Relationships between Bicycle Helmet Design Characteristics, Price, and Impact Attenuation

Megan L. Bland[*], Becky C. Mueller[#], David S. Zuby[#], Steven Rowson[*]

[*]Dept. Biomedical Engineering and Mechanics
Virginia Tech
325 Stanger Street, Blacksburg, VA 24060, USA
email: mbland27@vt.edu, rowson@vt.edu

[#]Insurance Institute for Highway Safety
988 Dairy Road, Ruckersville, VA 22968, USA
email: DZuby@iihs.org, BMueller@iihs.org

Keywords: cycling, brain injury, acceleration, biomechanics.

1 INTRODUCTION

According to data from the US Consumer Product Safety Commission (CPSC), cycling was the leading cause of sport-related head injuries treated in US emergency rooms in 2009 [1]. Beyond the US, cycling is a popular sport, recreational activity, and mode of transportation in many countries, making head injury from cycling a concern worldwide. Bicycle helmets reduce risk of head injury, and are required to pass a CPSC safety standard to be sold in the US. The impact attenuation portion of this standard mandates that helmets reduce peak linear acceleration (PLA) of the head to <300 g, a level associated with moderate risk of severe brain injury [2].

While current standards ensure helmet design minimizes risk of catastrophic injury, pass-fail certification does not provide information on which helmet designs offer superior protection or how well price correlates to safety. Additionally, tests at lower impact energies are not conducted, which are common in real-world cyclist accidents [3-4]. Studies have also shown that helmets are most commonly impacted at the front and sides in real-world accidents, and often around the rim [3-5]. However, the rim is below the testable area in standards, so current helmet design is unregulated at this location. Knowledge of how helmets perform in these common impact scenarios and how price and design relate to performance would enable consumers to make more informed purchasing decisions.

The objective of this study was to investigate relationships between bicycle helmet design characteristics, price, and impact performance during standard-specified and common real-world impact conditions.

2 METHODS

Ten bicycle helmet models of varied design and price were tested on a standard CPSC twin-wire drop rig with a flat anvil. Each model was impacted at a frontal rim location and a temporal location. Impact sites were mirrored on helmets, with each location tested once. Two impact velocities were also specified: 3.4 m/s, representing the median value of a distribution of digitized helmet damage replication data (Fig. 1) [3-4], and 6.2 m/s, in accordance with the CPSC standard and representing the 96^{th} percentile of the damage replication data. The two impact locations and velocities produced four possible impact configurations. Four trials were conducted per configuration for each model, totaling 160 impact tests.

Linear acceleration data were collected for each test and low-pass filtered at CFC-1000 (SAE J211). Head injury criterion (HIC) was determined for each impact test and used to calculate risk of AIS≥4 brain injury [2]. A weighted cumulative risk (WCR) was used to characterize overall helmet performance. WCR was calculated for each helmet by weighting computed risks based on how probable each impact condition is in real-world cycling accidents, and then summing across configurations according to Equation 1:

$$WCR = 25 * risk_{f,3.4} + 25 * risk_{t,3.4} + 2 * risk_{f,6.2} + 2 * risk_{t,6.2} \quad (1)$$

where each risk variable has a subscript denoting impact location first (frontal: f, temporal: t), then velocity. Impact location was weighted equally, while velocity was weighted based on the percentile that each corresponded with in Figure 1: 3.4 m/s represents the 50th percentile, so the frontal and temporal locations were each weighted 25, while 6.2 represents the 96th percentile (meaning only 4% of impacts occur at greater velocities), so each location was weighted 2. This method of determining cumulative risk is similar to those previously employed for other sport helmets [6].

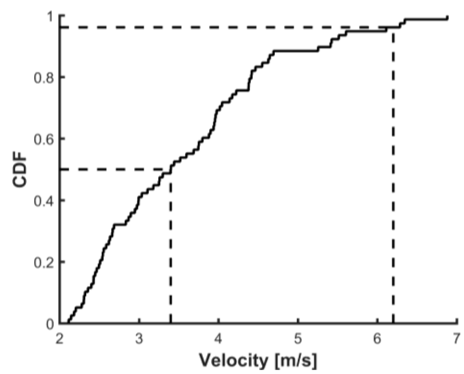

Figure 1: Digitized helmet damage replication data with dashed lines corresponding to the 50th and 96th percentiles.

WCR was correlated individually to helmet design parameters including mass, average liner thickness, shell thickness, and number of vents, as well as helmet price. Multiple linear regression (MLR) analysis was also conducted to investigate which combination of design parameters and/or price best predicted WCR.

3 RESULTS

Overall, the ten helmets produced PLAs of 105±22 g at 3.4 m/s and 227±46 g at 6.2 m/s, with temporal impacts producing higher PLAs on average than frontal impacts. This corresponded with a range in AIS≥4 brain injury risk of 0.2-97% across configurations. WRC ranged from 1.53-3.23.

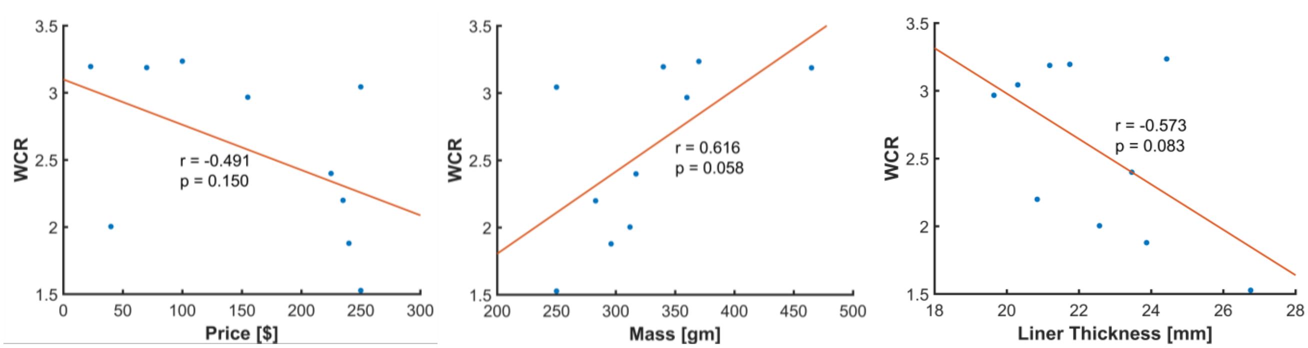

Figure 2: Correlations between WCR and helmet price, mass, and liner thickness. Price was not well correlated with WCR, while mass and liner thickness produced the best correlations compared to other design parameters.

WCR was found to correlate best with helmet mass and liner thickness (Fig. 2), although no correlation with any individual design parameter was statistically significant. Helmet price in particular produced a weak negative correlation with WCR ($r = -0.49$, $p = 0.15$), suggesting price is not a primary indicator of impact performance.

The MLR model that best predicted WCR included the parameters liner thickness and vent number (Eq. 2):

$$WCR = 9.08 - 0.25(Liner\ Thickness) - 0.047(Vent\ Number) \tag{2}$$

The associated adjusted R^2 was 0.59 ($p = 0.019$), and each coefficient was statistically significant ($p < 0.028$). All design parameters not included decreased the overall adjusted R^2 when incorporated.

4 DISCUSSION

The present study reveals considerable differences in the impact attenuation capabilities of bicycle helmets under both common real-world and standard-specified conditions. Different design parameters influenced these differences in performance. The individual parameters that correlated best with WCR were mass and liner thickness. More massive helmets performed worse, while thicker liners performed better. A thicker liner indicates that more crushable material is available to dissipate impact energy, potentially allowing a less stiff liner capable of mitigating a wider range of impact energies to be employed. The more massive helmets were generally all of a non-road style, characterised by a rounded shape, less venting, and thicker shells. Although non-road helmets produced higher WCR than road helmets on average, overall differences were not significant ($p = 0.059$). However, only a small sample of helmets was tested, limiting inferences made herein.

The MLR model that best predicted WRC included liner thickness and vent number. However, mass was not found to make a significant contribution to the model, even though mass alone correlated well with WRC compared to other individual parameters. Further investigation into this ostensibly contradictory trend revealed that helmet mass can be reasonably well modelled as a function of liner thickness and vent number (adjusted $R^2 = 0.59$, $p = 0.019$). In light of this relationship, it may be concluded that overall mass is reflective of a helmet's average liner thickness and amount of vents, and that while mass alone may be used as a lump descriptor of helmet performance, combining these two parameters in one model further enhances predictive value.

Although a weak negative correlation was observed, helmet price was not significantly correlated with overall performance. Many additional aspects likely play into helmet pricing aside from impact attenuation capabilities, including aerodynamics and aesthetics. While these factors are important to many cyclists, there is a need for objective impact data to be made available to the public so that consumers may also make safety a key consideration when purchasing helmets.

5 CONCLUSIONS

The helmets tested herein demonstrated a wide range in protective capabilities. Certain design parameters, such as mass, liner thickness, and vent number, were found to be predictive of performance, although price was not. These data can be used to inform helmet manufacturers and consumers alike, encouraging safer helmet design.

REFERENCES

[1] National Electronic Injury Surveillance System, *US Consumer Product Safety Commission*. Web, 2016.
[2] H. J. Mertz et al., "Biomechanical and scaling bases for frontal and size impact injury assessment reference values", *Stapp Car Crash J* 47 (2003), pp. 155-188.
[3] M. Williams, "The protective performance of bicyclists' helmets in accidents", *Accid Anal Prev* 23(2-3) (1991), pp. 119-131.
[4] T.A. Smith et al., "Evaluation and replication of impact damage to bicycle helmets", *Accid Anal Prev* 26(6) (1994), pp. 795-802.
[5] N. Bourdet et al., "Head impact conditions in the case of cyclist falls", *Proceedings, Inst Mech Engr, Part P: J Sports Eng Tech*, Sage Publications, Thousand Oaks, CA, 2012 282-289 pp.
[6] R. Rowson, S. Duma, "Development of the STAR evaluation system for football helmets: Integrating player head impact exposure and risk of concussion", *Ann Biomed Engr* 39(8) (2011), pp. 2130-2140.