), http://dx.doi.org/10.1016/j.aap.2012.09.003

Table 5
Untransformed log-linear model estimates for bicycle related head and arm hospitalisations before and after increased cycling infrastructure spending using population size (2002–2010) as the offset.

Variable	Estimate	95% CI	*p*-Value
TIME	0.059	0.042, 0.076	<0.001
INJURY	−0.544	−0.611, −0.478	<0.001
INFRASTRUCTURE	−0.048	−0.123, 0.027	0.213
TIME × INJURY	−0.013	−0.041, 0.016	0.383
TIME × INFRASTRUCTURE	−0.066	−0.095, −0.037	<0.001
INJURY × INFRASTRUCTURE	0.044	−0.083, 0.171	0.501
TIME × INJURY × INFRASTRUCTURE	−0.069	−0.118, −0.020	0.006

CBD and cycling participation estimates in NSW. There is evidence that the number of cyclists is increasing (Australian Bureau of Statistics, 1998, 2010; NSW Roads and Traffic Authority, 2008) and at a faster rate than population growth, which suggests that the trends in our exposure measures may be reasonable proxies for the trends in overall cyclist numbers. The results of the model using imports as the exposure implies that safety has remained steady overall for cyclists with no trend in arm injuries, but a noticeable improvement in head injuries with a reduction of about 24% between 2000 and 2009. Since there were no other interventions aimed at a specific type of injury mechanism in the period since MHL, it is likely that the ongoing divergence indicates that the positive effect of MHL on head injuries has been maintained.

There appears to be two distinct periods of head and arm injury divergence. The first period from 1991 to 2006 is noted by a steady increase in arm injuries which is associated with an increase in cycling numbers while head injuries have declined relative to bicycle imports and Sydney CBD cycling counts. The additional observed divergence between head and arm injury rates after 2006 may possibly be explained by marked improvements in cycling infrastructure around this time.

Fig. 1 indicates the rate of divergence between head and arm injuries increases from 2006 onwards. It was during this period that significant financial investment by various local NSW governments were being made and continued in the second half of the decade. Montoya (2010) points out that a total of $AUD29.3 million was spent by the then New South Wales state government Roads and Traffic Authority on bicycle facilities in 2008–09. Of this amount, more than $AUD5.6 million was provided in matching funding for 103 local cycleway projects in 80 council areas resulting in a total of 53 km of on-road cycleways and 44 km of off-road cycleways being built during this period. Montoya further indicates that rates of cycling generally mirror the amount invested in infrastructure. In a more recent survey of local councils throughout Australia, the Australian Bicycle Council (2012) indicated there was a five-fold increase from 2006 to 2010 in the number of bicycle strategies implemented by local government where the most common element was increasing bicycle infrastructure significantly. Local councils surveyed, of which 30% of the councils were from NSW and the largest proportion of any state, had increased from an average of 21 km on-road and 30 km off-road infrastructure in 2007 to 44 km on-road and 38 km off-road infrastructure in 2010. Similarly, the average spend per council increased from $194 K in 2007 to $239 K in 2010.

This hypothesis was tested using a log-linear model with 2006 as *TIME* = 0 and the addition of the indicator variable *INFRASTRUCTURE* that takes on the value 1 for years after 2006 and 0 otherwise. This model includes all two- and three-way interactions to adequately compare the trends in both injury mechanisms before and after the increase in cycling infrastructure spending. Unlike MHL, the increase in cycling infrastructure was not a fixed point in time and thus 2006 was considered a transition year. Further, only years 2002–2010 were used in the model so there is a balance in the number of years pre- and post-intervention. The results, given in Table 5, suggest the increase in infrastructure is associated with an 8.5% decline per annum in head injuries and a slight decline in arm injuries that was preceded by a steady increase of 6% per annum. Further, the benefit was more pronounced for head injuries than arm injuries ($p = 0.006$). The steady decline as opposed to a sharp instantaneous drop in all injuries is consistent with a slow to implement intervention such as the building of cycling infrastructure (Shadish et al., 2002).

When segregating cyclists away from motorised vehicles, the likelihood of being struck by a motorised vehicle is significantly reduced. Cyclists travel speeds average around 20 km/h (Grzebieta et al., 2011). Car speeds can vary anywhere up to 80 km/h in urban environments. A cyclist being struck by a motorised passenger vehicle at any differential speed in excess of 60 km/h are usually associated with skull fractures with the consequence of a very low probability of survival (Otte, 2004, 2006; Chen et al., 2010). Thus, any crashes that occur on off-road cycleways would be at a much reduced cyclist speed. The mechanism of injury of a cyclist crash on an off-road cycleway would likely have less involvement of the head and more likely involve an outstretched arm (Pang et al., 2008). Hence, this may explain the change in trend for both head and arm injuries from 2006 onwards. Although the proportion of on-road/off-road cycling is unknown, the annual change in Sydney CBD cycling counts from 2002 to 2009 (increase of 14% per year) has significantly outpaced trends in bicycle imports and estimated cycling participation rates (2% and 3% per year respectively) lending credence to the idea that the proportion of off-road cycling is increasing. The additional benefit for head injuries in this period is likely due to the biomechanical aspects of segregating cyclists away from motorised vehicles. When a rider is struck by a car as opposed to falling from a bicycle or striking a pedestrian on a shared footpath, it is often the head that is injured as a result of a head strike into the hood or windshield of the car. The rider is usually thrown forward and when they eventually land on the roadway a second head strike to the ground can occur. This second head strike is at a lower speed than the head strike during the vehicle impact phase. Otte (2004) also found that the head strike with the ground, in contrast to the primary strike into the hood or windshield, occurs when the vehicle impact speed is lower. Furthermore, the impact force sustained by the rider is usually much higher with a motorised vehicle than if a rider was to fall from their bicycle on an off-road cycleway or strike a pedestrian on a shared footpath. This is because the motorised vehicle is often travelling at a much higher speed than the cyclist. Moreover, when a cyclist falls from a bicycle in a single vehicle crash or an impact with a pedestrian (Short et al., 2007), it is usually the extended arm that strikes the ground during the fall and thus is injured (Otte, 2004).

The estimate for the *INJURY* term in both models for MVCs are positive which indicates that head injury rates were higher than arm injury rates at *TIME* = 0, i.e. 1991. This does not mean a lack of MHL efficacy for this subgroup since head injury rates still decreased more than arm injury rates at the time of MHL (Walter et al., 2011). It does, however, show that risk of head injury is higher for cyclists, particularly children, involved in MVCs compared to those involved in non-MVCs, and that even after the reduction in head injuries due to MHL, head injury rates still remain higher than arm injury rates. This is consistent with another study that observed significantly increased risk of head injury among cyclists involved in MV crashes (Maimaris et al., 1994).

A limitation of using bicycle imports as a proxy exposure is that there may be some delay between a bicycle being imported into the country and it then being purchased and ridden by an individual. Although this would mean a temporal shift in the data, the generally increasing trend in imports would not be affected. The use of survey data through physical counts or telephone questionnaires is an additional limitation; however, the general trend in these numbers is likely proportional to that in the overall population. In addition to solving the issue of lack of exposure data, a further strength of jointly modelling head and limb injuries is that it also accounts for changes that affect all injuries, i.e. changes to the cycling environment, cyclist numbers and cycling behaviour. Taking this into account then allows identification of the impact of factors affecting head and arm injuries differentially. It is unknown whether cyclists captured in the APDC were wearing a helmet at the time of their injury; however, our analyses are directed at assessing MHL and not the related issue of actual helmet use. This is a conservative approach as it is equivalent to assuming everyone has worn cycling helmets post-MHL and no one wore helmets pre-MHL.

Our study shows that the beneficial effect of MHL in NSW has been maintained since enactment of the law over 20 years ago. This signals a need to focus on other aspects of bicycle safety in order to further reduce cycling-related injuries. Collisions involving motor vehicles clearly have a high risk of head injury indicating that the interaction between cyclists and MVs is a key area for intervention through further changes to transport infrastructure and modification of cyclist and motorist behaviour.

5. Conclusions

This paper presents two important findings regarding bicycle safety in NSW. First, the benefit of MHL to lowering head injuries has been maintained over a long period with the rates of bicycle head injuries 46% less than arm injuries by 2006 compared to 19% in the immediate post law period when the data is aggregated on a yearly level. Secondly, bicycle related head injuries have steadily declined in the years after 2006 which is associated with an increase in spending on cycling infrastructure. This additional safety benefit is unlikely related to MHL as it began 15 years after the helmet law and a benefit was noted in arm injuries as well. It does, however, signify the potential for significant future cyclist injury reduction through further infrastructure development.

References

Attewell, R., Glase, K., McFadden, M., 2001. Bicycle helmet efficacy: a meta-analysis. Accident Analysis and Prevention 33, 345–352.

Australian Bicycle Council, 2012. Australian Local Government Bicycle Account 2011. Austroads.

Australian Bureau of Statistics, 2010. Participation in Sport and Physical Activity 2009–10. Cat. No. 4177.0. ABS, Canberra.

Australian Bureau of Statistics, 2008. Historical Population Statistics, 2008. Cat. No. 3105.0.65.001, ABS, Canberra.

Australian Bureau of Statistics, 1998. Participation in Sport and Physical Activity 1997–98. Cat. No. 4177.0. ABS, Canberra.

Australian Sports Commission, 2010. Exercise, Recreation and Sport Survey (ERASS): Methodology Report 2010. Available from: http://www.ausport.gov.au/information/casro/ERASS

Benz, G., McIntosh, A., Kallieris, D., Daum, R., 1993. A biomechanical study of bicycle helmets' effectiveness in childhood, European journal of pediatric surgery official journal of Austrian Association of Pediatric Surgery et al. Zeitschrift fur Kinderchirurgie 3 (5), 259–263.

Cameron, M., Vulcan, A.P., Finch, C.F., Newstead, S.V., 1994. Mandatory bicycle helmet use following a decade of helmet promotion in Victoria Australia – an evaluation. Accident Analysis and Prevention 26 (3), 325–337.

Chen, Y., Yang, J., Otte, D., 2010. A Comparison Study on Head Injury Risk in Car-to-Pedestrian Collisions in Changsha and Hannover, SAE Technical Paper 2010-01-1167, SAE International, Warrendale, USA.

Cycling Promotion Fund CPF Annual Report 2009/10. Canberra (AUST): CPF; 2010. Available from: http://www.cyclingpromotion.com.au/content/view/506/153/

Cycling Promotion Fund, 2011. Riding a Bike for Transport, 2011 Survey Findings. Available from: http://www.cyclingpromotion.com.au/images/stories/MediaReleaseDocs/CyclingPromotionFund_Riding_a_Bike_for_Transport_Survey_Report_2011.pdf

Dobson, A.J., Barnett, A.G., 2008. An Introduction to Generalized Linear Models, third ed. Chapman and Hall/CRC, Boca Raton.

Dorsch, M.M., Woodward, A.J., Somers, R.L., 1987. Do bicycle safety helmets reduce severity of head injury in real crashes. Accident Analysis and Prevention 19 (3), 183–190.

Elvik, R., 2011. Publication bias and time-trend bias in meta-analysis of bicycle helmet efficacy: a re-analysis of Attewell. Accident Analysis and Prevention 43 (3), 1245–1251.

Grzebieta, R.H., McIntosh, A.M., Chong, S., 2011. Pedestrian–cyclist collisions issues and risk. In: Australasian College of Road Safety Conference–Safe System: Making it happen, Melbourne.

Haworth, N., Schramm, A., King, M., Steinhardt, D., 2010. Bicycle Helmet Research (CARRS-Q Monograph 5), Brisbane, Australia, QUT, CARRS-L Q.

Hunter, J.E., Schmidt, F.L., 1990. Methods of Meta-Analysis: Correcting Error and Bias in Research Findings. SAGE Publications, Newbury Park, CA, London, New Delhi.

Lardelli-Claret, P., Luna-del-Castillo, J.D., Jimenez-Moleon, J.J., Garcia-Martin, M., Bueno-Cavanillas, A., Galvez-Vargas, R., 2003. Risk compensation theory and voluntary helmet use by cyclists in Spain. Injury Prevention 9 (2), 128–132.

Macpherson, A.K., To, T.M., Macarthur, C., Chipman, M.L., Wright, J.G., Parkin, P.C., 2002. Impact of mandatory helmet legislation on bicycle-related head injuries in children: a population-based study. Pediatrics 110 (5), e60.

Maimaris, C., Summer, C.L., Browning, C., Palmer, C.R., 1994. Injury patterns in cyclists attending an accident and emergency department: a comparison of helmet wearers and non-wearers. BMJ 308 (6943), 1537–1540.

Marshall, S.W., 2007. Power for tests of interaction: effect of raising the Type I error rate. Epidemiology and Perspective Innovations 4, 4.

McIntosh, A., Dowdell, B., Svensson, N., 1998. Pedal cycle helmet effectiveness: a field study of pedal cycle accidents. Accident Analysis and Prevention 30 (2), 161–168.

McIntosh, A., Pang, T.Y., Thai, K., Schilter, E., Rechnitzer, G., Finch, C.F., McCrory, P., 2010. Crash characteristics of helmeted pedal cyclists. In: Australasian Road Safety: Research Policing and Education Conference Handbook, Canberra, p. 35.

McIntosh, A., Patton, D.A., 2012. Impact reconstruction from damage to pedal and motor-cycle helmets. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology 226 (3/4), 274–281.

Montoya D., 2010. Cycling and Transport Policy in NSW, Briefing Paper No. 8/2010, NSW Parliamentary Library Research Service, ISBN 978-0-7313-1869-8.

NSW Roads and Traffic Authority, 2008. Cycling in Sydney: Bicycle Ownership and Use. RTA, Sydney.

Otte, D., 2004. Use of throw distances of pedestrians and bicyclists as part of a scientific accident reconstruction method. SAE Technical Paper 2004-01-1216. SAE International, Warrendale, USA.

Otte, D., 2006. Technical parameters for determination of impact speed for motorcycle accidents and the importance of relative speed on injury severity, SAE Technical Paper 2006-01-1562, SAE International, Warrendale, USA.

Pang, T.Y., Sakeran1, H., Short, A., McIntosh, A.S., Rechnitzer, G., Thai, K., 2008. Numerical analysis of real-world cyclist crashes: impact speed, collision mechanism and movement trajectories. In: Proceedings of Australasian Road Safety Research, Policing and Education Conference, Adelaide, Australia.

Pang, T.Y., Thai, K.T., McIntosh, A.S., 2009. Head and neck dynamics in helmeted Hybrid III impacts. In: Proceedings of International IRCOBI Conference on the Biomechanics of Injury, York, UK.

Povey, L.J., Frith, W.J., Graham, P.G., 1999. Cycle helmet effectiveness in New Zealand. Accident Analysis and Prevention 31 (6), 763–770.

Rivara, F.P., Thompson, D.C., Thompson, R.S., Rogers, L.W., Alexander, B., Felix, D., Bergman, A.B., 1994. The Seattle childrens bicycle helmet campaign – changes in helmet use and head-injury admissions. Pediatrics 93 (4), 567–569.

Robinson, D.L., 1996. Head injuries and bicycle helmet laws. Accident Analysis and Prevention 28 (4), 463–475.

Roseman, M., Milette, K., Bero, L.A., Coyne, J.C., Lexchin, J., Turner, E.H., 2011. Reporting of conflicts of interest in meta-analyses of trials of pharmacological treatments. The Journal of the American Medical Association 305 (10), 1008–1017.

Rosenthal, R., 1979. The file drawer problem and the tolerance for null results. Psychological Bulletin 86 (3), 638–641, doi:10.1037/0033-2909.86.3.638.

Shadish, W.R., Cook, T.D., Campbell, D.T., 2002. Experimental and Quasi-Experimental Designs for Generalized Causal Inference. Houghton Mifflin Company, Boston.

Short, A., Grzebieta, R.H., Arndt, N., 2007. Estimating bicyclist into pedestrian collision speed. International Journal of Crashworthiness 12 (2), 127–135.

Slavin, R.E., 1986. Best-evidence synthesis: an alternative to meta-analytic and traditional reviews. Educational Researcher November 15, 5–11.

Smith, N., Milthorpe, F., 1993. An Observational Survey of Law Compliance and Helmet Wearing by Bicyclists in New South Wales – 1993. NSW Roads and Traffic Authority, Rosebery, NSW.
Scuffham, P., Alsop, J., Cryer, C., Langley, J.D., 2000. Head injuries to bicyclists and the New Zealand bicycle helmet law. Accident Analysis and Prevention 32, 565–573.
Thompson, D., Rivara, F., Thompson, R., 2004. Helmets for Preventing Head and Facial Injuries in Bicyclists (Review). The Cochrane Library Issue 2. John Wiley & Sons Ltd, Chichester, UK.
Thompson, D.C., Patterson, M.Q., 1998. Cycle helmets and the prevention of injuries – recommendations for competitive sport. Sports Medicine 25 (4), 213–219.
Walker, M., 1990. Law compliance and helmet use among cyclists in New South Wales. Road Safety Bureau, NSW Roads and Traffic Authority, Rosebery, NSW.
Walker, M., 1991. Law Compliance and Helmet Use Among Cyclists in New South Wales, April 1991. Road Safety Bureau, NSW Roads and Traffic Authority, Rosebery, NSW.
Walker, M., 1992. Law Compliance Among Cyclists in New South Wales, April 1992: a Third Survey. NSW Roads and Traffic Authority, Rosebery, NSW.
Walter, S.R., Olivier, J., Churches, T., Grzebieta, R., 2011. The impact of compulsory cycle helmet legislation on cyclist head injuries in New South Wales, Australia. Accident Analysis and Prevention 43 (6), 2064–2071.

Please cite this article in press as: Olivier, J., et al., Long term bicycle related head injury trends for New South Wales, Australia following mandatory helmet legislation. Accid. Anal. Prev. (2012), http://dx.doi.org/10.1016/j.aap.2012.09.003