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The Health Impact of Mandatory Bicycle Helmet Laws

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This article seeks to answer the question whether mandatory bicycle helmet laws deliver a net societal health benefit. The question is addressed using a simple model. The model recognizes a single health benefit—reduced head injuries—and a single health cost—increased morbidity due to foregone exercise from reduced cycling. Using estimates suggested in the literature on the effectiveness of helmets, the health benefits of cycling, head injury rates, and reductions in cycling leads to the following conclusions. In jurisdictions where cycling is safe, a helmet law is likely to have a large unintended negative health impact. In jurisdictions where cycling is relatively unsafe, helmets will do little to make it safer and a helmet law, under relatively extreme assumptions, may make a small positive contribution to net societal health. The model serves to focus the mandatory bicycle helmet law debate on overall health.

KEY WORDS: Bicycling; cost-benefit analysis; health or risk tradeoffs; helmets

1. INTRODUCTION

It is generally accepted that compulsory bicycling helmet laws reduce cycling injuries and fatalities. This reduction in harm is usually attributed to the protective effect of helmets.(1) Others(2) have pointed out that bicycle helmet laws reduce the amount of cycling, and, hence, at least part of the reduction is attributable to reduced exposure to accidents. The magnitudes of these two effects are subject to much discussion.(3,4)

The disincentive effect of helmets on cycling may be due to the small burden of wearing a helmet, or to the possibly disproportionate attention it draws to the risks associated with bicycling.(5,6) For a balanced overview of the debate, see Hurst(7) or Towner *et al.*(8) Generally, there has been solid support for bicycle helmet laws in Canada, Australia, New Zealand, less so in the United States and the United Kingdom, and little support in northern European countries such as the Netherlands, Germany, and Denmark, where cycling is more popular.

A reduction in cycling has negative health consequences. DeMarco(9) opines: "Ultimately, helmet laws save a few brains but destroy many hearts." The efficacy of helmet laws is thus judged by assessing whether the positive benefits—fewer head injuries—outweigh the negative effects—less exercise. This article displays a quantitative model permitting a detailed health assessment.

A central result from this model is that a mandatory bicycle helmet law leads to a net societal health benefit[1] if and only if the fraction of injury costs preventable with a helmet exceeds the net health cost of reduced cycling. In symbols:

$$eq > \mu\beta \ . \qquad (1)$$

Here, $0 \leq eq \leq 1$ is the preventable fraction of injury costs in unhelmeted cycling, that is, the fraction of injury costs avoided if all cyclists responding to the law wore helmets. Further, β is the ratio of health

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[1] To avoid a tedious terminology, unless otherwise indicated, here and below, a net health benefit means a positive net health impact and a net health cost means a negative net health impact.

Table I. Glossary of Main Symbols and Definitions

Symbol	Description	Range
v	Health benefit of 1 km of accident-free cycling	$v \geq 0$
m	Prelaw unhelmeted kilometer cycling of the behavior changing group	$m > 0$
p	Behavioral response parameter: probability a cycling kilometer is not maintained postlaw	$0 \leq p \leq 1$
$\mu \equiv \frac{p}{1-p}$	Odds a cycling kilometer is not maintained	$\mu \geq 0$
c^*, c	Expected injury costs per accident, with and without a helmet	$c > c^* \geq 0$
λ	Rate of accidents per kilometer	$\lambda > 0$
λc	Expected health cost per kilometer unhelmeted cycling	$\lambda c > 0$
$v - \lambda c$	Expected health benefit per kilometer of unhelmeted cycling	$v - \lambda c > 0$
$\beta \equiv \frac{v-\lambda c}{\lambda c}$	Benefit-cost ratio of unhelmeted cycling	$\beta > 0$
e	Helmet effectiveness: proportional reduction in head injury costs when wearing a helmet	$0 \leq e \leq 1$
q	Head injury costs as fraction of total injury costs in unhelmeted cycling	$0 < q < 1$
$eq = \frac{c-c^*}{c}$	Helmet preventable fraction of accident costs	$0 < eq < 1$

benefit to health cost in unhelmeted cycling: a figure of 20 is often quoted for a representative rider indicating health benefits outweigh health costs by a factor of 20. Finally, μ is the odds a unit of cycling is not maintained when a helmet law comes into effect. As the notation in Equation (1) indicates, the preventable fraction eq is the product of two proportions: $0 \leq e \leq 1$, measuring the effectiveness of the helmets, and $0 \leq q \leq 1$, indicating the proportion of injury costs due to head injuries in unhelmeted cycling. Definitions and estimates for β, μ, e, and q are given in Table I and Section 3.

The size of each of the four quantities in Equation (1) are uncertain. This is an issue except that over a wide range of plausible estimates, the inequality (1) fails. For example, because $eq \leq 1$, the inequality fails whenever $\mu\beta > 1$. In particular, Equation (1) fails if $\beta = 20$ and $\mu = 0.1$, even if helmets are 100% effective and all health costs are head injury costs. Hence, even with very optimistic assumptions as to the efficacy of helmets, relatively minor reductions in cycling on account of a helmet law are sufficient to cancel out, in population average terms, all head injury health benefits.[2]

The relationship between the amount of cycling and mandatary helmet laws is subject to controversy. The literature is reviewed in Section 3 together with the literature on the health benefits of cycling. This article does not present new evidence on the amount by which helmet laws reduce cycling, or the health benefit of cycling, or the effectiveness of helmets in reducing head injuries. However, we do use widely cited estimates as inputs into our model to arrive at the net implied benefit. These inputs can be disputed and varied. However, if one accepts the premisses of the model then one must accept its implications.

Before proceeding, it is useful to address a number of issues. First, the analysis in this article assumes that a properly fitted helmet has, on average, a health benefit in accidents involving the head, that is, $e > 0$. Thus, even if the analysis suggests there is no net societal health benefit to a mandatory bicycle helmet law, this does not argue that an individual is not benefited by wearing a helmet. To emphasize, this article deals with whether a mandatory bicycle helmet law is good public policy, not whether it is advantageous for an individual to wear a helmet.

Second, a reduction in cycling does not necessarily imply an equal reduction in exercise because cycling may be "substituted." This view of cycling as a substitutable exercise sport may be correct in some jurisdictions—many parts of North America spring to mind. However, this article deals with cycling as a mode of transport with health benefits. This is the normal daily cycling carried out by many millions of cyclists around the world. For example, relatively few Dutch or Chinese, who bicycle as part of their daily routine, would increase gym visits or take up other exercise activities if, as a result of a mandatory bicycle helmet law, they were discouraged from cycling. Related is that for many people, exercise is only sustainable if it is integrated into daily routine, such as shopping errands or traveling to and from

[2]The present article relates to the wider literature on risk or health tradeoffs.[10,11] A pertinent quote[11] is: "The countervailing risks of well–intended actions to reduce a target risk are not always analyzed or openly discussed in public policy debates. Because advocacy groups, elected officials, and bureaucracies may benefit from an exclusive focus on target risk, they may choose to ignore — or even suppress discussion of — the countervailing risks of proposed policies."

work. In any case, in the analysis below, substitution effects can be accommodated by lowering the assumed health benefit of each kilometer of cycling.

Third, the health impacts calculated below do not reflect the possibly negative health or economic impacts associated with shifts to other modes of transportation such as cars.

Fourth, the discussion below is in terms of statistical averages and sets off gains and losses across different individuals. The analysis is based on a "representative" bicyclist and does not distinguish between different groups of bicycle riders. Different groups may have different parameters and a targeted helmet law may be warranted. Further, groups of riders may have different parameter configurations, making for a misleading "average" analysis. This is further discussed in Section 6.

Relation (1) is based on assumptions detailed, discussed, and analyzed in subsequent sections. The next section presents the key expressions for evaluating the net health impact of a helmet law. The key parameters and their values in these expressions are discussed in Section 3. Section 4 uses figures from European countries and the United States to compute potential net health impacts. Section 5 displays further sensitivity calculations. Substitution and environmental effects are considered in Section 6. Conclusions are presented in Section 7.

2. THE NET HEALTH IMPACT OF A HELMET LAW

This section shows that Equation (1) is a necessary condition for there to be a net health benefit to a mandatory bicycle helmet law. The argument is based on a "representative" cyclist model. The cyclist accrues a gross health benefit v from each accident-free kilometer of cycling. The gross health benefit v is denominated in an appropriate unit such as dollars, increased life expectancy, reduced mortality risk, or other.

Representative riders are assumed to suffer bicycling accidents according to a Poisson process with expected accident rate of λ per kilometer.[12] If there is an accident, the expected health cost if no helmet is worn is c, reducing to c^* if a helmet is worn. Accident costs are denominated in the same units as health v. Here and below, quantities with an asterisk indicate values when a helmet is worn. Thus, $v - \lambda c$ is the expected health benefit of 1 km of helmetless cycling, and $v - \lambda c^*$ is the expected health benefit of cycling 1 km with a helmet.

A mandatory helmet law affects only cyclists who do not wear helmet before the law and who either start wearing a helmet or choose to give up cycling. This group is called the behavior changing group. Thus, suppose those who already wear a helmet prior to the law and those unhelmeted riders who choose to ignore the law do not change behavior.[3] Suppose there are m km ridden by the behavior changing group before the law, of which proportion p is given up as a result of the law. Then the health benefit of cycling for the group is $m(v - \lambda c)$ before the law, and $(1-p)m(v - \lambda c^*)$ after. The net health impact of the law, expressed as a fraction of helmet preventable health costs, is:

$$\Psi \equiv \frac{\text{Net health impact of helmet law}}{\text{Helmet preventable health cost}} \tag{2}$$

$$= \frac{(1-p)m(v-\lambda c^*) - m(v-\lambda c)}{m\lambda(c-c^*)}$$

$$= \frac{(1-p)\lambda(c-c^*) - p(v-\lambda c)}{\lambda(c-c^*)}$$

$$= (1-p)\left(1 - \frac{\mu\beta}{eq}\right) \tag{3}$$

$$= (1-p) - \frac{p\beta}{eq}\,, \tag{4}$$

where the equalities follow from direct manipulation and the fact that helmets are only useful in preventing head injuries:

$$\frac{c-c^*}{c} = \frac{qc-(1-e)qc}{c} = eq\,.$$

The advantage of the expressions in Equations (3) or (4) is that Ψ is stated in terms of testable and readily estimated intelligible constructs and does not explicitly involve the units of measurement of v.

Note, $\Psi \leq 1$ with $\Psi > 0$ indicating benefits exceed costs, whereas $\Psi < 0$ indicates an unintended net health cost. Further, $\Psi > 0$ if and only if $eq > \mu\beta$ as in Equation (1). The ratio

$$\frac{\mu\beta}{eq} = \frac{pm(v-\lambda c)}{(1-p)m\lambda(c-c^*)} \tag{5}$$

is the cost-benefit ratio of a helmet law with $p = 0$ implying the cost is zero and the helmet law effectiveness $\Psi = 1$.

[3] The number of riders who ignore the law and hence the size of the behavior changing group will depend on the degree to which the law is enforced.

The definition Ψ in Equation (2) is based on an "average" or "representative" rider and λ, v, c, and c^* are average values across riders. In practice, riders are heterogenous. It is assumed that those changing their bicycling as a result of the law are average with respect to accident rates, injury costs, and health benefits. This is further discussed in Section 6. Further, it is assumed the accident rate λ and benefit v are unaffected by wearing a helmet. Finally, if many cyclists already wear helmets or many riders ignore the law then Ψ measures health impact of a limited group.

As an example, Australian data[13] suggest pre- and postlegislation helmet wearing rates as 35% and 84%, respectively. Suppose the law led to an overall 10% reduction in cycling. Then direct calculations show, assuming all drops in cycling occurred among the unhelmeted group, proportion $p = 0.22$ of cycling in the unhelmeted group is "lost" as a result of the law and $\mu = p/(1-p) = 0.28$. Hence, Equation (1) holds if $\beta < eq/0.28$. If $\beta \geq 1/0.28 = 3.51$ there is a net health cost even if helmets are 100% effective and all injuries are head injuries.

Equation (2) can be used to evaluate the health impact of campaigns aimed at increasing voluntary bicycle helmet wearing. The intervention in this case is a campaign stressing the head injuries that may be avoided if wearing a helmet. Although the campaign may induce helmet usage, it may also frighten people off cycling.[14] Suppose only unhelmeted riders are possibly frightened off riding. Write m as the kilometer cycled by unhelmeted riders before the campaign, reducing to $(1-p)m$ after the campaign, of which, say, proportion ϕ is helmeted. Similar to Equation (2), the net health impact of the campaign, expressed as a fraction of the helmet preventable health cost, is:

$$\Psi = \frac{\phi(1-p)m\lambda(c-c^*) - pm(v-\lambda c)}{m\lambda(c-c^*)} = (1-p)\left(\phi - \frac{\mu\beta}{eq}\right).$$

The campaign has a net health benefit if $\phi > \mu\beta/(eq)$. Even if the campaign is 100% successful, $\phi = 1$, there is a net health cost if $\mu\beta > 1$.

3. PARAMETER ESTIMATES

This section reviews the literature on the health benefit of cycling (β), the effectiveness of helmets (e and q), and the effect of bicycle helmet laws on the amount of bicycling (p or μ). The literature is used to indicate the likely size of each of these parameters. These estimates are used in Section 4 to throw light on the likely magnitude of Ψ.

3.1. The Health Benefit of Cycling

Regular daily exercise has substantial health benefits[15] and bicycling is an excellent form of exercise.[16] Exercise is especially sustainable when ingrained as part of daily routine.[17] Hence, bicycling as a daily mode of transport is an excellent form of sustainable exercise. It is safe, especially for adults.[6] It is less safe when mixed in with a preponderance of motorized traffic.

The Hillman[18,19] report for the British Medical Association compares the exercise benefit of cycling to accident risks. Actuarial data are examined to determine life years gained by people engaged in exercise, which is compared to years lost through cycling accidents. Hillman[19] concludes "even in the current hostile traffic environment, the benefits gained from regular cycling outweigh the loss of life years in cycling fatalities by a factor of around 20 to 1." The 20 to 1 ratio is an estimate of β in Equation (1). The estimate must be interpreted with care. It is an average with likely variations depending on locality, age, experience, and even individual rider. Transport policies are instrumental in determining the value of β by shaping the bicycling environment.

The expression for β in Table I indicates β is the benefit-cost ratio of cycling without a helmet. Given $c^* = (1-eq)c$, a detailed calculation shows that the benefit-cost ratio of cycling with a helmet is $(\beta + eq)/(1-eq)$. Hence, if β is low, helmets do little to improve β unless eq is near 1. If β is high, then mandatory helmet legislation is likely to be counterproductive as even small reductions in cycling are likely to swamp the direct health benefits.

3.2. The Effectiveness of Helmets

Helmets can reduce head injuries in accidents in one of three ways: by reducing the probability of a head injury, by reducing the magnitude of a head injury if there is an accident involving the head, or both. To formalize the situation, write π as the probability of a head injury in an accident, h as the expected cost of a head injury in an unhelmeted accident involving the head, and b as the expected cost of a "body" or nonhead injury given there is an accident. Then in terms of the notation of Section 2:

$$q = \frac{\pi h}{\pi h + b}, \qquad e = \frac{\pi h - (\pi h)^*}{\pi h} = 1 - \frac{(\pi h)^*}{\pi h},$$

where $(\pi h)^*$ denotes the expected cost of head injuries in a helmeted bicycling accident.

Using this notation suggests three possibilities for modeling the protective effect of a helmet. First, a helmet may reduce the probability π of an accident involving the head but leave h unchanged. In this case, $(\pi h)^* = \pi^* h$ and $e = 1 - \pi^*/\pi$. Second, a helmet may reduce the expected severity of a head injury but leave the probability π unchanged. In this case, $(\pi h)^* = \pi h^*$ and $e = 1 - h^*/h$. Thus in either case $0 < e < 1$ is interpreted as the "efficiency" of a helmet.

A third possibility is where helmets may protect against proportion e of head injuries below threshold τ, say, and for those exceeding τ the cost of the head injury is reduced by τ. Using a Pareto severity distribution[20] for head injuries, it may be shown that in this situation $(c - c^*)/c \approx eq$. In the further discussion below, to keep the discussion aligned with previous literature, it is assumed that $e = 1 - \pi^*/\pi$.

Thompson *et al.*[21] review, reference, and discuss the effectiveness of helmets in preventing head injuries—see also Attewell[22] and Robinson.[13] Their summary finding is "wearing a helmet reduced the risk of head or brain injury by approximately two-thirds or more" indicating $e = 1 - \pi^*/\pi \geq 2/3$. In the reviewed studies, the relative risk π^*/π is estimated from the observed odds ratio of helmet wearing comparing head-injured to non-head-injured bicyclists. Thompson *et al.*[21] pool estimates of the odds ratio derived from a variety of studies yielding an odds ratio estimate of 0.31 ± 0.05, where the limits indicate 95% error bounds. Attewell[22] finds the "consensus" estimate of the odds ratio higher depending on the nature of head injury. Hence, from this literature, it appears safe to assume $e < 0.69$.

Although the relative risk π^*/π is the subject of much study, there is much less literature on the preventable fraction eq. In the Netherlands, where bicycle helmets are rare, 27.5% of bicyclists admitted to hospital have head injuries,[23] suggesting $\pi = 0.275$ providing π is defined as the probability of a head injury in an accident necessitating a hospital visit. This estimate of π is broadly consistent with Australian data of bicycle accident victims who present themselves to the emergency department at a Sydney hospital.[24] In Sydney, $\phi \approx 1$ and based on hospital data about 2/3 of patients have minor bumps and scratches, and go home after a dressing or patch. The remaining 1/3 are recorded in the trauma registry; during 2008–2010, a total of 287 patients were completely recorded. Of these, 25% had head injuries, respectively indicating 25% of trauma registered admissions had head injuries.

Hence, $\pi = 0.275$ appears reasonable. Writing $b = \pi b_1 + (1 - \pi) b_2$ where b_1 and b_2 are the average non-head-injury cost of a head-injured and non-head-injured bicyclist then:

$$\frac{1-q}{q} = \frac{\pi b_1 + (1-\pi) b_2}{\pi h} = \frac{b_1}{h} + \frac{1-\pi}{\pi} \times \frac{b_2}{h} .$$

If $\pi = 0.275$ then $(1 - \pi)/\pi = 2.64$ while $b_1 = 0$ and $h = b_2$ imply $q = 0.275$. To arrive at $q = 0.75$, equivalent to a left-hand side odds of 1/3 requires, if $b_1 = 0$, that $h = 3 \times 2.64 \times b \approx 8b_2$. This seems extreme. Thus, $q = 0.75$ appears extreme.

If $e = 0.67$ and the proportion of injury costs due to head injuries is $q = 0.75$ then $eq = 0.5$, which appears, given the above discussion, an optimistic estimate of the helmet preventable fraction of injury costs.

3.3. Helmet Laws and the Amount of Bicycling

Many motorcyclists dislike helmets.[21] It is safe to assume the same is true for bicyclists. Thus a mandatory bicycle helmet law will, if anything, reduce cycling. Drops in cycling may also result from helmets and helmet laws instilling an exagerated perception of the risks of cycling.

Many Western countries have experienced large reductions in per capita cycling since the 1940s as well as even more substantial reductions in bicycles' modal share of transport. The secular downward trend necessitates a careful analysis to detect a "helmet law" effect in those jurisdictions where a law has been passed. The main statistical studies[2,4,13] attempting to quantify the impact of helmet laws on bicycling use before and after data from Australian states that have enacted and enforced mandatory helmet legislation. These data suggest that the effect of legislation is to reduce bicycle riding by 20%–40%. The permanence of any reductions is subject to debate. An eventual return to previous levels begs the question of what cycling levels would have been in the absence of the law.

4. NET HEALTH IMPACTS FOR SELECTED COUNTRIES

This section estimates the net health benefit of mandatory cycle helmet laws for the different

Table II. Helmet Law Net Impact and Annual per Capita Health Benefit

	Death Rate	Cycling Rate	Helmet Rate	β	$p = 0.10$ Ψ	$p = 0.10$ Φ	$p = 0.20$ Ψ	$p = 0.20$ Φ
Austria	6.8	0.4	0.05	2.7	0.4	6.9	−0.3	−5.1
				6.4	−0.4	−3.5	−1.7	−16.4
Denmark	2.3	1.7	0.03	9.9	−1.1	−29.7	−3.1	−87.2
				20.7	−3.2	−45.0	−7.5	−103.8
Finland	5.0	0.7	0.20	4.0	0.1	2.0	−0.8	−16.4
				9.0	−0.9	−9.2	−2.8	−28.6
Germany	3.6	0.8	0.02	5.9	−0.3	−6.0	−1.6	−32.5
				12.9	−1.7	−17.3	−4.4	−44.9
Great Britain	6.0	0.1	0.22	3.2	0.3	0.9	−0.5	−1.6
				7.3	−0.6	−1.0	−2.1	−3.6
Italy	11.0	0.2	0.03	1.3	0.6	10.1	0.3	4.5
				3.5	0.2	1.5	−0.6	−4.8
Netherlands	1.6	3.0	0.01	14.6	−2.0	−70.2	−5.1	−175.2
				30.2	−5.2	−89.3	−11.3	−196.0
Norway	3.0	0.4	0.08	7.3	−0.6	−4.6	−2.1	−17.2
				15.7	−2.2	−9.0	−5.5	−22.0
Sweden	1.8	0.9	0.17	12.9	−1.7	−16.5	−4.4	−42.8
				26.8	−4.5	−21.9	−9.9	−48.6
Switzerland	3.7	0.5	0.10	5.8	−0.3	−3.1	−1.5	−18.3
				12.5	−1.6	−9.7	−4.2	−25.6
United States	7.5	0.3	0.38	2.3	0.4	3.8	−0.1	−1.2
				5.7	−0.2	−1.0	−1.5	−6.5

Notes: Death rate is deaths per 100 million kilometers of cycling. Cycling rate is kilometer per person per day.[7,27] The helmet rate is the proportion of cyclists wearing helmets.[28] Bicycling benefit-cost ratio β_i derived from death rate as discussed in text. Ψ and Φ assume $eq = 0.5$.

countries listed in Table II. The countries span a range of cycling cultures.[25]

Cross-country comparisons are used to throw light on the likely size of the benefit-cost ratio of bicycling β in different jurisdictions and in turn the likely values of the standardized health impact Ψ. The likely size of β in different countries is established using two reference points: the country-specific per kilometer death rate from bicycling injuries and the reference value $\beta = 20$ suggested in Hillman report to the British Medical Association.[18]

Values for the bicycling death rate d_i per kilometer of bicycling for different countries i are displayed in Table II. Suppose the accident rate λ in country i is proportional to the bicycling death rate d_i per kilometer: $\lambda_i = \kappa d_i$ where κ is a constant, independent of the country. Then if the gross health benefit v and expected cost c per accident are the same for all countries:

$$\beta_i \equiv \frac{v - \lambda_i c}{\lambda_i c} = \frac{v}{\kappa d_i c} - 1 = \frac{\alpha}{d_i} - 1\,, \qquad (6)$$

where $\alpha \equiv v/(\kappa c)$ does not depend on i. Equation (6) can be used to determine α from the death rate d_i and β_i for a particular country. Given α and the death rates permits the determination of β_i for all other countries.

Hillman[18] suggests $\beta_i = 20$ for the United Kingdom, a not particularly safe bicycling country as indicated by the bicycling mortality rates d_i in Table II. Assume $\beta_i = 20$ applies to the Netherlands, the safest bicycling nation listed in Table II. This is clearly a pessimistic view of the benefit-cost ratio of cycling. Given $d_i = 1.6$ for the Netherlands then $\alpha = d_i(1 + \beta_i) = 1.6 \times 21 = 33.6$. Hence, $25 < \alpha < 50$ appears a pessimistic range for α. The two extreme values for α yield, when substituted into Equation (6), the two β_i values for each country listed in Table II. The resulting β_i values range from a low of 1 in Italy, to a high of 30 in the Netherlands. The resulting β_i values for Great Britain are 3 and 7, very pessimistic given the assessment of Hillman.[18] The overall range of pessimistic β_i values for different countries i gives a reasonable range that may be used in a variety of other jurisdictions, say, Austin, Texas or Melbourne, Victoria or Kyoto, Japan.

The β_i for each country i in Table II is combined with two reductions in cycling: $p = 0.10$ and $p = 0.20$. These relatively modest reductions should be compared to the range 20%–40% reported in the studies cited in Section 3.3. In all cases, it is assumed the preventable fraction $eq = 0.5$ corresponding to an optimistic view of helmet effectiveness, achieved, for example, with $e = 0.67$ and $q = 0.75$.

The Ψ figures given in Table II have a maximum of 1. The figures are positive whenever $eq > \mu\beta_i$ or $\beta_i < 1/(2\mu)$, equal to 5 and 2.5, if $p = 0.1$ and $p = 0.2$, respectively. That is, for a net health benefit, cycling must be very dangerous as occurs, for example, in Italy for both β scenarios or Great Britain for the worse β scenario. With $p = 0.2$ and the more optimistic β scenario, only Italy displays a net health benefit.

If a helmet law is strictly enforced then all prelaw unhelmeted cycling is sensitive to a helmet law in the sense that either it is "lost" or converted to a helmeted kilometer. The annual per capita net health impact of a strictly enforced mandatory helmet law in units v is thus:

$$\Phi \equiv \frac{(1-\phi)m\lambda(c - c^*)}{nv}\,\Psi = \frac{(1-\phi)meq}{n(1+\beta)}\Psi\,, \quad (7)$$

where n is the population of the country and $(1 - \phi)m$ is the annual per capita rate of unhelmeted bicycling. Daily cycling rates $m/(365n)$ and helmet wearing rates ϕ for different countries are displayed in Table II together with resulting estimates for Φ. For example, for the United States, with $\beta = 5.7$ and $p = 0.1$ then $\Phi = -1$, indicating a per capita per annum health cost equivalent to the health benefit of 1 km of accident-free cycling. For Great Britain using $\beta = 7.3$ and $p = 0.20$, the net health cost of a mandatory helmet law is $3.6v$ per person per annum. For countries where cycling is very safe and popular, such as the Netherlands, Denmark, and Sweden, the net health costs of a mandatory bicycle helmet law are large.

Table II shows that for most countries, under assumptions favorable to the helmet legislation case, the unintended health costs cancel out the direct health benefit. Note, these are not costs to "solve the head injury problem" but figures showing the extent to which the problem is exacerbated.

The rates in Table II provide evidence on the relationship between the bicycling death rate d_i, the bicycling rate b_i, and helmet usage ϕ_i. In particular, suppose $\ln d_i \approx \alpha + \delta \ln b_i + \gamma \phi_i$. Then δ models the "safety in numbers" effect.[26] Further, $1 - e^{\gamma}$ is the reduction in the relative risk of death due to helmets. Least squares estimation leads to estimates of δ and γ of -0.54 and -0.40, respectively. The δ estimate is highly significant (p-value 0.01), whereas the helmet effect is insignificant (p-value 0.76). Hence, the reduction in death risk on account of helmets is estimated as $1 - e^{-0.40} = 0.33$ with a wide margin of error. In comparison, the δ estimate suggests a halving in cycling increases the death rate by about $1 - (0.5)^{-0.54} = 0.31$. With a behavioral response of p, an enforced helmet law reduces bicycling from b_i to $\phi_i b_i + (1 - p)(1 - \phi_i) b_i = b_i\{1 - p(1 - \phi_i)\}$. The net effect of a strictly enforced helmet law is thus to reduce the death rate by proportion:

$$1 - e^{\gamma(1-\phi_i)+\delta \ln\{1-p(1-\phi_i)\}} \approx (1 - \phi_i)(p\delta - \gamma).$$

Using the estimates, the proportionate reduction $-\gamma = 0.40$ is, on account of "safety in numbers," modified to $0.40 - 0.54p$, which in turn is multiplied by the fraction of unhelmeted riders before the law. With $p = 0.10$ or $p = 0.20$, as used in Table II, the modification has a marginal effect.

5. SENSITIVITY ANALYSIS

Fig. 1 plots Ψ versus preventable fraction eq for a variety of parameter combinations. In each panel, it is assumed no helmets are worn prehelmet law and there is proper 100% postlaw compliance. Different panels correspond to different values of p. Note, if helmets are 67% effective and 75% of injury costs are due to head injuries, then $eq = 0.50$. Different β correspond to the different lines.

Fig. 1 indicates a net health benefit is difficult to achieve except in extreme circumstances: a small behavioral response (p or μ is small), helmets highly effective (eq near 1), and a low health benefit of cycling (β small), indicating either minimal exercise benefits or a dangerous bicycling environment.

6. NONHEALTH COSTS, SUBSTITUTION, AND GROUPING

The analysis of the previous sections focuses solely on health costs. This is inappropriate in an overall appraisal of a mandatory bicycle helmet law, given that bicycling is often substituted for by more costly and less environmentally benign modes of transport. Bicycles, on average, pose small risks to others, especially when compared to, say, cars.

Suppose reducing cycling by 1 km leads to, on average, an increase in environmental costs of $\epsilon(v - \lambda c)$. Hence, the environmental cost is denominated in terms of the expected health benefit of 1 km of cycling. Then the standardized health impact combined with the environmental cost is:

$$\Psi - \frac{p\epsilon(v - \lambda c)}{\lambda(c - c^*)} = (1 - p)\left\{1 - \frac{\mu\beta(1 + \epsilon)}{eq}\right\}. \quad (8)$$

Thus factoring in environmental costs is equivalent to increasing β by 100ϵ percent. For example, if the environmental cost of 1 km of lost cycling equals the expected health benefit of 1 km of cycling, then $\epsilon = 1$ and factoring in environmental costs is equivalent to increasing β by 100%. Using the lower β values in Table II as a starting point and $\epsilon = 1$, then factoring in environmental costs is equivalent to approximately moving from the lower β to the higher β. Hence, even with a 10% reduction in cycling and very pessimistic assumptions about β, factoring in environmental costs of $\epsilon = 1$ suggests no benefit for any country except for Italy.

Substitution effects can be handled similarly. Suppose ϵ is the proportion of lost kilometers substituted with other forms of equally healthy exercise. Then the net health impact is similar to Equation (8) except that $-\epsilon$ replaces ϵ. Hence, substitution effects of ϵ are accommodated by reducing β. Environmental costs and substitution can be incorporated via a joint calculation. For example, if 70% of lost cycling is substituted and the environmental costs of each kilometer of lost cycling is $2(v - \lambda c)$

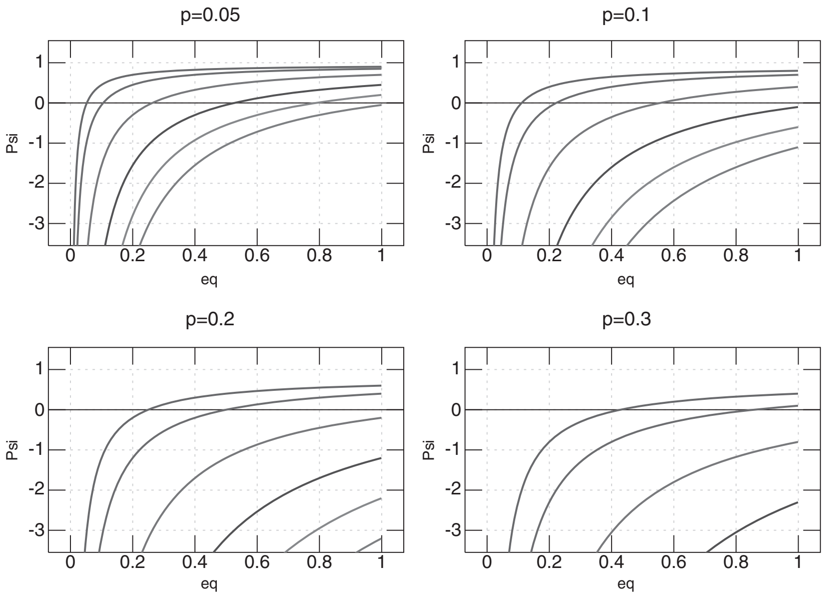

Fig. 1. Ψ plotted against the preventable fraction eq. Different panels correspond to different assumed reductions in cycling as indicated. Lines in each panel correspond (from highest to lowest) to $\beta = 1, 2, 5, 10, 15$, and 20.

then $\epsilon = 2 - 0.7 = 1.3$, and hence for purposes of computing Ψ, β is increased by 130%.

Finally, consider the situation where bicyclists are grouped into distinct groups i with group i cycling m_i km, having accident rate λ_i, behavioral response p_i, and bicycling benefit-cost ratio β_i. Then the overall net health impact is, assuming helmets confer a common per accident benefit $c - c^*$,

$$\Psi \equiv \frac{\sum_i m_i \lambda_i \left\{(1-p_i)(c-c^*) - p_i(v_i - \lambda_i c)\right\}}{\sum_i m_i \lambda_i (c - c^*)}$$

$$= \sum_i w_i \Psi_i \ ,$$

where Ψ_i is the standardized health impact for group i and $w_i = m_i\lambda_i / \sum_i m_i\lambda_i$ is the proportion of accidents arising from group i. An analysis based on population average values of β, μ, e, and q may suggest $\Psi < 0$ even though some or even all $\Psi_i > 0$ or vice versa. This again argues for a detailed appraisal of the four key parameters, this time at a group level.

7. CONCLUSIONS

Using elementary mathematical modeling and parameter estimates from previous studies leads to reasonable bounds for the net health impact of a mandatory bicycle helmet law. The model highlights the importance of four parameters in any evaluation: helmet efficiency, the behavioral response of riders to the law, the benefit-cost ratio of cycling, and the proportion of injuries in cycling due to head injuries. These key parameters offer critical testable points for assessing the net impact.

A (positive) net health benefit emerges only in dangerous bicycling environments under optimistic assumptions as to the efficacy of helmets and a minor behavioral response. Resolution of the issue for any particular jurisdiction requires detailed information on the four key parameters.

The calculations are based on a "representative" bicyclist model. It may be the case that those giving up cycling are not representative: they may be more accident prone, less susceptible to the health stimulus, or more inclined to substitute cycling with other exercise activities. A disaggregated model can be used to address such issues, which in turn requires a detailed appraisal of the four key parameters at a disaggregated group level.

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