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Analysis of the consequences of car to micromobility user side impact crashes

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ABSTRACT

Introduction: The strong rise in modes of travel commonly referred to as micromobility has changed the mobility patterns and lifestyles in cities worldwide, especially after the COVID-19 pandemic. It has led to a significant increase in the number of crashes involving these types of vehicles, especially bicycles and stand-up e-scooters. The risk of crashes is higher at intersections where motor-vehicles perform a turning maneuver crossing a bike lane. *Method:* The consequences of a passenger car-to-micromobility vehicle side-impact crashes, considering both bicycle and e-scooter, were studied based on the results of the simulation of several scenarios with PC-Crash software. Two injury criteria were applied: Head Injury Criterion (HIC_{15}) and 3 ms chest acceleration criterion. *Results:* When motor-vehicle speed is lower than 50 km/h, the 3 ms chest acceleration never exceeds the 60 g threshold. However, at 50 km/h, it is close to 50 g in the case of e-scooter rides. At this speed, HIC_{15} is considerably greater than 1000, both for bicycles and for e-scooters, and the safety margin of 700 is exceeded at 45 km/h for e-scooters. *Conclusions:* In case of motor vehicle-to-micromobility vehicle side-impact crash, riding a bicycle is safer than riding an e-scooter since the observed HIC_{15} experienced by the cyclists is lower than that experienced by the e-scooter rider when motor vehicle speed is greater than 30 km/h. *Practical Applications:* To reduce micromobility users injury risk at intersections, motor vehicle speed limit should be equal or lower than 40 km/h. At this impact speed, the activation of hood or bumper airbags could be justified.

1. Introduction

Urban mobility patterns have changed in recent years worldwide, thanks to the strong rise on vehicles of micromobility. Bicycle riding is the most widespread micromobility transport mode, followed by stand-up electric scooters (e-scooters) (Hardt et al., 2019). Since 2019, bicycle use has considerably increased among EU countries, as well as among regions of the United State and Canada (Buehler & Pucher, 2021). However, the increase in the use of the e-scooter has been greater, since the lack of physical effort contributes to their potential impact on substituting and supplementing other modes of transport, such as public transport and cars, for even longer trips (Laa & Leth, 2020).

This increase in use has also led to an increase in related crashes. In fact, current statistics show that the number of crashes related especially to e-scooters has been rapidly on the rise. In Swedish cities, the number of e-scooter accidents has dramatically increased since the introduction of e-scooter in 2018 (Stigson et al. 2021). The same trend has been observed in Spanish cities, where, while the number of crashes involving bicycles has decreased by 4% from 2018 to 2020, the number of crashes involving e-scooters and other personal mobility vehicles (PMV) has increased eightfold (Sanjurjo-de-No et al. 2022).

Both cyclists and e-scooter riders are vulnerable road users and are likely to sustain severe injuries in crashes, especially with motor vehicles. Therefore, there is a need for analyzing interactions of them with other road users (Kazemzadeh et al., 2023). In fact, in Spanish cities, 65% of fatal micromobility crashes involved a motor-vehicle (Sanjurjo-de-No et al., 2022).

Head and face injuries are the most common injury types for micromobility riders involved in collisions (Kazemzadeh et al., 2023). Therefore, kinematic responses of micromobility users in crashes are fundamental to injury mechanism studies and establishment of safety standards and regulations. However, riders' kinematics responses are difficult to collect directly from the traffic crashes scenes and these data are not included in crashes statistics. As a primary approach, different from epidemiologic studies, sev-

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eral typical crashes involving micromobility users with detailed information were reconstructed through simulation tools such as PC-Crash, MADYMO, and LS-DYNA. These simulation technologies have also been widely used in traffic safety research to study the effects of several variables on the dynamic response of vulnerable road user, such as vehicle types, collision types, and collision speeds.

Several studies have analyzed the pedestrian-to-ground impact injury risk in vehicle-to-pedestrian collisions considering the effects of the motor-vehicle type, specifically its front-end design, and the vehicle speed, performing the simulations with MADYMO (Crocetta et al., 2015; Xu et al., 2016; Yin et al., 2017; Shi et al., 2018) and with PC-Crash (Tian et al., 2020).

Regarding bicycles, MADYMO has been used to evaluate the head impact conditions in the case of cyclist falls (Bourdet et al. 2012). McNally and Rosenberg (2013) analyzed the consequences of not only falls, but also other typical incidents involving child cyclists with and without the use of a helmet, using MADYMO dynamics software. The same methodology was used by McNally and Whitehead (2013) to study the influence of helmet wearing on head injury risk in adult cyclists. In both studies, one of the scenarios modeled was a side-impact by a vehicle, where the cycle is struck side-on by a car. This last type of crash and other motor vehicle-to-bicycle crashes have been deeply studied. Nie and Yang (2014) studied the kinematics response of bicyclists and the correlation of the injury severity with vehicle impact speed in car-to-bicycle crashes based on reconstruction car-bicycle crashes using MADYMO. Xu et al. (2016) considered frontal impact in a straight line and lateral impact at the cross intersection.

Several authors also included in the simulated scenarios electric two-wheel (E2W) vehicles. Gao et al (2021) generated a large number of e-bike to car accident conditions and analyzed cyclists' head kinematic responses and injury risk using decision tree model. The e-bike-to-car impact multi-rigid body model was developed in MADYMO and verified by an accident reconstruction by Gao et al. (2020). Liu et al. (2022) developed an intelligent method for accurate, high-efficient reconstruction of accidents involving cars an e-bikes based on MADYMO. Huang et al. (2020) compared the factors influencing kinematics and head injury risks between E2W-vehicle and bicycle-vehicle collisions.

PC-Crash, as a crash simulation software, has been also used in the study of vehicle-to-bicycle and e-bicycle collisions. Wang et al. (2014) reconstructed a car-to-electric bicycle side collision. Zhang et al. (2012) evaluate the throw distance of a bicyclist when he is struck side-on by a car. Li and Lu (2011) analyzed the characteristic of cyclist throw distances and head injuries in car to electric-bicycle side-impact accidents. Wan et al. (2020) studied the dynamic response and injury patterns after collision between cars and three kinds of two-wheelers (bicyclist, e-bicyclist, and motorcyclist) simulating side-impact and rear-end impact. Sokolovskij and Juodka (2022) examined a simulated rear-end collision between a car and a cyclist, assessing the trajectory of the cyclist's movement after the impact (throwing distances and angles). Wei et al. (2021) studied the injury mechanism of electric cyclists in the collision between right turn of truck and electric bicycle. Zhang et al. (2022) analyzed the movement and injury characteristics of the human body in a side collision between the front of a small car and a bicycle.

Most studies have been focused on bicycles and electric bicycles, whereas only a few of them have analyzed other micromobility vehicles crashes consequences. Xu et al. (2016) studied four types of VRU-vehicle accidents were numerically modeled based on MADYMO platform: pedestrian-vehicle, solowheel-vehicle, doublewheel-vehicle and bicycle-vehicle accidents. Wang at al. (2022) reconstructed several typical single electric self-balancing scooters (solo-wheeler and two-wheeler) accident scenarios via MADYMO and assessed the risk of riders' head injury.

Focusing on e-scooters, which are the most widespread PMV, Posirisuk et al. (2022) carried out a computational prediction based on MADYMO of head-ground impact kinematics in e-scooter falls. They predicted the head-ground impact force and velocity of e-scooter riders in different falls caused by potholes. Wei et al. (2023) developed and validated a finite element model of a hybrid III dummy riding an E-scooter to reproduce 27 falls caused by the collision with a curb, in which there were different riding speeds, curb orientations, and e-scooter orientations. Head-ground impact velocities and locations were evaluated with and without helmet.

Ptak et al. (2022) analyzed the e-scooter user kinematics after a crash against SUV when the e-scooter drives into the side-front of the vehicles, a side B-pillar crash and a frontal impact initiated by the e-scooter to the front-end of the vehicle. However, they did not study the consequences of a car to e-scooter side-impact crashes. The full model setup encompassed two numerical codes–LS-DYNA for handling finite element (FE) code (the vehicle and scooter model) and MADYMO for multibody code (dummy model).

Although car to bicycle and electric bicycle crashes has been deeply studied, there is limited previous work on kinematics and biomechanics of e-scooter crashes, especially car-to-e-scooter side-impact crashes. Therefore, the aim of the current study is to study the micromobility user (cyclist and e-scooter rider) kinematics and injury risk after a car-to-micromobility user side-impact crash. The analysis is based on numerical simulations with PC-Crash software.

2. Methods

2.1. Crash scenarios

According to data from the General Directorate of Traffic of the Spanish Government, in 2021 (the last year with consolidated data), there were 4,691 collisions involving a motor vehicle and a micromobility user (primarily bicycles and e-scooters). The most frequent type of crash was the side-impact collision (2482 crashes), followed by the lateral collision (765 crashes), rear-end collision (339 crashes), and frontal collision (186 crashes). Out of the side-impact collisions, 72% occurred at intersections. Among them, 122 resulted in serious injuries or fatalities.

This is the reason why the study is focused on the analysis of side-impact crashes where a motor vehicle collides with a micromobility vehicle. This situation can occur when a vehicle is traveling straight ahead and the bicycle or e-scooter crosses perpendicularly, when the vehicle exits a roundabout, or during a right turn at an intersection, provided that the bike lane is set back enough for the vehicle to reach a perpendicular position to the bike lane (Fig. 1). In both the first and second cases, the motor vehicle can reach speeds close to 50 km/h or higher, while in the latter case, its expected speed will be lower.

In order to assess the consequences of a passenger car-to-micromobility user side-impact crash, two types of collisions have been numerically modeled and compared based on PC-Crash software (i.e., vehicle-to-bicycle and vehicle-to-e-scooter). The tests simulated a cyclist and an e-scooter rider traveling in front of the car, perpendicular to its direction of travel (Fig. 2).

PC-Crash is a crash reconstruction program developed by Autrian DSD company. It offers the ability to simulate collisions involving multibody objects interacting with 3D vehicle mesh models. Pedestrian and micromobility systems, such as rider-and-e-scooter and cyclist-and-bicycle, are usually simulated as multibody objects. A multibody is a system of rigid bodies (head, torso, pelvis, etc) interconnected with pivoting joints. Each body

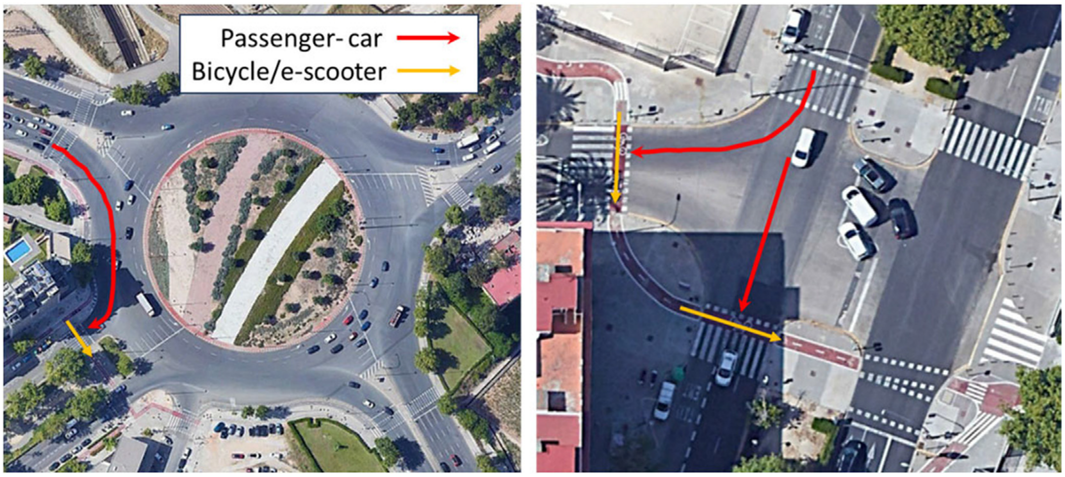

Fig. 1. Simulated traffic crash scenarios.

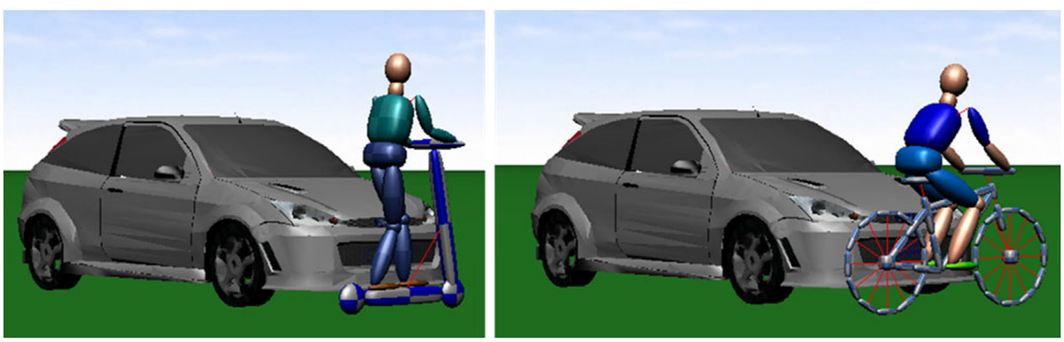

Fig. 2. Scenarios simulated with PC-Crash.

has different properties like geometry, mass, contact stiffness and coefficients of friction. The geometry of each body is defined by a general ellipsoid of degree n.

In the analyzed scenarios, three types of impacts are simulated: (i) ellipsoid to ellipsoid contact, which represents collisions between cyclists and bicycles or e-scooter riders and their vehicles; (ii) ellipsoid to vehicle contact, which models interactions between cyclists/riders and motor vehicles, as well as between micromobility vehicles and motor vehicles; and (iii) ellipsoid to ground contact, which describes the interaction between micromobility users and the ground. The calculation of last two types of contacts is similar, with the only difference being that ground slope polygons have zero velocity and that it is assumed that a force on a ground polygon does not result in any motion of the polygon (Datentechnik, 2013).

This software is widely applied in the study of crashes reconstruction and analysis of collisions, and its representativeness has been validated (Moser et al. 2000, Rose & Carter 2018, Condrea et al. 2020a, Condrea et al 2020b, Fatzinger et al. 2021).

As mentioned earlier, in this study, PC-Crash was used to simulate two different scenarios: a motor vehicle-to-bicycle collision and a motor vehicle-to-e-scooter collision. In all cases, the speed of the micromobility vehicle was kept constant at 25 km/h. The tests were run at six different vehicle speeds: 25, 30, 35, 40, 45, and 50 km/h. In Spain, the speed limit on urban roads with more than one lane per direction is 50 km/h and on urban road with only one lane per direction is 30 km/h.

2.2. Micromobility vehicles and riders' models

In the current study, a bicycle, an e-scooter, and their riders' multibody systems were used (Fig. 3). The detailed dimensions are shown in Table 1.

2.3. Vehicle model

From PC-Crash multi-rigid library, a Ford Focus 2.0 TDCi (length: 4.340 m, width: 1.840 m, height: 1.490 m, weight: 1300 kg, wheelbase: 2.640 m) was chosen for crash scenarios since it is one of the most common vehicles in Spain (Fig. 4).

2.4. Injury criteria

Head injuries are the most common injury types for micromobility riders involved in collisions (Kazemzadeh et al. 2023). Therefore, head injury criterion HIC_{15} was adopted as the main injury criterion (Eq. (1). It was adopted by Federal Motor Vehicle Safety Standards (FMVSS) as injury criterion with the safety margin of HIC_{15} = 700. The HIC_{15} value of 700 represents a 5% risk of severe injury, which corresponds to level 4 or higher of the Abbreviated Injury Scale (AIS). HIC_{15} is usually chosen, instead of HIC_{36}, to assess the severities of head injury because most of the head impacts duration is within 15 ms and it is vital to concussions and skull fractures (Xu et al. 2016).

$$HIC = max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}(t_2 - t_1) \tag{1}$$

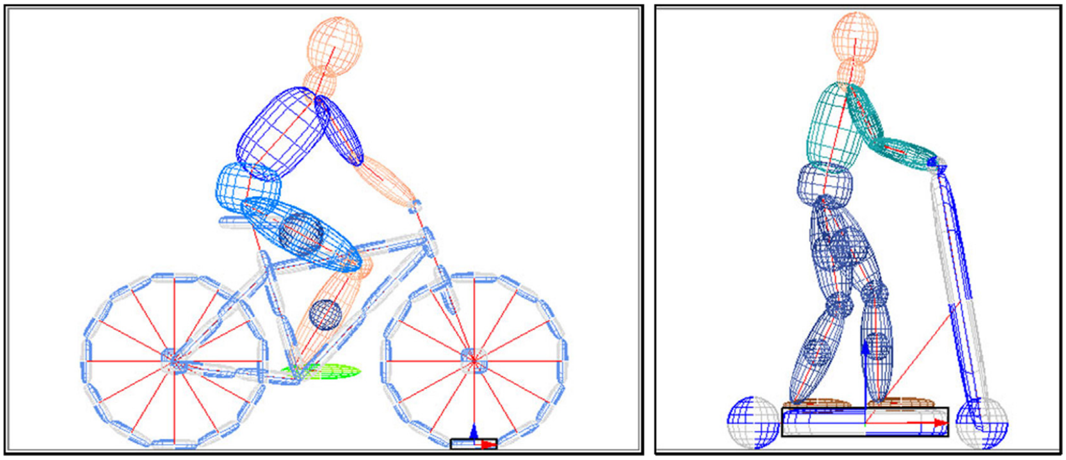

Fig. 3. Micromobility vehicles and riders' multibody models.

Table 1
Micromobility vehicles and riders' dimensions.

Micromobility vehicle	Bicycle	e-scooter
Length (m)	1.521	1.180
Width (m)	0.6	0.680
Height (m)	0.992	1.232
Weight (Kg)	15	16
Rider height (m)	1.75	1.75
Rider weight (kg)	80	80

Fig. 4. PC-Crash vehicle model.

Where t_1 and t_2 are the initial and final time points of the interval that HIC attains a maximum value and $t_2 - t_1 \leq 15ms$, and $a(t)$ is the function of head center gravity linear resultant acceleration with time.

In addition, 3 millisecond chest acceleration criterion was considered, whose safety threshold is 60 g, according to FMVSS 208, since this threshold corresponds to a 25% probability of AIS4 + injury (Stapp, 1970; Mertz & Gadd, 1971).

3. Results

As a results of the scenarios simulations, cyclists and e-scooter rider's head and chest acceleration were obtained.

During the crash, the lower extremities of the riders would first collide with the bumper area, the upper bodies then fell onto the hood and then the riders' head collided with the windshield. After that, the rider begins to slide down along the windshield or hood and finally hit the ground and stop. Fig. 5 shows the cyclists and e-scooter riders' resultant head acceleration for all the side-impact scenarios. The first set of peaks observed in this figure corresponds to the impact of the head against the car windshield, while the second set corresponds to the impact of the head with the ground. There are also at the beginning several small peaks of head acceleration caused by the flip over of the human body after the suddenly imposed deceleration due to the rider-vehicle contact.

The highest cyclists' acceleration of 1227 m/s^2 is observed in a motor vehicle-to-bicycle crash when the vehicle impact speed is 50 Km/h. When the vehicle struck an e-scooter at this speed, the highest rider's head acceleration is 1411 m/s^2. In the case of car-to-bicycle side-impact crashes, after the maximal acceleration value, at least one more acceleration peak can be observed. However, in the case of car-to-e-scooter side-impact crashes, there is only one significant peak, especially in the highest vehicle speed scenarios.

Fig. 6 shows the riders' chest acceleration for all the side-impact scenarios. The highest cyclists' chest acceleration of 295 m/s^2 is observed in a motor vehicle-to-bicycle crash when the vehicle impact speed is 40 Km/h. However, the highest e-scooter rider's chest acceleration is observed when the motor-vehicle speed is 35 Km/h, being higher (333 m/s^2). While at these speeds the peaks occurred for short periods of time, when the vehicle speed is higher, the maximum accelerations last longer and their values are lower.

4. Discussion

Considering the results of the simulations, the variation in the chest acceleration and in the HIC_{15} as a function of the motor-vehicle speed was studied.

In the case of 3 ms chest acceleration (Fig. 7), it increases as the motor vehicle speed does, never exceeding the 60 g threshold. However, when a car-to-e-scooter crash occurs at 50 km/h the chest acceleration is close to 50 g, which can be considered very high value. It could indicate that at this speed both cyclist and e-scooter rider will suffer serious injury in torso.

On the other hand, both in car-to-e-scooter crash and in car-to-bicycle side-impact crash, HIC_{15} increases as motor-vehicle speed increases (Fig. 8). This conclusion agrees with previous research, which observed this phenomenon in car-to-bicycle or electric bicycle side-impact crashes (Lin et al., 2011; Huang et al., 2020).

HIC_{15} is always higher in the case of e-scooters when the motor vehicle speed is greater than 30 Km/h. When the car approaches at 45 km/h, HIC_{15} experienced by riders e-scooter exceeds the safety margin of 700, and it is very close for cyclists (675). It agrees with

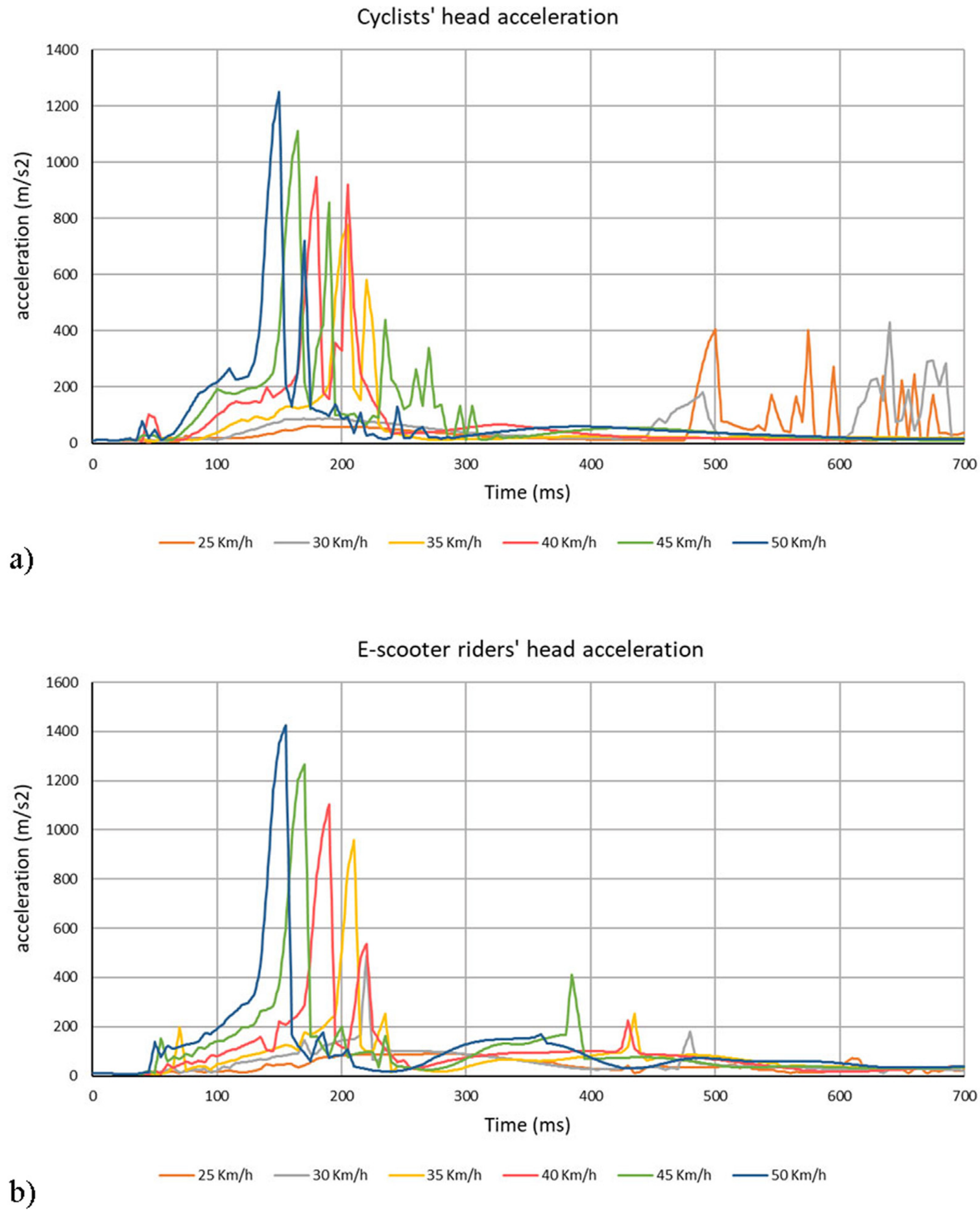

Fig. 5. A) cyclists' head acceleration, b) e-scooter riders' head acceleration.

Wan et al. (2020), who concluded that in car-bicycle side-impact, HIC_{15} is higher than 600 when vehicle speed is 45 km/h. However, they identified a peak in HIC_{15} when the impact speed is 40 km/h, which is higher compared to both 35 km/h and 45 km/h or even higher speeds. This peak has not been identified in the current study.

The curves developed by Prasad and Mertz (1985) showed that an HIC of 1000 is equivalent to an 18% probability of a severe (AIS 4) head injury, a 55% probability of a serious (AIS 3) injury and a 90% probability of a moderate (AIS 2) head injury to the average adult. Current study results show that when the motor vehicle speed is 50 km/h, cyclists' HIC_{15} is less than 1000 (888). Hence, the vehicle speed threshold of cyclist head impact injury in side-impact crashes of 50 km/h, as Lin et al. (2011) stated, could be acceptable. However, at this speed, e-scooter rider's HIC_{15} is considerably higher than 1000 (1223). Therefore, a speed limit of 50 km/h cannot be considered safe for micromobility users.

Besides, these are the results considering a medium passenger car, but it would be expected that the consequences would be more serious in the case of a larger vehicle, such as a truck. In fact, in a collision between right turn of truck and electric bicycle, the maximum HIC_{15} is 1628 according to Wei et. (2021). Considering that current research results show that e-scooter rider's HIC_{15} is higher than cyclist's HIC_{15}, in the case of truck-to-e-scooter side-impact crash HIC_{15} would be expected to be even higher.

Therefore, it can be concluded that crashes occurring during motor vehicles right turn maneuvers crossing a bike lane could be serious or even fatal, especially when the motor vehicle strikes a micromobility user. In fact, when an e-scooter drives into the side of the vehicle the highest head acceleration is 777 m/s^2 (Ptak et al., 2022), whereas when the motor vehicle strikes an e-scooter the highest head acceleration is 1411 m/s^2.

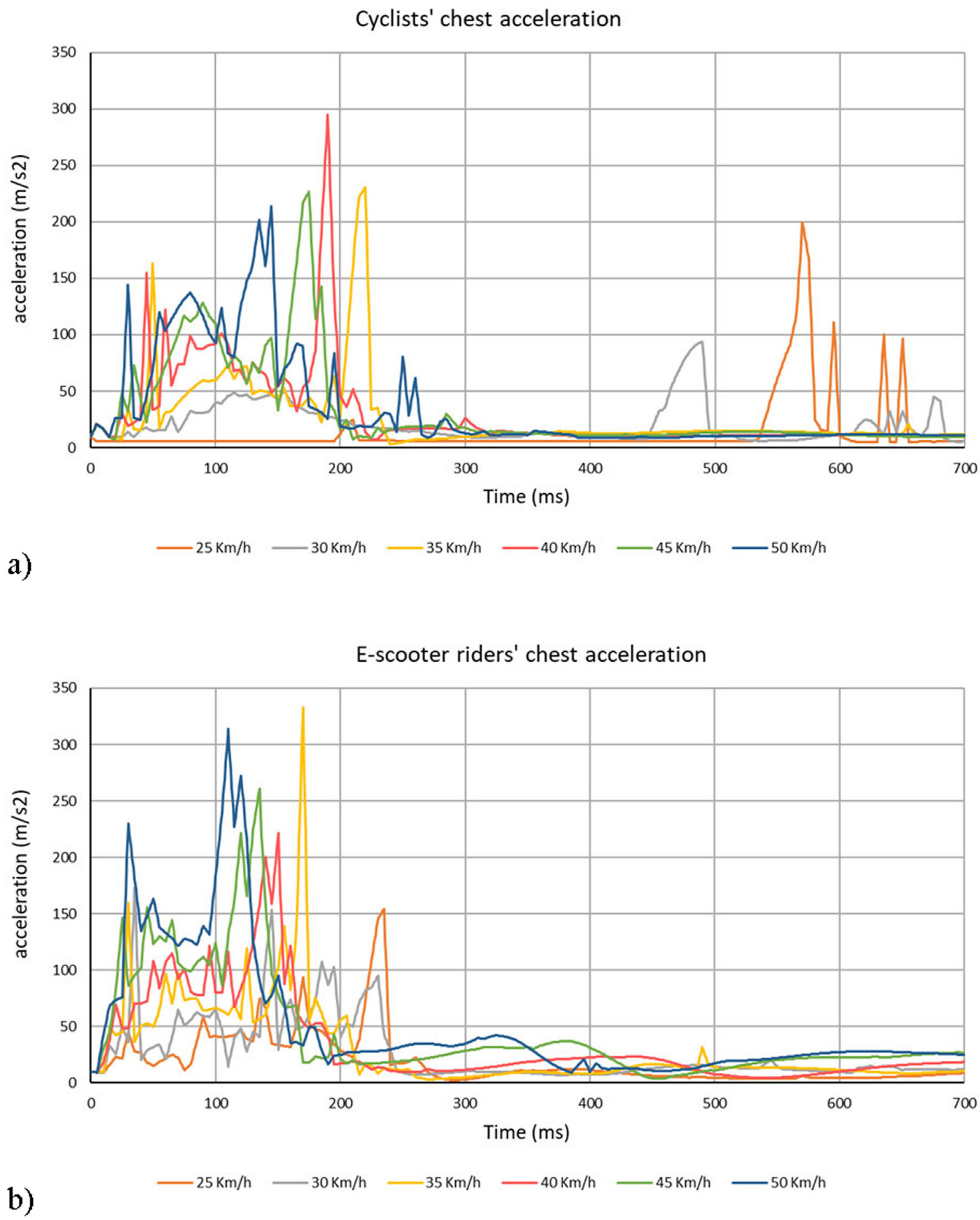

Fig. 6. A) cyclists' chest acceleration, b) e-scooter riders' chest acceleration.

4.1. Limitations of this study

This study has evaluated the consequences of a passenger car-to-micromobility user side-impact, considering only one type of bicycle, e-scooter, rider, and passenger car. However, it is known that the rider characteristics (gender, stature, age), the type of the vehicle (SUV, MPV, truck, bus), its front-end design, and the type of micromobility vehicle are likely to affect the crash consequences. Therefore, future research lines should go in this direction.

Indeed, in terms of vehicle type, Huang et al. (2020) found out distinct kinematics and head injury risks for bicycle riders when comparing SUVs and sedans. Furthermore, the findings from Shi et al. (2018), who simulated collisions between pedestrians and five vehicle types (sedan, minicar, SUV, MPV, and one-box), revealed diverse kinematic and dynamic responses for pedestrians depending on the front-end geometries of each vehicle type. Additionally, Crocetta et al. (2015) identified notable variations in impact mechanisms between low-fronted and high-fronted vehicles, as well as differences when pedestrians were male, female, or children. Although these studies primarily focused on motor

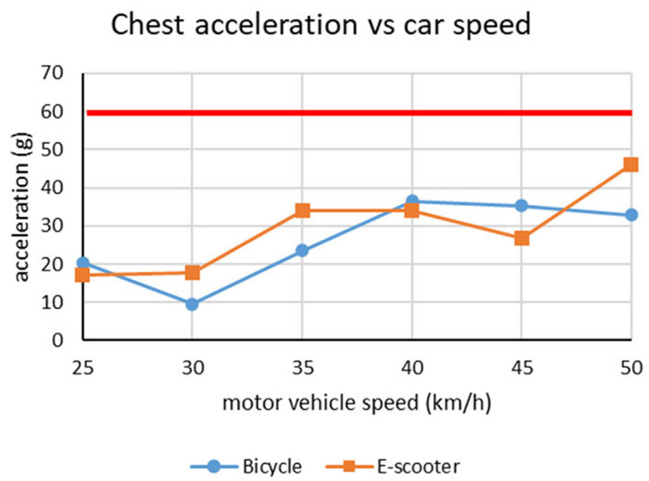

Fig. 7. Variation of 3 ms chest acceleration as a function of motor vehicle speed.

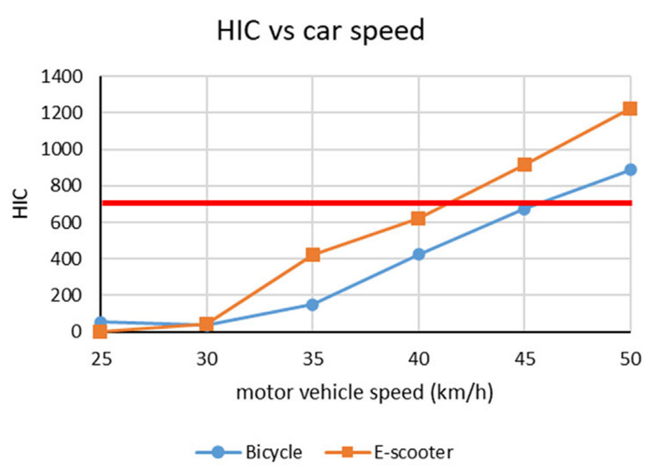

Fig. 8. Variation of HIC_{15} as a function of motor vehicle speed.

vehicle–pedestrian collisions, it is reasonable to infer that similar differences could occur in the case of cyclists and e-scooter riders.

5. Practical Applications

Considering this research results, speed limit lower than 40 Km/h should be implemented in sections where motor vehicles cross a bike lane, along with other safety countermeasures to ensure the safety of micromobility users, especially at non-signalized intersections. In fact, this limit should be even lower since the present study only considers an adult male micromobility user and the modeled car is a sedan. It is possible that if, for example, a female or a child is considered as the rider and a SUV is modeled, the speed at which serious injuries occur would be lower, and therefore the speed limit should be lower as well.

Additionally, awareness campaigns should be carried out to increase helmet use among cyclists and e-scooter riders. Moreover, from the point of view of cars, passive safety devices should also be considered, such as an airbag on the front of the bonnet. This device may block the drivers' field of view or may cause a more serious injury in low speed collisions. For this reason, the activation of the airbag will only be justified when the vehicle speed is greater than 40 km/h.

6. Conclusions

The mobility patterns and lifestyles have changed thanks to the strong rise of micromobility, especially bicycles and e-scooters, becoming a serious safety concern. The risk of a crash is greater at intersections and their severity is also greater there due to the interaction between micromobility vehicles and motor-vehicles.

The consequences of a car-to-micromobility user (cyclist and e-scooter rider) side-impact crash have been analyzed based on the results of different scenarios simulated with PC-Crash. After the above analyses the following conclusions could be stated:

- During vehicle-to-bicycle side-impact crash, two head acceleration peaks have been observed, whereas there is only one significant peak in the case of car-to-e-scooter crash.
- Considering impact speed up to 50 km/h, the 3 ms chest acceleration never exceeds the 60 g threshold. However, at 50 km/h, it is close to 50 g in the case of e-scooter riders.
- HIC_{15} increases as motor-vehicle speed does.
- HIC_{15} is always higher in the case of e-scooters when the motor vehicle speed is greater than 30 Km/h.
- HIC_{15} experienced by e-scooter riders exceeds the safety margin of 700 when the car approaches at 45 km/h, and, at 50 km/h, HIC_{15} is considerably greater than 1000.
- Speed limit at intersection where motor vehicles cross a bike lane should be lower than 40 km/h.
- Passive safety equipment, such as hood airbags or bumper airbags, could be activate when the speed impact is greater than 40 km/h.

In conclusion, results showed that the risk of sustaining a (severe) head injury in case of a side-impact collision between a motor vehicle and a micromobility user is lower for a bicyclist compared to an e-scooter rider since the observed HIC_{15} is lower. However, in both cases, motor-vehicle speeds close to 45 km/h increase probability of serious injury and even death of the rider.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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