Finite Element Analysis of Child Occupant Protection in Cargo Bikes

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I. INTRODUCTION

The cargo bike market remains robust, with child transport identified as its second most frequent application [1][2]. While Austrian statistics (2024) indicate that cargo bikes represent only 0.1% - 0.5% of total cycling incidents [5], these figures likely underestimate the actual risk due to documented underreporting bias and a lack of data detail in police records [6,17]. Despite low total frequencies, the vulnerability of young passengers is significant. Children under four years old represent for approximately 29% of all injured bicycle passengers [18]. Recent German EUSKa data further suggest that the increasing adoption of heavier and faster e-cargo bikes (pedelecs) elevates the risk of severe injury [6]. French national data shows that 56% of children in e-bike accidents were passengers and 16% of e-scooter incidents involved illegal co-riding [22]. Furthermore, passenger cars are identified as the most frequent accident opponent (64%), with car drivers found at fault in over 75% of cases [19]. Although single-vehicle crashes are common, collisions with motor vehicles pose the highest threat for fatal outcomes [17]. Crucially, existing child protection in cargo bikes often relies on rudimentary harnesses and belts that are not subject to automotive-grade standards (e.g., UN R129 [15]) and have shown failure risks in crash tests, including ejection and strangulation [3–4]. To address these risks, this study investigates the physical loads on children as well as the restraint systems during cargo bike accidents, to establish design guidelines for improved restraint systems. By utilising finite element (FE) models across the most relevant age groups, the study identifies critical safety gaps and provides a technical foundation for developing enhanced occupant protection and restraint system designs. This approach allows for the development of safety countermeasures before higher frequencies of real-world accident data emerge.

II. METHODS

A cargo bike comparative review of Statistics Austria [5] and UDV [6] reveals a high proportion of single-vehicle accidents. However, in multi-vehicle scenarios, intersection collisions with passenger cars remain the most frequent and severe accident type. Although the current sample sizes are small (n = 60 - 69), the data points toward a clear pattern in accident severity. Based on CEDATU data [21], key parameters including average collision speeds, impact configurations, and the Principal Direction of Force (PDOF) are shown in Fig.1. These data are used for this work to establish the impact speeds, directions, and contact points used in the FE simulations.

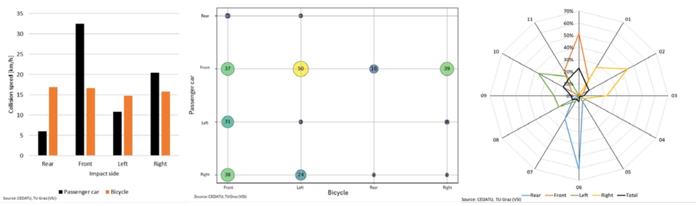

Fig. 1. CEDATU (Central Database for In-Depth Accident Study) data

FE Model for Car–Cargo Bike Collision Analysis

This study employs FE simulations to analyse the most used type of cargo bike “LongJohn” [2][7] collisions with cars in different configurations. The setup integrates a cargo-bike model (based on an open-source bicycle [8]), free available car models [9][10], Q3 and Q6 child dummies [11] with bicycle helmet [12], and the Viva+ 50M model [13] to quantify belt system loads and injury risks. As shown in Fig. 2, representative of a wider study scope, Case A and Case B were selected which represent the most common intersection collision configurations.

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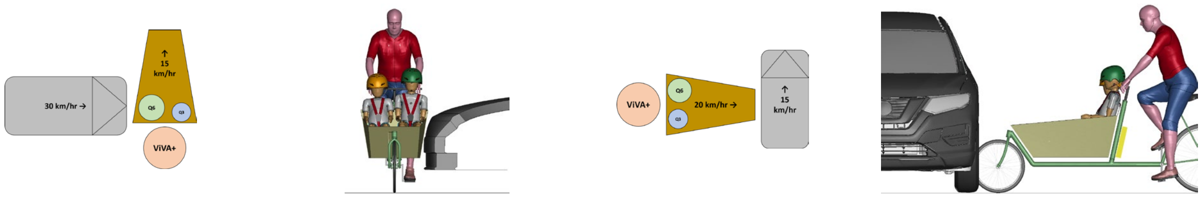


Case A (121_H) Case B (151_H)

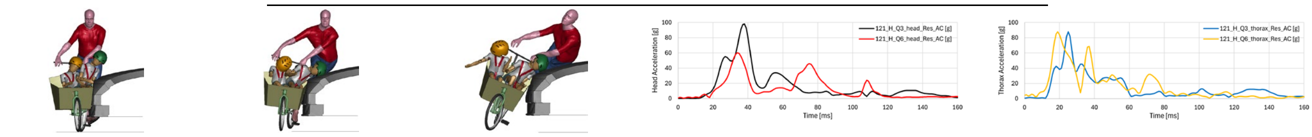
Fig. 2. Impact configuration for Case A and Case B

III. INITIAL FINDINGS

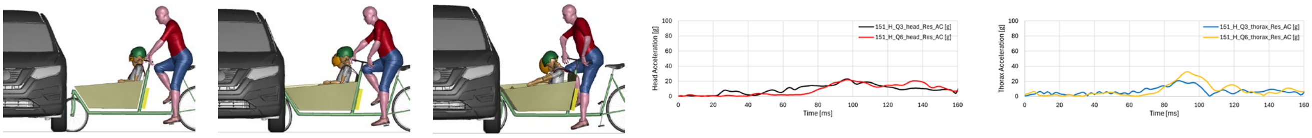
Table I shows the HIC15, Head a3ms, Chest a3ms, Chest deflection, Neck tension and Neck flexion from the two simulations of each setup. Figure 3 shows Q dummies kinematics from 40 milliseconds to 120 milliseconds and accelerations during the impact. These combined datasets provide an overview of the biomechanical responses observed under the simulations.

TABLE I
Q-Dummies Overview Injury Criteria

Case	Dummy	HIC_{15} /Limit [14]	$Head_{a3ms}$ (g) /Limit [15]	$Chest_{a3ms}$ (g) /Limit [15]
Case A (121_H)	Q3	606/800	91/80	88/55
	Q6	183/800	55/80	88/55
Case B (151_H)	Q3	25/800	23/80	21/55
	Q6	28/800	22/80	33/55



Case A 40ms Case A 80ms Case A 120ms Case A Head Acceleration Case A Thorax Acceleration



Case B 40ms Case B 80ms Case B 120ms Case B Head Acceleration Case B Thorax Acceleration

Fig. 3. Q-Dummies kinematic and acceleration during the simulation

IV. DISCUSSION

The comparative analysis between Case A and Case B reveals significant differences in injury risks for both dummies. Case A represents a high-risk scenario primarily because the side of the cargo bike offers minimal structural protection. The proximity to the impacting car and the lack of energy absorption materials resulted in problematic head kinematics. Specifically, the Q3 dummy's head struck the Q6 dummy's shoulder, while the Q6 dummy directly impacted the bonnet of the impacting car. Consequently, Case A exceeded several safety thresholds. The $Head_{a3ms}$ for Q3 reached 91 g and the $Chest_{a3ms}$ for both dummies reached 88 g, that surpassed the Euro NCAP and UN R129 limits. While system-level validation remains a challenge for such complex models, the results is consistent with recent physical crash tests conducted by Meincke et al. [20]. Their study demonstrated that high-velocity impacts in cargo bikes, characterized by rigid frames and limited energy absorption, can lead to extreme occupant loads and frequent failure of rudimentary restraint systems. In contrast, Case B showed a much lower risk of injury as the front of the cargo bike absorbed a portion of the impact energy. In this scenario, injuries were limited to those caused by inertia and the restraint system. Case B metrics remained well within safety limits, with maximum $Head_{a3ms}$ and $Chest_{a3ms}$ values of 23 g and 33 g respectively. The primary safety concern in Case B is associated with the structural failure of the cabin and the risk of direct contact with the collision partner.

As a next step, additional load cases will be investigated to derive injury mitigation strategies and child restraint design recommendations. Further effective loads on the belts and anchor points will be analysed to derive a profound load collective as base for child restraint design, in order to diminish the risk of failing belts. Future physical crash tests are scheduled to verify these simulation results and the overall efficacy of the proposed safety measures.

V. ACKNOWLEDGEMENTS

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