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Are L-category quadricycles safe enough? A simulation assessment of future safety based on current crash constellations

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Abstract

In recent years, there has been growing interest in light vehicles, particularly L6e and L7e quadricycles, as a sustainable solution for urban mobility. Their increasing adoption reflects the need to reduce emissions, improve energy efficiency, and minimize environmental impact through compact, lightweight designs that facilitate circulation and parking in dense urban areas. At the same time, traditional small cars are progressively being replaced by smaller, often electric vehicles, altering the overall composition of the vehicle fleet [1,2].

However, this transition raises important safety concerns. Heavy quadricycles differ substantially from M1 passenger cars in terms of mass, stiffness, and impact energy absorption capacity. These features, combined with less stringent European crashworthiness requirements, increase occupant vulnerability—especially in collisions with heavier vehicles [3,4,5]. EuroNCAP assessments in 2014 highlighted significant shortcomings, indicating that minimum legal standards do not ensure protection levels comparable to those of M1 vehicles.

According to the EU Commission Road Safety Statistics 2024, collisions within the cluster of M1 cars and light four-wheeled vehicles (L6e/L7e) represent the most frequent fatal vehicle-to-vehicle scenario (15.2%). This share exceeds M1 interactions with powered two-wheelers (8.5%), heavy vehicles (10.8%), or pedestrians (11.7%), which remain a separate safety priority. Due to the limited market share of L6e/L7e quadricycles, available crash test data and accident databases are insufficient for statistically robust analyses.

Therefore, this study adopts an advanced simulation-based approach capable of virtually reproducing L–M1 collision dynamics and estimating occupant Injury Risk (IR), to explore realistic impact scenarios and assess how the growing presence of quadricycles in urban fleets affects traffic safety.

The proposed analysis uses real-world M1–M1 car-to-car crashes from an accident database as the foundation for simulation. The initial sample was drawn from the international IGLAD database (2010–2023), restricted to car-to-car collisions. A sub-sample representative of serious injuries (MAIS 3+) in Germany was taken as a reference constraint to build a larger, statistically consistent dataset aligned with the same severity distribution. Collisions were grouped into four impact configurations (141 Front-to-Front, 348 Front-to-Rear, 125 Front-to-Side, and 52 Side-to-Side) and categorized into speed scenarios: 90 km/h for rural roads (666 crashes), 50 km/h for urban environments (466 crashes), and 30 km/h for low-speed city zones (159 crashes), consistent with the operational ranges of L6e/L7e vehicles. Each crash was assigned to a scenario based on the higher collision speed between the two vehicles (e.g., vehicle A = 47 km/h, vehicle B = 25 km/h → 50 km/h scenario). Based on IGLAD data, each crash was reconstructed in its pre-impact configuration (i.e., directions, collision speeds, and contact points) using physical compatibility criteria derived from more than 120 IGLAD variables. These reconstructed conditions served as inputs for the simulations.

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The simulations relied on a reduced-order two-dimensional dynamic model for road collisions [6], validated on 47 cases (both real crashes and crash tests) [7]. Although validated primarily on M1 cars [7], the model is applicable to any collision where 3D effects—such as rollover, sliding, or road user projection—are negligible. Within this planar framework, the formulation is category-independent and valid for all four-wheeled vehicles, as structural variations are captured through vehicle-specific inertial, stiffness, and 2D geometry properties [6]. By providing specific mass and stiffness inputs for L6e and L7e quadricycles, the model effectively reproduces their characteristic collision dynamics.

In the absence of injury risk functions specific to L-category quadricycles, analogy is assumed with M1 vehicles in injury mechanisms, supported by structural and kinematic similarities. Accordingly, the IR for occupants of both L and M1 vehicles was estimated using Jurewicz's MAIS 3+ logit-based IR curves as a function of ΔV and impacted area (rear, front, far-side, near-side) [8].

To assess the effect of penetration in the fleet, more than 2,600 simulations were performed starting from a baseline scenario composed exclusively of M1 vehicles. New samples were generated by replacing vehicle A, vehicle B, or both with an L-category quadricycle, thereby modelling a gradual increase in L-vehicle presence within the fleet. For each penetration rate from 0% to 100%, 100 pseudo-random samplings were run to compute mean ΔV and IR values and their variability.

Table 1 compares the ΔV distributions obtained from simulations with the ΔV reference values from current EuroNCAP crash tests. The comparison was performed for both a 0% penetration rate of L-category quadricycles in the circulating M1 fleet (Type M1 hit by M1 in the table) and a 50% penetration rate (Type L hit by M1). Two speed scenarios were analysed: 90 km/h (all simulations) and 50 km/h (urban conditions, where both vehicles travel below 50 km/h).

When the frontally struck vehicles are M1 cars (0% penetration) in the 90 km/h scenario, the simulated ΔV is almost always lower than the EuroNCAP reference threshold of 56 km/h. Although the maximum outlier reaches 60.8 km/h, the third quartile (Q3, 75th percentile) is less than half the EuroNCAP reference value, at 23 km/h. When the frontally struck vehicle is replaced by an L-category quadricycle (50% penetration), the interquartile range (IQR) increases from 13.9 km/h to 20.1 km/h, indicating a more uniform distribution of ΔV values. This occurs because ΔV decreases for conventional vehicles and increases for quadricycles, due to momentum conservation. In this case, the maximum ΔV (88.3 km/h) greatly exceeds the EuroNCAP reference for L-vehicles (56 km/h), although Q3 remains lower at 33 km/h.

For side impacts at 90 km/h, similar considerations apply at 0% penetration, where EuroNCAP protocols are well established. However, when L-vehicles are struck by M1 cars (50% penetration), Q3 (32.5 km/h) exceeds the EuroNCAP reference (31 km/h), and distribution outliers reach up to 68.9 km/h, showing that current EuroNCAP side-impact protocols for L-vehicles may underestimate actual crash severity.

When the speed is reduced to the 50 km/h scenario, results remain broadly consistent. Only one lateral M1–M1 impact exceeds the EuroNCAP reference for conventional cars (30.8 km/h versus 25 km/h). For L-vehicles, several impacts yield higher ΔV values than EuroNCAP limits, and Q3 (28.1 km/h) approaches the 31 km/h reference while remaining slightly below it. The maximum for side impacts on L-vehicles reaches 39.3 km/h.

Overall, these findings suggest that current EuroNCAP side-impact protocols underestimate the real-world risk for quadricycles, particularly at higher-speed (90 km/h) scenarios.

Table 1: *Comparison between EuroNCAP reference ΔV values and the main statistical parameters of the ΔV distributions obtained through simulations.*

CRASH	**TYPE**	**EuroNCAP** [km/h]	**MEAN** [km/h]	**MEDIAN** [km/h]	**STD** [km/h]	**Q1** [km/h]	**Q3** [km/h]	**IQR** [km/h]	**MAX** [km/h]
Scenario 90 km/h									
Frontal	**M1** hit by M1	**57**	17.3	14.5	11.1	9.2	23	13.9	60.8
Frontal	**L** hit by M1	**56**	24.6	21.2	15.7	12.8	33	20.1	88.3
Lateral	**M1** hit by M1	**25**	12.2	11.2	6	7.6	15.6	8.1	30.8
Lateral	**L** hit by M1	**31**	25.3	23.4	11.8	17.4	**32.5**	15.2	68.9
Scenario 50 km/h									
Frontal	**M1** hit by M1	**57**	14.7	12.9	8.7	8.2	19.4	11.2	54.5
Frontal	**L** hit by M1	**56**	20.7	18.3	12.1	11.3	28.2	16.9	64.6
Lateral	**M1** hit by M1	**25**	11.3	10.6	5.5	7.2	14.4	7.3	30.8
Lateral	**L** hit by M1	**31**	21.6	21.5	8.5	15.9	**28.1**	12.2	39.3

Figure 1a shows the effect of the gradual introduction of L-category quadricycles into the vehicle fleet in terms of ΔV for the 90 km/h scenario. The plot reports the average ΔV for the entire fleet (All vehicles), for quadricycles only (L only), and for passenger cars only (M1 only), each with its corresponding confidence interval obtained from the sampling process.

In the 90 km/h extra-urban scenario with 0% penetration (only traditional cars on the road), the mean ΔV for all vehicles involved is 12.8 km/h. As the penetration rate increases, the fleet-wide mean ΔV also rises, peaking around 50–60% penetration where the curve reaches its maximum. This indicates that the highest ΔV occurs when roughly equal numbers of M1 vehicles and heavy quadricycles share the road, corresponding to the maximum frequency of L–M1 collisions. Beyond 60% penetration, ΔV gradually decreases to 13.3 km/h. Therefore, even with a complete replacement of traditional cars by quadricycles, ΔV remains higher than in the initial 0% condition. This suggests that during the transition toward a mixed fleet, L-vehicle safety temporarily worsens at intermediate penetration rates. Consequently, revising lateral crash test protocols for L-vehicles by introducing more demanding conditions (ΔV ≈ 35–40 km/h compared to the current 31 km/h) could provide valuable guidance for improving structural crashworthiness in the design.

Figure 1b shows that the average IR follows a similar trend. The values remain low (between 0.5% and 2%) because they represent averages over multiple impact types, speeds, and ΔV levels. The IR confidence intervals mirror the pattern observed for ΔV (Figure 1a). Although average IR values remain modest, the mid-transition phase is the most critical for fleet safety, as it maximizes collisions between light and conventional vehicles, with the highest IR occurring at 50–60% penetration (corresponding to a mean ΔV of 14.2 km/h). For passenger cars, IR remains nearly constant.

In the 50 km/h and 30 km/h scenarios (Figures 1c and 1d), IR values are lower than in Figure 1b because of the reduced collision and closing speeds [9,10]: ΔV is proportional to closing speed, and IR is derived from logistic IR functions [8]. The resulting IR values are very low, with those at 30 km/h being roughly half those at 50 km/h. The 50 km/h trend closely resembles that at 90 km/h. IR for M1 vehicles slightly decreases as penetration increases, and a similar pattern appears in the 30 km/h scenario, where the fleet-wide curve is nearly flat. At 30 km/h, the maximum IR value is extremely low (<0.4%), suggesting that the adoption of 30 km/h city zones—combined with the spread of L-category quadricycles—could substantially reduce overall injury risk for all vehicle types involved.

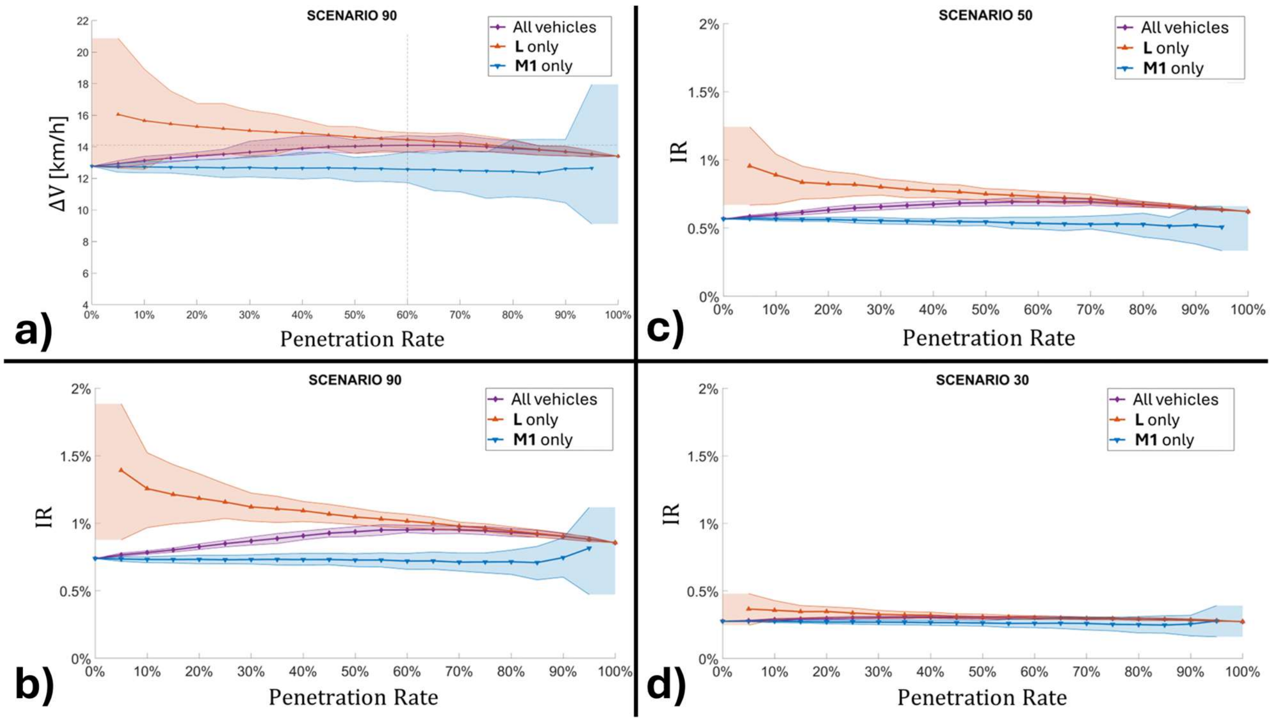

Figure 1. *ΔV and IR as penetration varies in various speed scenarios.*

Increasing the share of L-category quadricycles—relative to a baseline scenario composed solely of M1 passenger cars—worsens overall safety when these vehicles are allowed to operate outside urban areas. This outcome is driven by higher IR rather than by ΔV alone. Conversely, traffic environments regulated at 30 km/h can reduce the likelihood of severe injuries by roughly half, regardless of vehicle type. Overall, the expansion of “30 km/h cities” is the most promising strategy for supporting the transition toward more sustainable mobility models without compromising road safety.

In conclusion, L-category quadricycles offer environmental and urban mobility benefits—lower emissions, reduced energy consumption, and compact dimensions—but their lightweight structures and less stringent safety requirements pose significant risks to occupants. Using IGLAD data and simulation-based analysis, this study highlights marked differences in ΔV and injury risk (IR) when L-vehicles are involved. At higher speeds (90 km/h), maximum ΔV values exceed the coverage of current EuroNCAP tests, suggesting the need to revise test protocols (especially the ones for side crash tests). In urban contexts (50 km/h), existing procedures are more representative, though quadricycles still exhibit higher risk levels than M1 vehicles. The highest ΔV and IR values occur when quadricycle fleet penetration reaches 50–60% at 90 km/h, while both metrics drop significantly in 50 km/h and 30 km/h scenarios—the latter emerging as the safest. Overall, integrating quadricycles into road traffic requires caution: speed management (e.g., 30 km/h zones), updated crash test protocols, and proactive vehicle design are key to balancing sustainability with safety.

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