

An investigation of Electric Self-Balancing Scooter Riders' Head Injury in Traffic Accident

Shi Shang^{1, 2}, Jun Xu^{1, 2, 3}

¹ Department of Automotive Engineering, School of Transportation Science and Engineering, Beihang University, Beijing, P.R. China, 100191

² Advanced Vehicle Research Center, Beihang University, Beijing P.R. China, 100191,

³ Beijing Key Laboratory for High-efficient Power Transmission and System Control of New Energy Resource Vehicle, Beihang University, Beijing, China, 100191
Email: junxu@buaa.edu.cn

Abstract: With the pressing demand of environmentally friendly personal transportation vehicles, mobility scooters become more and more popular for the short-distance transportation. Similar to pedestrians and bicyclists, scooter riders are vulnerable road users and are expected to receive severe injuries during traffic accidents. In this research, a MADYMO model of vehicle-scooter crash scenarios are numerically setup. The model of the vehicle with the scenario are validated in pedestrian-vehicle accident investigation with previous literatures in terms of throwing distance and HIC₁₅ value. HIC₁₅ values gained at systematic parametric studies. Injury information from various vehicle crashing speeds angles, contact positions are extracted, analyzed and then compared with those from widely studied pedestrian-vehicle and bicycle-vehicle accidents. Results show that the solowheel provides better impact protection for the riders, pedestrians would receive the most severe injuries at the same conditions in terms of head injury. The responsible reasons should be the smaller friction coefficient between the wheel-road than the heel-road interactions, different body gestures leading to different contact positions and forces. Results may shed lights upon the future research of mobility scooter safety analysis and also the safety design guidance for the scooters.

Keywords: Self-balancing scooter; Traffic accidents; Numerical simulation; Head injuries

电平衡车骑车人在交通事故中的头部损伤研究

尚诗^{1, 2}, 许骏^{1, 2, 3}

¹北京航空航天大学交通科学与工程学院汽车工程系, 北京, 中国, 100191

Email: junxu@buaa.edu.cn

摘要: 随着环保型私人交通工具需求的增多, 电动车在短距离代步的使用中越来越受欢迎。与行人和骑车人类似, 电平衡车骑车人也被视作弱势道路使用者, 在交通事故中可能会遭受严重的损伤。本研究运用 MADYMO 建立了一个汽车-电平衡车的碰撞模型, 根据此模型与先前的行人-汽车交通事故的第一落地点抛距和 HIC₁₅ 值的对比, 验证模型可用。HIC₁₅ 值可以由参数化研究得到。通过改变汽车的碰撞速度、碰撞角度和接触位置等提取的电平衡车骑车人损伤情况, 与行人/骑车人-汽车碰撞得到的损伤作了分析和对比。结果显示单轮电平衡车相比自行车和双轮电平衡车, 在碰撞中对骑车人的保护性能更好一些, 而在相同的碰撞条件下, 行人会受到最严重的头部损伤。造成此结果的原因是车轮-地面的摩擦系数相比行人脚踵-地面的摩擦系数要小, 不同的身体姿态导致了不同的碰撞位置和碰撞力。本研究对电平衡车安全现状进行了分析, 其结果可以指导平衡车的安全设计。

关键词: 电平衡车; 交通事故; 数值模拟; 头部损伤

1 引言

电平衡车作为一个新型的零排放交通工具因为其便捷的优点而越来越受欢迎, 人们通常在短途路程中或长途路程中乘坐地铁后使用电平衡车代步^[1]。高科技公司已经制造生产出多种类型的电平衡车并投入市场, 比如单轮电平衡车和双轮电平衡车。电平衡车骑车人与行人、骑车人类似, 也是弱势道路使用者, 在交通事故中可

能会受到严重的伤害。虽然很多先进的行人保护系统已经广泛应用到当今的汽车上，但据世界卫生组织统计^[2]，在所有的交通事故死亡人数中，弱势道路使用者仍占了一半左右。

有关行人和骑车人在交通安全中的研究可以在公开的文献中找到，研究方法主要有深入事故分析的方法^[3-6]、数理统计模型^[7-10]、数值仿真^[11, 12]和结构力学测试^[13, 14]等方法。弱势道路使用者在所有的交通事故中的致命伤中，头部损伤占了 80%左右^[10, 15]。根据实验和仿真的结果，碰撞速度^[16-18]、步行/自行车速度^[19, 20]、人体姿态^[4]、汽车类型^[19, 21-23]、碰撞位置^[3, 18, 20, 24, 25]和身高^[19]等变量对弱势道路使用者头部损伤的影响很大。现有的关于电平衡车的研究主要集中在机器自己的自适应控制方法和算法以达到自平衡和偏航操纵的目的^[26, 27]。由于缺少电平衡车的交通事故案例，有关其在交通事故中的碰撞安全性的研究尚处于空白。然而，电平衡车的高速行驶和行驶过程中的突然转弯，很有可能会导致交通事故，所以，在取代步行和自行车之前，应当首先考虑它的安全因素。

尽管自平衡车在中国已经使用了很多年，交管局还是没有出台明确的法律法规。导致的结果是，生产厂商和公司没有安全标准去优化设计它们的产品使其保护骑车人的安全性能提升。为了跨越这个鸿沟，本文研究了电平衡车在其与汽车碰撞事故中安全性。考虑到汽车、电平衡车和骑车人的运动学和动力学耦合的复杂性，将 HIC(Head Injury Criteria)值作为评价头部损伤的指标。数值模拟的碰撞场景在 MADYMO 操作平台上建立，选择两种具有代表性的电平衡车，通过改变碰撞速度、角度、位置等，研究电平衡车骑车人的损伤情况。同时，将行人和骑自行车人作为对比，全面揭示电平衡车的碰撞安全性并且为将来提高其安全性能提供指导。

2 实验方法

本文利用 MADYMO 建立了汽车-电平衡车/行人/自行车的碰撞模型，将侧面碰撞设为基本碰撞场景（汽车行驶方向与弱势道路使用者行走方向成 90 度夹角，第一碰撞点在汽车车头前端的中间）。另外，设置汽车轮胎与地面的摩擦系数为 0.8 并且汽车持续制动。

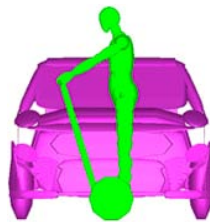


Figure 1. A baseline scenario of crash model

图 1. 碰撞模型的标准场景

其中行人和骑车人模型使用百分之五十分位成年男性行人模型，汽车模型选用丰田凯美瑞为原始模型，自行车选用中国很流行的飞鸽牌自行车，电平衡车选取最常见的两种车型-单轮电平衡车 Solowheel 和双轮电平衡车 Ninebot。利用 HIC₁₅ 指标去评价头部与汽车第一次接触所遭受的损伤。

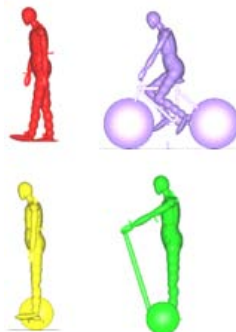


Figure 2. Four types of vulnerable road users multibody models

图 2. 四种弱势道路使用者的模型

3 结果与讨论

3.1 不同碰撞速度下弱势道路使用者头部损伤比较

行人和自行车/电平衡车骑车人被汽车撞后，人体发生翻转导致头部与汽车的发动机罩或风挡玻璃相撞，随后跌落在地面。图 3 是第一落地点抛距(Airborne Flying Distance)与汽车碰撞速度的关系。弱势道路使用者被汽车碰撞后的第一落地点抛距随着车速的增大而增大。

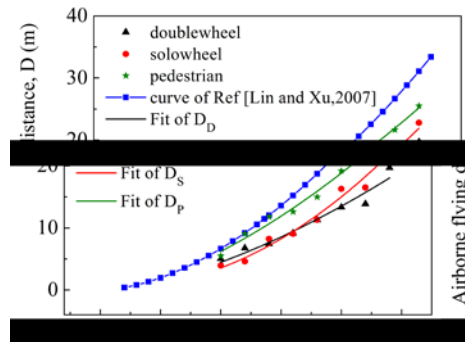


Figure 3. The relation of impact speed and VRUs' AFD at side impact cases
图 3. 侧面碰撞下弱势道路使用者的第一落地点抛距与碰撞速度的关系

模型公式如下，其中 V_C 为汽车速度， D_D 、 D_S 、 D_P 分别双轮车骑车人、单轮车骑车人和行人的第一落地点抛距，这个结果与文献^[24]相接近，从而验证了本文模型的可用性。

$$D_D = 0.1145 V_C^{1.5918} \quad (1)$$

$$D_S = 0.0298 V_C^{2.0763} \quad (2)$$

$$D_P = 0.1585 V_C^{1.5946} \quad (3)$$

现有的研究表明，很多控制因素对弱势道路使用者头部损伤有很大影响，其中汽车碰撞速度被认为是主要因素。通常车速越快，导致弱势道路使用者头部损伤越严重。图 4 揭示了头部的 HIC_{15} 值与车速的关系。可以看到，在相同的碰撞条件下，四种弱势道路使用者中，行人是最脆弱的，单轮平衡车骑车人是最安全的。

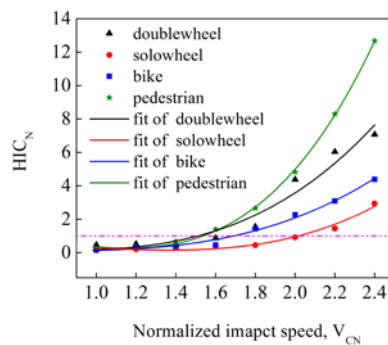


Figure 4. A baseline scenario of crash model
图 4. 碰撞模型的标准场景

3.2 碰撞速度和碰撞角度的耦合作用

本文做了一些列耦合因素的仿真，图 3 显示的是在三种不同碰撞速度（10m/s、15m/s、20m/s）下，各种碰撞角度（如图 5）下的头部 HIC_{15} 值的比较。

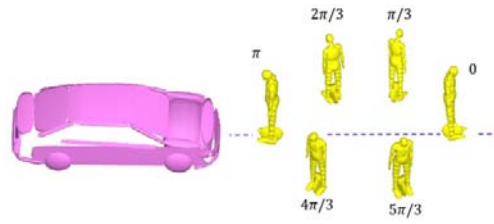


Figure 5. Description of different impact angles
图 5. 不同碰撞角度的描述

如图6结果显示碰撞速度为10m/s和15m/s时,单轮车骑车人的头部HIC₁₅值大多数都处于安全界限下(HIC₁₅ < 700)。当单轮车骑车人面向或背对车头时,头部损伤较严重。

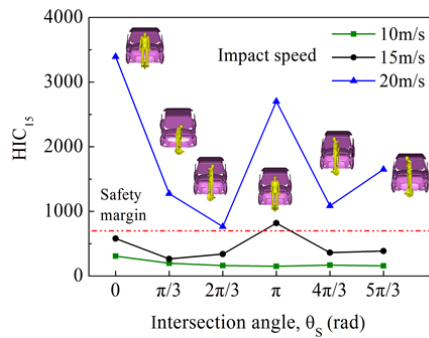


Figure 6. Coupling effect of impact speed and angles on HIC15 of solowheel rider
图 6. 碰撞速度和角度耦合对单轮骑车人头部 HIC₁₅ 影响

相比之下,双轮平衡车骑车人的头部 HIC₁₅ 值波动比较大,如图 7。当人面向车头时,损伤较小,有可能是因为操纵杆对人体有一个缓冲的作用,吸收了一部分碰撞力和能量。使得头部-汽车的碰撞力减小,损伤相对较轻。

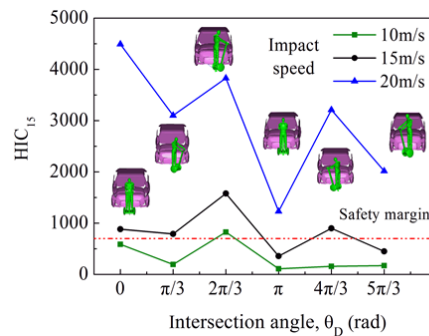


Figure 7. Coupling effect of impact speed and angles on HIC15 of doublewheel rider
图 7. 碰撞速度和角度耦合对双轮骑车人头部 HIC₁₅ 影响

对行人而言,在三种车速下背对车头的方向, HIC₁₅ 值会很高(如图 8)。

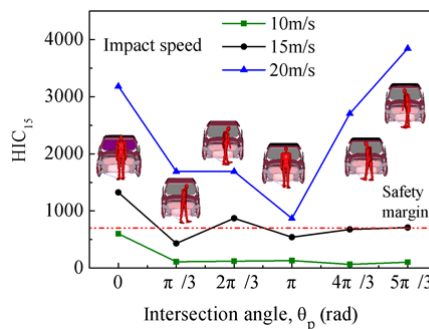


Figure 8. Coupling effect of impact speed and angles on HIC15 of pedestrian
图 8. 碰撞速度和角度耦合对行人头部 HIC₁₅ 影响

3.3 碰撞速度和碰撞位置的耦合作用

弱势道路使用者与汽车的第一碰撞点决定了头部与汽车接触的位置和人体姿态，并最终影响头部损伤的严重性。为了研究碰撞速度和碰撞位置耦合作用对电平衡车骑车人头部损伤的影响，本文做了一系列仿真。

为了将定量分析转为定性分析，将归一化的水平距离 d 作为代表第一碰撞位置的输入参数，如图 9。

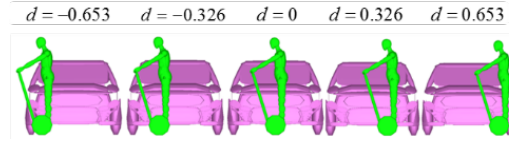


Figure 9. Description of different impact positions
图 9. 不同碰撞位置的描述

其中 $d = d_0/L$ (d_0 是汽车的中心到碰撞点的水平距离, L 是半个车头的宽度)。本节研究分析了电平衡车骑车人在三种不同车速和五种不同碰撞位置的情况下，头部损伤的情况。图 10 揭示了汽车-单轮平衡车第一碰撞点和骑车人头部 HIC_{15} 的关系。在 10m/s 和 15m/s 的碰撞速度下， HIC_{15} 的变化不大；碰撞速度为 20 m/s 时，波动很大。

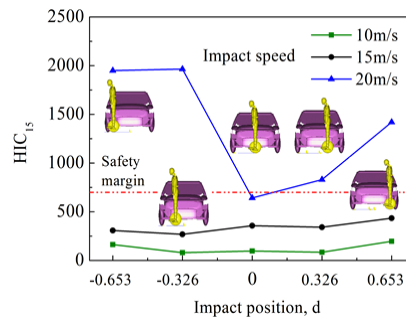


Figure 10. Coupling effect of impact speed and impact position on HIC_{15} of solowheel
图 10. 碰撞速度和位置耦合对单轮骑车人头部 HIC_{15} 影响

通过提取头部加速度随时间变化的曲线，由图 11 可以看到，当车头中间位置碰到单轮车后，骑车人的头部撞到了风挡玻璃；当车头中间靠右的部位撞向单轮车，骑车人头部碰到了风挡玻璃和发动机罩的交接处，这块区域容易产生更严重的伤害。

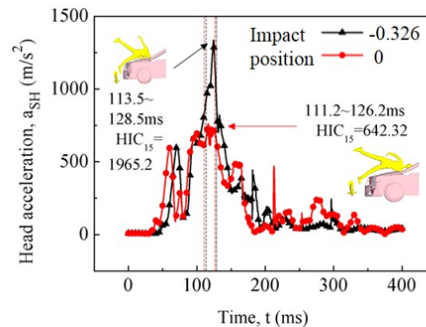


Figure 11. Head acceleration-time history of solowheel rider at 20m/s impact cases
图 11. 单轮车骑车人在 20m/s 的碰撞速度下不同接触位置的头部加速度曲线

双轮车骑车人的头部 HIC_{15} 值和第一碰撞位置的关系如图 12 所示。汽车初始速度为 20 m/s 时，当车头右端 ($d = -0.653$)和中间靠右($d = -0.326$)的部位撞向双轮车时， HIC_{15} 值较低。

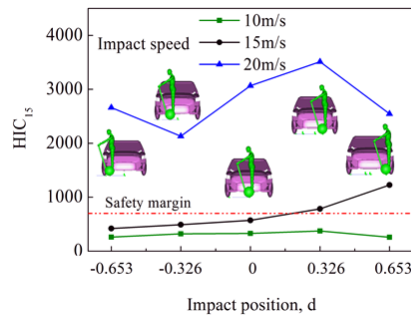


Figure 12. Coupling effect of impact speed and impact position on HIC_{15} of doublewheel

图 12. 碰撞速度和位置耦合对双轮骑车人头部 HIC_{15} 影响

比较其头部加速度曲线（如图 13），发现其波动很相似。更进一步分析发，车头右端撞向双轮车后，骑车人头部 HIC_{15} 值较低的原因是竖直方向的加速度偏低，降低了损伤的严重程度。

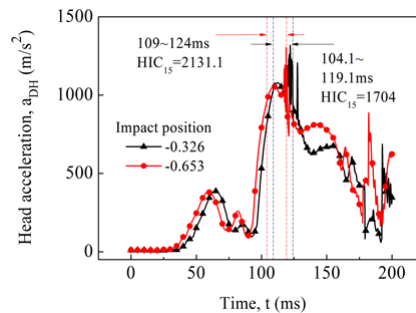


Figure 13. Head acceleration-time history of doublewheel rider at 20m/s impact cases

图 13. 双轮车骑车人在 20m/s 的碰撞速度下不同接触位置的头部加速度曲线

4 总结

电平衡车的需求越来越大，所以很有必要对其安全性进行研究。本文通过数值模拟典型的交通碰撞场景分析电平衡车的安全性。首先，根据比较先前研究的抛距验证了模型可用，接着分析研究了弱势道路使用者的重心高度和汽车前端尺寸对人头部损伤的影响。然后，通过单一控制因素（如碰撞速度、碰撞位置和碰撞角度）和双因素耦合的参数化仿真实验，对比行人和自行车，从而揭示影响电平衡车安全性的因素。结果表明，单轮和双轮电平衡车在相同的碰撞条件下，头部遭受严重损伤的几率要比行人小。该结果可以为推广电平衡车而扫清障碍，也可以为潜在交通事故的司法鉴定提供帮助。

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