*Acta Polytechnica CTU Proceedings* **51**:6–13, 2024
https://doi.org/10.14311/APP.2024.51.0006

Published by the Czech Technical University in Prague

# PASSIVE SAFETY OF LIGHT VEHICLES – EFFECT OF SPEED ON THE BEHAVIOR OF THE VEHICLE FRAME STRUCTURE

Michal Cenkner*, Josef Svoboda, Přemysl Toman

*Czech Technical University in Prague, Faculty of Transportation Sciences, Konviktská 20, 110 00 Prague 1, Czech Republic*

* corresponding author: cenknmic@cvut.cz

Abstract. Due to growing concerns about the climate change situation, an increasing number of restrictions are being introduced. One of them is the shift towards smaller and lighter vehicles that are less demanding to produce, operate, and subsequently recycle. These are specifically L6 and L7 vehicles (four-wheelers called quadricycles). In addition, even for these vehicles, there is an attempt to make their operation even more environmentally sustainable by introducing government regulations on the powertrain, which will have to be purely electric from 2035. However, the growing popularity of these vehicles has one major drawback: safety. In the framework of the urban electric vehicle project located at the Faculty of Transportation Sciences, CTU in Prague, from the already mentioned category, safety is one of the main topics we want to address. This paper discusses the passive safety of quadricycles and the role of FEM simulations throughout the design and development phase of vehicles. The main objective is to validate the main frame of the developed vehicle at an extensive range of impact velocities. In this way, the behavior of the proposed front crumple zone design and their roles in frontal impact can be determined. The metrics to be monitored are, for example, the maximum accelerations on the structure in each part of the frontal crumple zone or the preservation of the survival space.

Keywords: Passive safety, quadricycles, light vehicles, urban mobility, FEM, LS Dyna, explicit dynamics, crash test, electric vehicle.

## 1. Introduction

Car transport is very popular. This is evident from the fact that there is an average of 570 cars per 1 000 inhabitants in Europe [1]; moreover, this number is still growing. Despite the increasing share of alternative drives, cars are not decreasing.

Even though the number of vehicles in society continues to grow, the roads are getting safer. Fatalities decreased by 36 % between 2010 and 2020 [2]. The direct impact is due to the adjustment of legislation towards modern safety technologies, such as the obligation to have advanced emergency braking systems. The general objective is to meet “Vision 0”, which aims for zero road fatalities by 2050.

A major influence on road safety can also be attributed to the ever-improving design of vehicles, with manufacturers motivated not only by European legislation but also by user tests, most popular in Europe being the European New Car Assessment Programme (Euro NCAP). The specificity of these tests consists of worse conditions for the vehicle being tested, typically higher impact speeds, and different choices of collision partners [3]. Vehicles are then scored with a certain number of stars according to how safe they are in the context of passive and active safety.

### 1.1. Definition of quadricycle

Quadricycles, shown in Figure 1 and referred to in legislation as L6 and L7, are a relatively new vehicle category. They are popular in Europe as a four-wheeled replacement for motorcycles. They have the advantage of low weight and, therefore, higher fuel efficiency.

Focusing directly on the definition of the L6 and L7 categories, the main parameters distinguishing them from passenger vehicles (M category) are the maximum weight, which must not exceed 350 kg for the L6 and 450 kg for the L7 [5]. The weight does not include the mass of the batteries. Other parameters are a speed limit of $45\,\mathrm{km\,h^{-1}}$ for the L6 and a power limit of 15 kW for the L7. Vehicles in these categories must always have four wheels. The maximum permissible load is 200 kg of passengers or 1 000 kg of cargo.

Given the strict weight limits and low power, vehicle design aims to keep the body structure as light and, therefore, simple as possible. The vehicle body mostly comprises a combination of tubular frames, carbon-based composite elements, and aluminum profiles, as seen in Figure 1.

### 1.2. Passive safety of quadricycles

Apart from internal strength analyses, quadricycles are not subject to passive safety verification as part of the certification process. Euro NCAP decided to test the passive safety of selected vehicles from the L6 and L7 categories [5]. According to their standards for passenger car testing, vehicles in these categories have been proven to have a very low level of passive safety [6].

Figure 1. Ligier vehicle from category L7e [5] on the left and Aixam vehicle frame from category L7e [4] on the right.

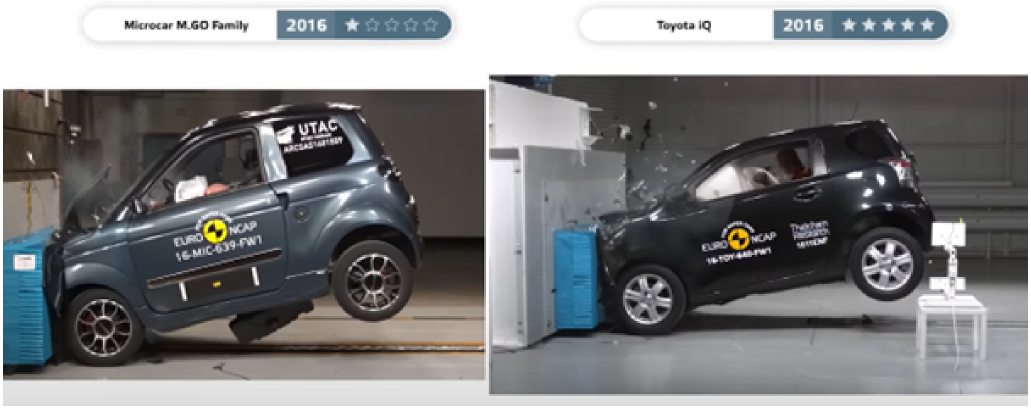

Figure 2. Comparison of quadricycle – Microcar M.GO (left) and full-size car – Toyota IQ (right) in frontal impact [6].

The vehicles were tested at a 50 km h$^{-1}$ impact speed into a deformable barrier with 100 % overlap [6]. This speed was chosen even though all vehicles tested have a top speed between 80–100 km h$^{-1}$. The testing company itself has expressed concern over the lack of restraint systems (absence of airbags and seatbelt pre-tensioners), which would lead to severe or fatal injuries. Justification for the said concern is also found in the fact that the selected quadricycles visually look like similarly sized passenger vehicles and will, therefore, be in direct competition with them.

To support its argument, Euro NCAP's campaign compared different quadricycles and the Toyota iQ [6], which was classified as a passenger car despite being virtually identical in size and receiving five stars in the rating. In contrast, all the tested quadricycles received only one star. Figure 2 shows a comparison of a frontal impact between a quadricycle and a passenger car under the same initial conditions.

The same issue was covered in the TLR report [7], where one section compared Japanese minicars, known as Kei-cars, which are similar in size and weight to quadricycles. The two main conclusions as to why small cars are more dangerous are based on the fact that there is not enough space to absorb energy from a crash due to the small size, and the small weight puts the small car at a disadvantage in a collision with a larger vehicle due to momentum transfer. Kei-cars try to compensate for the lack of crumple zones with restraint systems. For example, the seat belt pre-tensioner is set for greater downforce, but this can cause fatal injuries for persons over 65, as shown in Figure 3. This brings a whole new perspective to the passive safety of quadricycles.

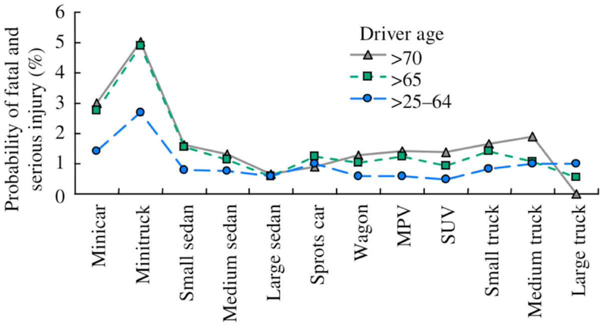

Figure 3. The probability of serious or fatal injury for drivers of different ages [7].

## 1.3. State-of-the-art in the field of passive safety of quadricycles

The level of passive safety of quadricycles is deficient compared to full-sized passenger cars. This is evident from the Euro NCAP crash tests carried out [6], de-

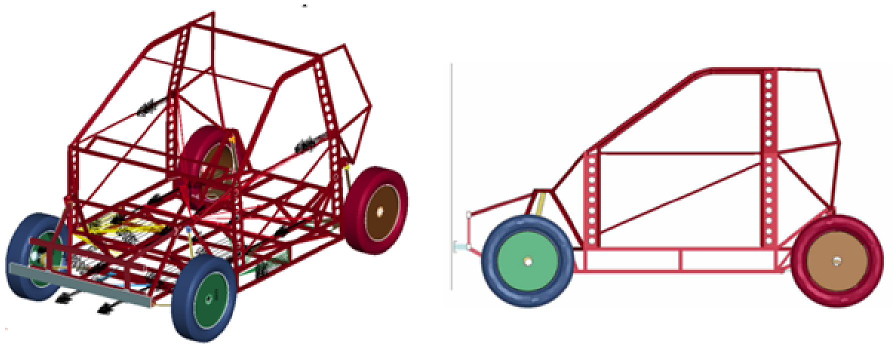

Figure 4. The overview of the tested EV numerical model and initial conditions of the simulation.

scribed in more detail in the previous chapter. This situation is not helped by the fact that the higher level of passive safety is not regulated and, therefore, not tested [7].

However, as the passive safety of full-size passenger vehicles increases, safety is also starting to be addressed at the level of manufacturers and research organizations working on new solutions for crumple zones and other elements of passive safety.

A paper on the passive safety of urban electric vehicles [8] discusses and summarizes structure testing of bodies made in completely different ways. In the first variant, a plastic variant reinforced with carbon fiber was tested by simulation to prove that the vehicle can be safe even if it is very light. However, the front and rear crumple zones were made of aluminum. In testing, the effect was that the deformation did not hit the survival area at low speeds [9]. The second variant involved using a combination of materials, namely aluminum, magnesium, structural plastic, and multiple-strength steels [10]. For this experiment, more parameters were already monitored; besides deformation, acceleration was also monitored, aiming to not exceed 50 g in a frontal impact at $64\,\mathrm{km\,h^{-1}}$. Subsequently, the restraint systems were also evaluated, simulating the pulse of acceleration at impact. This resulted in a comparable level of passive safety to passenger vehicles. The last variant described in this paper was a frame structure consisting of high-strength steel [11]. This material proved very suitable as it can absorb kinetic energy well, even though it is heavier. For this variant, the validation of the calculations was followed by a real crash test.

Addressing passive safety makes sense. At lower speeds (approx. $17\,\mathrm{km\,h^{-1}}$), the use of restraint systems can already be decisive [12]. Vehicles are now equipped with a wide range of restraint systems, such as seat belts and seat belt pre-tensioners, airbag systems, deformable steering columns, and even special safety glasses. In addition to restraint systems, passive safety is also affected by the crumple zone system. These are specially tuned for different types of impact. For example, the frontal crumple zone must absorb a large amount of crumple energy, which is converted into plastic deformation. A lot of material is required at higher speeds. For this reason, using alternative materials has been an effort, especially in lightweight vehicles such as quadricycles.

### 1.4. Role of Simulations in Passive Safety

The use of finite element simulations (FEM) is a standard in the vehicle development cycle [5]. The standard procedure is to perform a crash test of a prototype vehicle under development to obtain the initial pulse of energy at impact, followed by debugging of all vehicle components and all restraining systems made possible by increasing computational power, and then followed again by realistic crashes of the vehicle to verify the FEM simulations and debugging before actual production. Crash tests, in general, are not only to evaluate the passive safety of the vehicles but also to analyze and test the structure and deformation zone of barriers in the traffic environment [13].

In small-scale production or prototype development of quadricycles, at least the first phase of crash tests is often skipped [6], sometimes even the validation phase. One reason is that simulations using FEM can be very accurate and sufficient for simpler vehicles. Still, the primary reason is that physical crash tests are not required by legislation [5], as described earlier. Examples of the use of FEM in the development of quadricycles are given, where further iterative modifications are subsequently made in addition to the verification of the proposed vehicle design [12, 14]. Therefore, the question for the future is whether it would be sufficient to verify the passive safety of quadricycles by FEM simulations alone.

## 2. Methods

The following chapter provides information about the numerical model and the setup of the performed simulations.

### 2.1. Numerical model of the EV

The electric vehicle numerical model shown in Figure 4 was created in LS PrePost software and is based on the original CAD 3D model designed. This 3D model was simplified for simulation purposes, meaning that

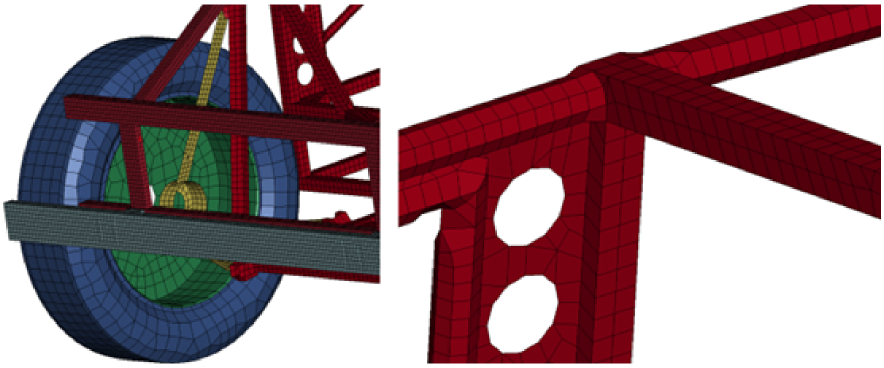

Figure 5. Detail of the created mesh and detail of the profile junctions.

| **Chassis Parts** | **Material** | **Material formulation** | $\varrho$ **[kg m$^{-3}$]** | $E$ **[GPa]** | $\upsilon$ **[/]** | $SIGY$ **[MPa]** |
|---|---|---|---|---|---|---|
| Frame profiles<br>Wheel discs<br>Bumper<br>Car axles | Steel S235JR | Isotropic, elastic-plastic | 7850 | 210 | 0.3 | 220 |
| Tires | Synthetic rubber | Isotropic, linear elastic | 990 | 0.15 | 0.45 | – |
| Collision wall | Rigid material | Rigid material | – | – | – | – |

The column of material formulation describes the selected material model from the LS Dyna software library, where $\varrho$ is the density of the material, $E$ is Young's modulus of elasticity, $\upsilon$ is the poison ratio, and $SIGY$ is the yield strength of the material.

Table 1. Material characteristics used for parts of the numerical model.

some objects with complex geometry or material characteristics were substituted by abstract point mass replacement with the same COG and weight. This substitution was made wherever the original geometry could be neglected, e.g., an electric motor, battery boxes, and seats.

The chassis and car body are composed of steel profiles (rectangular and circular cross-sections) modeled as shell elements. Specifically, it was section shell type 16 (Beathe-Dvorkin transverse shear) that provided us with the most accurate solutions and allowed us hourglass control. In a similar way, wheels and pneumatics were modeled where the difference was in chosen thicknesses and the assigned material. The mesh was created using the auto-mesher function and was composed of 0,5 million elements. The characteristic length of the smallest element was 4,72 mm. Some elements were manually edited, especially in parts where more profiles meet, as illustrated in Figure 5. The material specification for the entire model is in Table 1. Material Erosion has been added to achieve proper behavior. This property is the way to remove elements that have met defined conditions of failure and thus improve the behavior of the model.

### 2.2. Numerical model summary

The overview of the whole experiment is shown on the right in Figure 4. The numerical model consists of two submodels – the model of an electric vehicle and the barrier, which was modeled as a rigid collision wall. All scenarios were performed as frontal impact with 100 % overlap, and individual simulations differ and depend mainly on the impact speed of the vehicle within the range of 5–100 km h$^{-1}$. The initial position of the EV front model is unchanged during all simulation runs. To ensure a stable simulation in an acceptable timeframe, the whole numerical model was simplified and optimized. For example, the initial distance between the vehicle and the collision wall was minimalized.

To assess the passive safety of the electric vehicle, the body of the vehicle was divided into sections composed of the deformation zones D0-D3 and the survival space D3-D4 (Figure 6). The evaluation was carried out according to the values of acceleration and displacement achieved in each zone.

## 3. Results

This chapter presents examples of individual scenario results and an overview of data. Figure 7 shows the virtual crash test result of the full-frontal impact of the vehicle equipped with bumper reinforcement and deformation block in the front part of the vehicle at a speed of 20 km h$^{-1}$. The whole vehicle model is simplified for the purposes of the explicit dynamic simulation.

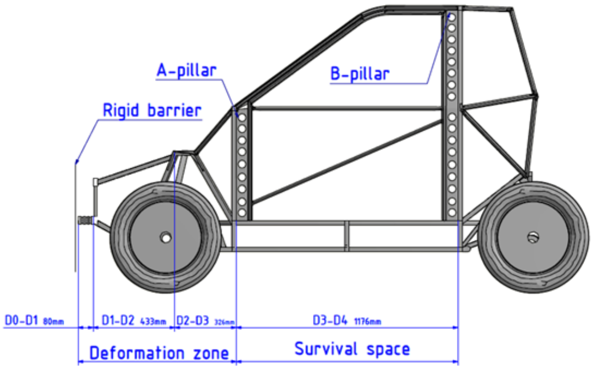

Figure 6. Deformation zones and survival space of the assessed vehicle.

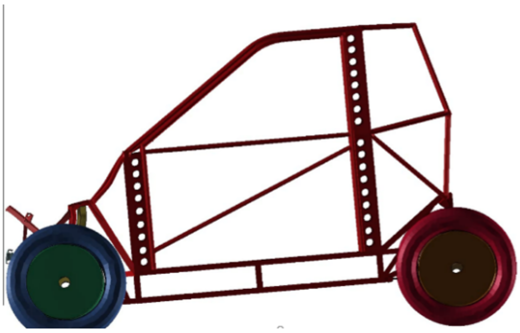

Figure 7. Results of the simulation, 20 km h$^{-1}$.

Figures 8–10 show the resultant acceleration at initial speeds of 20, 50, and 80 km h$^{-1}$. The simulations were conducted at an initial speed of 5 to 100 km h$^{-1}$. Each scenario evaluated the impact on the deformation zone and survival space. Areas of relevant zones are highlighted in the following figures as well.

Figure 11 shows the survival space assessment. The vertical axis represents the displacement in [mm] of the survival space and vehicle pillars. The shortening of the survival space is also presented in [%]. Survival space displacement was calculated from the displacement of the A and B pillars for each impact speed.

Figure 12 presents a detailed look at the deceleration peaks occurring in each zone based on impact speed. Table 2 then shows overall experiment results containing the vehicle pillar displacements, chassis shortening, and deceleration peak values in each zone.

## 4. Discussion

Virtual crash tests bring the possibility of more detailed assessment for various impact scenarios. Based on deceleration peak values for each impact speed, it's possible to observe which zones absorbed the kinetic energy of the crash and also which zones were unaffected (Table 2). Figures 8–10, representing the resultant acceleration on the bottom of the chassis, show the behavior of the deformation elements in the context of initial speeds and actual values observed on the chassis. From this point of view, it is possible to follow in which zones the acceleration starts to in-

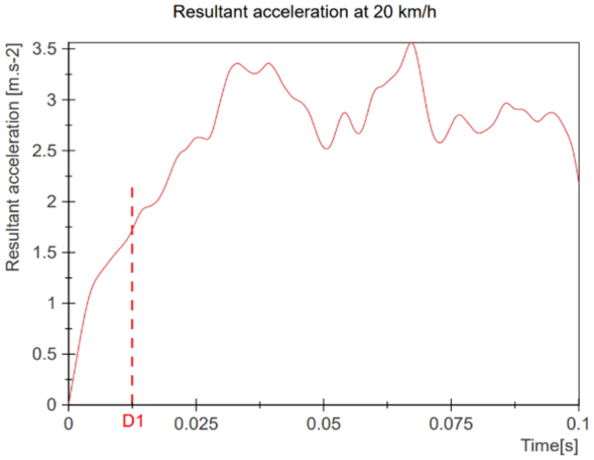

Figure 8. Resultant acceleration with initial speed 20 km h$^{-1}$.

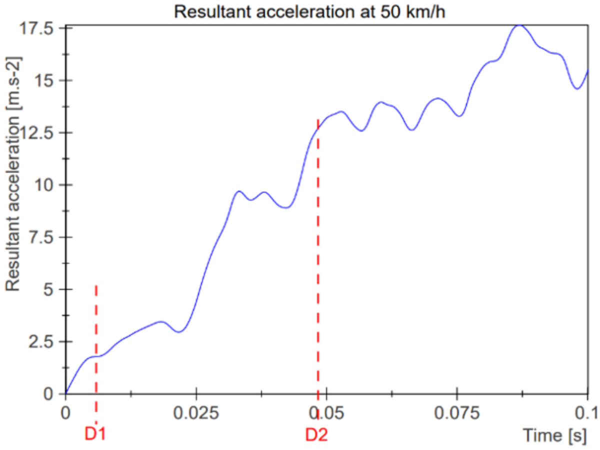

Figure 9. Resultant acceleration with initial speed 50 km h$^{-1}$.

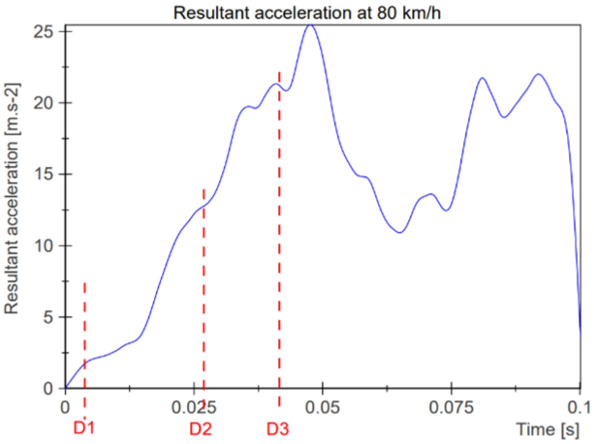

Figure 10. Resultant acceleration with initial speed 80 km h$^{-1}$.

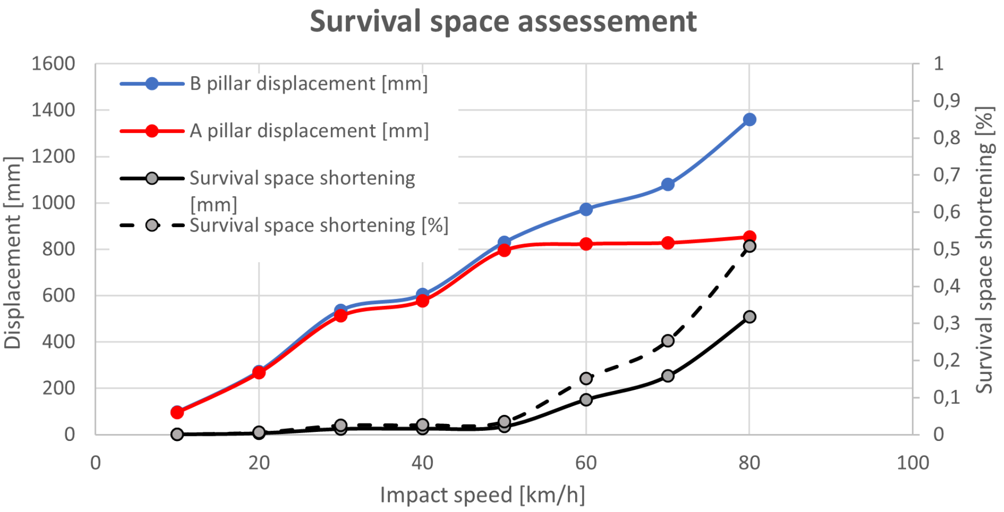

Figure 11. Survival space assessment.

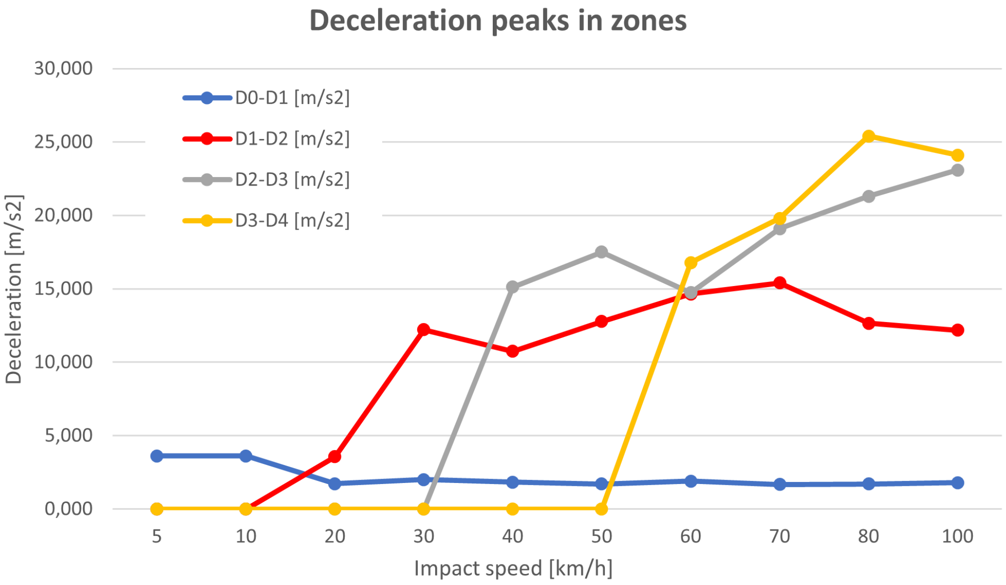

Figure 12. Deceleration peaks in zone assessment.

| **Initial velocity** [km h$^{-1}$] | **Survival space shortening** | | | | **Chassis shortening** | **Deceleration peaks of the chassis** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **B pillar displacement** [mm] | **A pillar displacement** [mm] | **Δ** [mm] | [%] | **Δ** [mm] | **D0-D1** [m s$^{-2}$] | **D1-D2** [m s$^{-2}$] | **D2-D3** [m s$^{-2}$] | **D3-D4** [m s$^{-2}$] |
| 5 | x | x | x | x | 36.380 | 3.610 | 0.000 | 0.000 | 0.000 |
| 10 | 97.4 | 96 | 1.4 | 0.140 | 100.977 | 3.620 | 0.000 | 0.000 | 0.000 |
| 20 | 273 | 267 | 6 | 0.600 | 282.834 | 1.730 | 3.560 | 0.000 | 0.000 |
| 30 | 537 | 512 | 25 | 2.500 | 566.725 | 2.000 | 12.220 | 0.000 | 0.000 |
| 40 | 604 | 578 | 26 | 2.600 | 631.105 | 1.820 | 10.750 | 15.130 | 0.000 |
| 50 | 830 | 795 | 35 | 3.500 | 866.267 | 1.700 | 12.780 | 17.500 | 0.000 |
| 60 | 973 | 822 | 151 | 15.100 | 1031.320 | 1.900 | 14.650 | 14.730 | 16.780 |
| 70 | 1080 | 827 | 253 | 25.300 | 879.138 | 1.680 | 15.400 | 19.100 | 19.800 |
| 80 | 1360 | 852 | 508 | 50,800 | 1490.110 | 1.710 | 12.650 | 21.300 | 25.400 |
| 100 | x | x | x | x | x | 1.800 | 12.180 | 23.100 | 24.100 |

x – not measurable

Table 2. Overall experiment result values.

crease rapidly compared to the deformation elements. It means primarily zone D1-D2 in the performed experiment. This zone creates the transition between low deceleration and higher acceleration peak areas while crashing into the barrier.

In terms of survival space assessment, it is possible to track the displacement of certain vehicle elements. In our case, the displacement of A and B pillars was analyzed. Based on the displacements, it is possible to explore the deformation of the whole survival space. From the point of view of tested construction fitted with a frontal deformation block, we observe survival space defamation from the speed of $50\,\mathrm{km\,h^{-1}}$ (see Figure 11). The displacement of vehicle pillars brings a detailed look at the course of deformation at various impact speeds. Thus, comparing different vehicle construction and passive safety system components is feasible.

The impact of the frontal crash on the vehicle chassis describes the deceleration peaks measured in defined zones. In compliance with the mutual displacement of A and B vehicle pillars, the higher deceleration peaks occur in the survival space zone from $60\,\mathrm{km\,h^{-1}}$. Moreover, in Figure 12, it is possible to observe gradual deformation within the front part of the vehicle.

Results of the first tested vehicle show the possibility of a detailed virtual testing methodology. Based on the data, critical speeds in the context of the survival space and deceleration progress in user-defined zones and peaks in defined locations can be observed.

## 5. CONCLUSIONS

Quadricycles in the L6 and L7 categories represent the innovative automotive trend for urban mobility. This category dynamically grows in recent years. As such vehicles are still relatively new, there are low passive safety legislative regulations. Quadricycles are primarily manufactured in small series productions. Therefore, the actual crash tests of passive safety systems used usually for mass production series of passenger cars are financially demanding for the quadricycle category.

One of the alternatives to the real vehicle assessment is explicit dynamic simulations in the form of virtual crash tests. In this paper, virtual crash tests were conducted at various impact speeds. Performed experiments aimed at complex quadricycles' passive safety methodology, combining virtual dynamic simulations and partial real verification tests to obtain credible results for various crash scenarios. The assessment of survival space shows the potential of critical speed definition for each vehicle. The evaluation of deceleration peak and construction element displacements brings the opportunity to assess the vehicle's passive safety systems and elements. For the future development of complex methodology based on the results of virtual crash tests, it is essential to perform subsequent simulations of the wider variety of quadricycle constructions. Moreover, it is necessary to include more complex testing scenarios regarding vehicle chassis and occupant safety assessment.

## ACKNOWLEDGEMENTS

This paper was supported by the Czech Technical University in Prague grant SGS23/131/OHK2/2T/16 Development of a Modular Urban Vehicle Research Platform for testing Alternative Energy Sources and HMI User Solutions.

## REFERENCES

[1] Eurostat. Number of cars per inhabitant increased in 2021, 2023. [2024-11-21]. `https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20230530-1`

[2] European Parliament. Road fatality statistics in the EU (infographic), 2019. [2024-11-21]. `https://www.europarl.europa.eu/topics/en/article/20190410STO36615/road-fatality-statistics-in-the-eu-infographic`

[3] M. van Ratingen, A. Williams, A. Lie, et al. The European New Car Assessment Programme: A historical review. *Chinese Journal of Traumatology* **19**(2):63–69, 2016. `https://doi.org/10.1016/j.cjtee.2015.11.016`

[4] AIXAM, N°1 for licence-free cars and safety. [2024-11-21]. `https://www.aixam.com/en/french-brand/commitments/safety`

[5] A. Pavlovic, C. Fragassa. General considerations on regulations and safety requirements for quadricycles. *International Journal for Quality Research* **9**(4):657–674, 2015.

[6] EURO NCAP. Quadricycle ratings explained, 2016. [2024-11-21]. `https://www.euroncap.com/en/car-safety/quadricycle-ratings-explained/`

[7] M. Edwards, M. Seidl, J. Carroll, A. Nathanson. Provision of information and services to perform an initial assessment of additional functional safety and vehicle construction requirements for L7e-A heavy on-road quads, 2014. Transport Research Laboratory. 75 p. [2024-11-21]. `https://ec.europa.eu/docsroom/documents/5466/attachments/1/translations/en/renditions/pdf`

[8] J. Romo, E. Canibano, J. C. Merino. Lightweighting and passive safety for urban electric vehicle. In *2017 Electric Vehicles International Conference (EV)*, pp. 1–5. IEEE, 2017. `https://doi.org/10.1109/EV.2017.8242113`

[9] European Commission. Advanced structural light-weight architectures for electric vehicles, 2014. [2024-11-21]. `https://cordis.europa.eu/project/id/265898/reporting`

[10] European Commission. Super light architectures for safe and affordable urban electric vehicles, 2018. [2024-11-21]. `https://cordis.europa.eu/project/id/605634`

[11] European Commission. Premium low weight urban sustainable e-MOBilitY, 2016. [2024-11-21]. `https://cordis.europa.eu/project/id/605502`

[12] G. I. Alexandru, C. G. Marius, T. F. Daniel, T. D. Dragos. Dynamics of frontal crash in/without the presence of passive safety systems. *IOP Conference Series: Materials Science and Engineering* **1220**(1):012044, 2022. `https://doi.org/10.1088/1757-899X/1220/1/012044`

[13] P. Vrtal, T. Kohout, L. Nouzovský, Z. Svatý. Dynamic tests of the protective and security barrier system probar. *Acta Polytechnica CTU Proceedings* **42**:83–86, 2023. `https://doi.org/10.14311/APP.2023.42.0083`

[14] S. Kongwat, T. Homsnit, C. Padungtree, et al. Safety assessment and crash compatibility of heavy quadricycle under frontal impact collisions. *Sustainability* **14**(20):13458, 2022. `https://doi.org/10.3390/su142013458`