THE EFFECT OF MICROCARS' LIGHTNESS AND COMPACTNESS ON SAFETY IN SIDE IMPACTS

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ABSTRACT

In this paper, the term 'microcar' refers to a car which is categorized as L7 by the UN and conforms to the Ultra Compact Mobility regulation in Japan. The car is much lighter and smaller than a conventional passenger vehicle. It is generally understood that a microcar has poorer crash safety performance than a conventional passenger car. In particular, the microcar would seem to have a disadvantage in terms of side-crash protection performance, since a smaller gap between an occupant and the door means a shorter distance to absorb the impact energy. On the other hand, having a lighter mass, it moves earlier when struck, meaning that the speed and depth of the door intrusion is reduced: an advantage. Thus the severity of a microcar side crash is not obvious. The aim of this study is to find out how the lightness and compactness of the microcar affect its side-crash protection performance.

This study was conducted using a numerical simulation of a Japanese K-car full-vehicle model. Two kinds of parameters were created. One is the Vehicle mass, the other is the Gap between the door inner panel and an occupant.

Three levels of mass were investigated (351 kg, 658 kg, and 1000 kg) by removing parts which do not contribute to vehicle body strength or adding weight to the center of gravity. The UN R95 load case was selected for the evaluation. To simulate the microcar, the crash dummy and the seat were repositioned outboard laterally from the original position, the seatbelt was fastened without a pretensioner, and there was no airbag.

The struck microcar's velocity was obviously affected by its vehicle mass: the lighter the mass, the sooner the vehicle moved after the Moving Deformable Barrier (MDB) impact. However, the door velocity profile was almost the same in every vehicle mass condition up to the time of the peak injury value, so the injuries were at the same level—except for the head region, which was impacted by the roof rail. The lighter vehicle produced the higher head impact velocity, resulting in higher head injury values.

As for the effect of door clearance, larger clearance seemed to reduce the injury level—slightly but demonstrably.

This study indicated that the effect of vehicle mass (in the 358 kg–1000 kg range) on crash severity seems to be very small for the chest-to-pelvis region. On the other hand, the lighter vehicle mass seems to carry a higher injury risk for the head region. Thus it is suggested that the focus for microcars' side-impact safety should be on protection performance for the head rather than the chest-to-pelvis area.

INTRODUCTION

Reflecting zero-emission vehicle requirements in this decade, small Electric Vehicles (EV) have been developed all over the world as one solution. These vehicles are seen mostly in Europe, China, and Japan. Europe and Japan already have official categories for EVs, and China has announced that Micro EV unique safety ratings will start soon in their New Car Assessment Program (NCAP).

The cars in the L7 category defined by the United Nations (UN), and the Ultra-Compact Mobility (UCM) category recently defined in Japan, are characterized by their small size and light weight. They are even smaller and lighter than a K-car, which is a major category in Japan. In this paper these L7 and UCM cars are called microcars. The definitions of L7, UCM, and K-car are shown in Tables 1 to 3 as a reference.

There is not much literature which describes the safety of this kind of car, although the EuroNCAP did release the results of the frontal-crash and side-crash tests for L7-category quadricycles in 2014 [1] and 2016 [2] as their safety campaign. Although the test protocol was a little more relaxed than the one for normal passenger cars, the results indicated very high injury risks for every tested vehicle.

Innovative micro-size concept cars equipped with a lightweight, stiff structure and high-performance restraint system have been developed, with the general understanding that a smaller vehicle has a higher injury risk than

a larger vehicle. Unselt et al. [3] created an ultra-compact electric vehicle concept named Visio.M which has a carbon fiber-reinforced plastic monocoque body, an aluminum crush structure, and advanced airbags (both inside the cabin and at the front of the body structure) to protect occupants by increasing energy absorption in a frontal crash. The concept achieved protection performance equivalent to normal passenger cars in both front- and side-crash tests. Fresnillo et al. [4] created a lightweight electric vehicle concept of similar size named BEHICLE, applying sandwich panels and foam to realize the light weight. In their unique concept, a driver is seated in the center in order to acquire enough clearance to the door panel to provide side-crash protection. In addition, the driver seat is equipped with a 4-point seatbelt system. The concept boasted excellent side-crash protection performance and acceptable front-crash protection performance, although it appears to be very expensive and looks much different than the current generic microcar.

In a frontal collision, when a small vehicle and a large vehicle crash, the small vehicle has the disadvantage in terms of protection performance. The issue has been understood as an incompatibility, and several methods to assess it have been proposed [5] [6]. The EuroNCAP started a compatibility rating in 2020 [7]. Mizuno et al. [8] clearly explain the disadvantage of small vehicles (K-cars in their paper), comparing data on deceleration levels, ride-down efficiency, injury severity, and firewall intrusion to other sizes of vehicle.

Because a microcar is one of the smallest vehicle categories, the collision partner will just about always be a larger and heavier vehicle; we have to realize that this load case is normal for microcars. It is difficult for microcars to have a sufficient crushable zone in front of the cabin to absorb the impact energy from larger vehicles. Thus it is natural that the microcar has a disadvantage in front-crash protection performance.

What about side impacts? Barbat et al. [9] evaluated which elements of geometry, stiffness, and mass are most relevant for determining crash severity; however, the striking vehicle mass ranged from 1680 kg to 2360kg, and was (as a single parameter) 1724 kg for the struck vehicle, which is far from the mass of a microcar. The main purpose of their paper was to grade the effect level of each parameter; in this paper, we focus on the mass parameter of the struck vehicle alone. Terazawa et al. [10] evaluated the side-impact protection performance of a microcar with full-scale physical testing. Their object vehicle was even smaller than the microcar defined in this paper and had no side door. In addition, the impact speed was 30kph, which is much lower than Japan's UCM regulation. Furthermore, the only injury probability evaluated was for the pelvis.

We have not found any literature that clearly explains how a microcar's compactness and light weight affect the occupant protection performance in a side crash from an injury mechanism approach. However, in spite of the lack of research, some effects can be inferred from the laws of physics. Downsizing certainly has the disadvantage that the gap between the door and the occupant becomes smaller, so there is less time and distance for the absorption of the impact energy, and the peak load to the occupant is greater. However, a lighter weight vehicle tends to move faster than a heavy vehicle when it is struck. It can be expected that the amount of door intrusion tends to be smaller than that of heavier vehicles, because the intrusion can be calculated as the time integral of the door's relative velocity against the moving vehicle body's velocity: when the moving body's velocity increases, the door's relative velocity decreases. This is an advantage for the occupant protection performance. When these facts are considered together, it is difficult to conclude whether the compactness and lightness result in an overall advantage or disadvantage in terms of crash safety performance. The aim of this paper is to clarify how the small size and light weight of the microcar affect the occupant protection system performance in a side collision using an injury mechanism approach.

As a side note, Davies et al. [11] indicated injury risks induced from the small car features and analyzed a crash case by reviewing the statistical data. Considering small cars' unique features together with the needs of the market and society, they proposed that a different safety assessment be developed, rather than applying the existing one which focuses on normal passenger cars.

Table 1.
L7 category definition

L7 vehicle image	Description
	✧ Vehicle weight (passenger) ≤ 400 kg (exclude battery for EV) ✧ Vehicle weight (commercial) ≤ 550 kg (exclude battery for EV) ✧ Maximum speed ≥ 45 kph ✧ Max. Net Power ≤ 15 kW ✧ No definition of vehicle size

Table 2.
Japanese UCM definition

UCM vehicle image	Description

	✧ Length: ≦ 2.5m
	✧ Width: ≦ 1.3m
	✧ Height: ≦ 2.0m
	✧ Rated power: ≧0.6kW
	✧ Max traveling speed: 60km/h
	✧ Sticker stating the vehicle must be driven < 60km/h shall be pasted on rear window
	✧ Not allowed on motorway
	✧ Crash regulations
	  ✓ UN R137: Full Rigid Barrier 40km/h
	  ✓ UN R94: Offset Deformable Barrier 40km/h
	  ✓ UN R95: Side MDB 50km/h

Table 3.
Japanese K-car definition

K-car vehicle image	Description
	✧ Length: ≦ 3.4m ✧ Width: ≦ 1.48m ✧ Height: ≦ 2.0m ✧ Displacement: ≦ 660 cc ✧ Rated power: ≧ 47kW ✧ Crash regulations ✓ Same as normal passenger cars

METHOD

All evaluations were performed by numerical simulation. It is difficult to define a generic microcar model, since no microcar model has ever been shared as an open source. However, there are many evaluation reports from Japan NCAP (JNCAP) regarding the Japanese K-car, the world's most widely available small car. Therefore, we have chosen a K-car sedan as the base model, modified to reflect the microcar features. In order to evaluate the effect of the lightness and compactness, two parameters were used: the vehicle mass and the gap between the inner door panel and the occupant.

For the vehicle mass parameter, three models were created. As a baseline, the base K-car model was applied as is; in addition, a lighter model was created by removing components from the base, and a heavier model was created by adding balance weights to the center of gravity. The adjusted masses are 351 kg, 658 kg, and 1000 kg, reflecting a microcar, the lightest (base) K-car, and the heaviest K-car, respectively. The distribution of the K-cars' masses, using data collected from models sold in the Japanese market in 2022 (65 cars), is illustrated in Figure 1. The data on the distribution of microcars' masses, in Figure 2, were collected from the available cars in the Japanese market in 2022 (11 cars).

Two models were created for the gap-to-door parameter. As a baseline, the K-car model as is was used. The second model, simulating the microcar, shortened the gap by 33mm by moving the occupant and the seat laterally outboard. The original gap setting was obtained from one microcar sold in Japan.

In order to evaluate the above two parameters, other conditions were held constant, as described below.

The occupant model was a well-known side impact Anthropomorphic Test Device (ATD), ES2. It was seated on the driver's seat according to the United Nation Regulation No.95 (UN R95) test protocol. The restraint system was modeled on a simple, low-cost system, given the price range of microcars. The seatbelt had only a locking function (when the belt is pulled out rapidly in an emergency), and there was no pretensioner (to reduce belt

slack in a crash) or load limiter (to avoid excessive belt tension). Side and curtain airbags were not installed, both to simulate the basic microcar and to avoid complicating mechanical factors.

The UN R95 load case condition for Moving Deformable Barrier (MDB) impact was applied. It is well known as a major testing protocol for automotive safety experts, and Japan adopted it as the side-crash regulation for UCM in 2021. This load case was selected since it is the one prioritized for side crashes in Japan. Every velocity evaluated in this paper is relative to the ground. Further details of the evaluation settings are explained below.
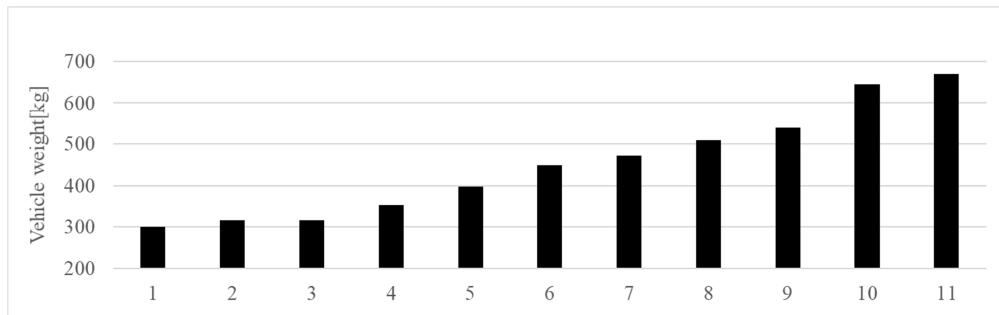

Figure 1. Microcar Mass Distribution in Japan

Figure 2. K-car Mass Distribution in Japan

Vehicle mass adjusted for Lighter model: 351 kg

The parts listed in Table 4 were removed. Before removal, the stress level of every part was reviewed to ensure that it underwent no stress in a side crash.

Table 4.
Removed parts list

Engine Compartment	Steering	Relay Box Right	Canister
Fuel Tank	Radiator	ABS	EPI
Door Metal Front Left	Hood	Air Cleaner	Horn
Back Door	Seat Rear	AB Pipe	Fuse Box
Door Metal Rear Left	Bumper Front	Fuel Pipe	
Seat Front Left	Relay Box Left	Head Lamp Left	
Battery	Wiper Front	Head Lamp Right	
Weight	Master Vac	Cowl Top	
Exhaust Pipe	Fender Left	Pedal	
Unit IP	Center Console	Glass Wind Shield	

Vehicle mass adjusted for Heavier model: 1000 kg

The weights were placed at the center of gravity of the vehicle.

Sensor location

In order to measure the velocities of the vehicle and the door intrusion, accelerometers were placed at appropriate locations. For the vehicle velocity, to avoid impact vibration noises, the side sill of the unstruck side was chosen, at the longitudinal center of the vehicle geometrically.

To measure door intrusion, three measuring points (UPR, MID, and LWR, as shown in Figure 3), corresponding to the ES2's body regions of chest, abdomen, and pelvis, respectively, were positioned on the driver door.
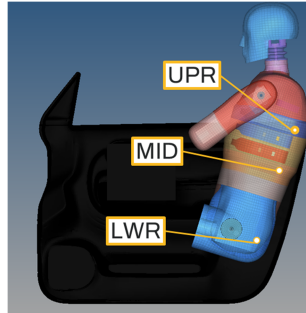

Figure 3. Accelerometer locations on the door

Gap-to-door setting

As noted, the gap between the ES2 and door panel was set to one of two distances. One, the K-car equivalent, is the original gap of the base K-car as is. The other, the microcar equivalent, comes from the benchmarked microcar—adjusted to the same clearance at the pelvis by moving the ES2 outboard (the seat was moved the same distance). The gaps are illustrated in Figure 4.
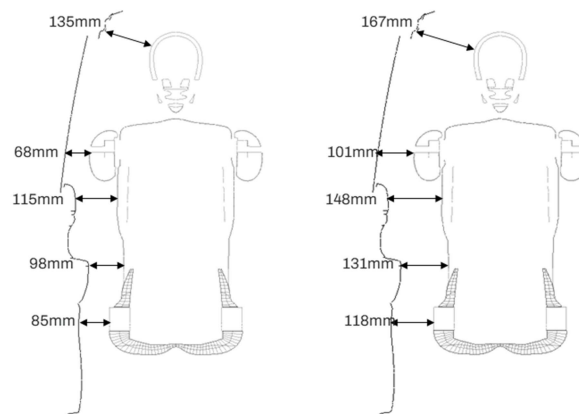

Figure 4. Gap-to-door (Left: microcar equivalent, Right: K-car equivalent)

Occupant model description

Side impact ATD of ES2 was selected. It represents the size of the 50%ile adult male, adapted to the UN R95 protocol. The model is produced by LSTC, version V0.101.

In order to evaluate how much external force is loaded onto which body regions, the contact areas were defined as in Figure 5.
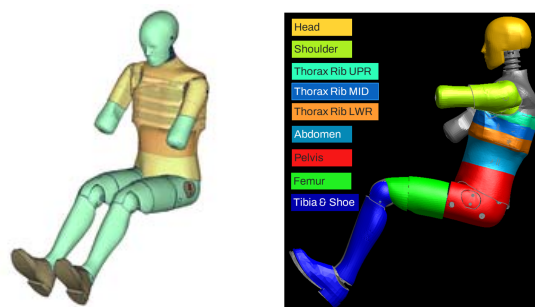

Figure 5. Contact area definitions of ES2

Crash condition

The key information about the UN R95 lateral collision test protocol is shown in Figure 6. Reflecting right-hand drive in Japan, the MDB strikes the right-hand side. The driver is the only occupant of the vehicle.
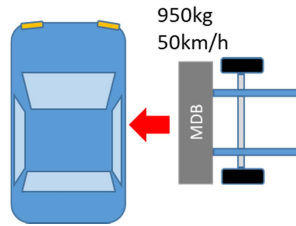

Figure 6. Crash condition

Test Matrix

The test matrix is shown in Table 5.

Table 5.
Test matrix

ID#	Gap-to-door	Vehicle Mass	Load case	ATD	with Seatbelt	with Airbag
1	microcar	351 kg	UN R95	ES2	Yes	No
2	↑	658 kg	↑	↑	↑	↑
3	↑	1000 kg	↑	↑	↑	↑
4	K-car	351 kg	↑	↑	↑	↑
5	↑	658 kg	↑	↑	↑	↑
6	↑	1000 kg	↑	↑	↑	↑

RESULTS

Velocity profiles: MDB and Vehicle

The results of IDs# 1 to 3 are overlaid onto Figure 7, left, to demonstrate the vehicle mass effect in the microcar gap condition. Hereinafter the striking vehicle is called the "MDB" and the struck vehicle is called the "Vehicle". The lighter the vehicle, the higher and earlier the end velocity. This result is no surprise, since it merely complies with the laws of physics.

The MDB velocity profile, rather, should be focused on. Because the MDB front surface and the vehicle door merge just after the door has been crushed, in principle the MDB velocity is correlated with door intrusion velocity, which is one of the most critical causes of occupant injuries. The change in MDB velocity is much slower than that of the vehicle. The obvious change can be seen after 40ms.

The same trend is indicated for the K-car gap condition of IDs# 4 to 6, shown in Figure 7, right.
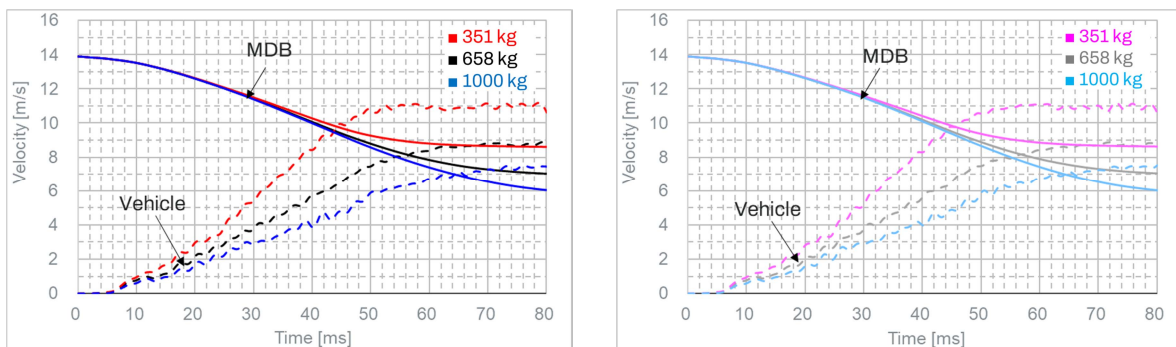

Figure 7. Velocity of MDB and Vehicle (Left: IDs#1–3, Right: IDs#4–6)

Injury indicator Summary

The Injury indicators of IDs# 1 to 3 are summarized in Figure 8, to demonstrate the vehicle mass effect in microcar gap condition. The evaluated injury indicators are Head Injury Criterion 36 (HIC36) for the head, Thorax Rib deflection for the chest, Abdomen force for the abdomen, and Pubic force for the pelvis. These are the major injury risk indicators for regulations and NCAPs globally. The regulation threshold values are shown as 100% in the graphs; lower percentage means lower injury risk.

The results at chest and pelvis were no different regardless of the Vehicle mass. This is due to the similarities of the door speed velocity profiles (illustrated in Figure 10). The results at the head were high percentages for the Vehicle masses of 351kg and 658kg, exceeding 200% of regulation threshold. In these tests, the roof rail of the Vehicle impacted the occupant's head, due to the fact that the Vehicle moving speed and acceleration increase as the vehicle becomes lighter as explained in the former paragraph.

It is the same pattern of results for the K-car gap condition of IDs# 4 to 6, the lighter vehicle produced the drastically higher HIC36 injury values and similar injury values at chest and pelvis, are indicated, shown in Figure 9.
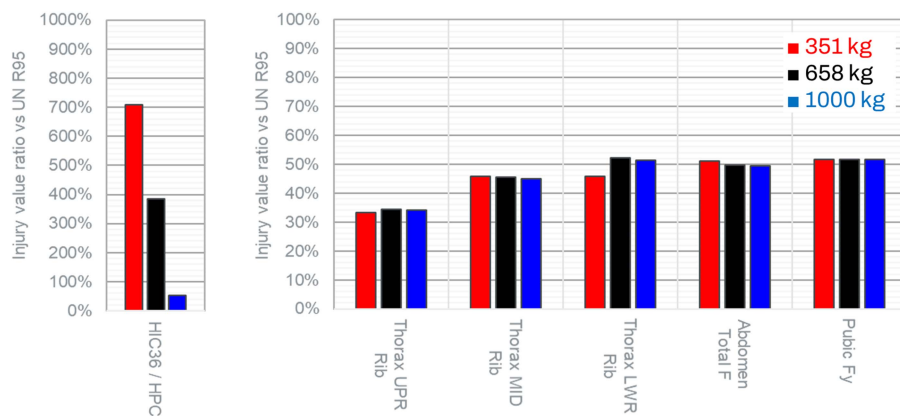

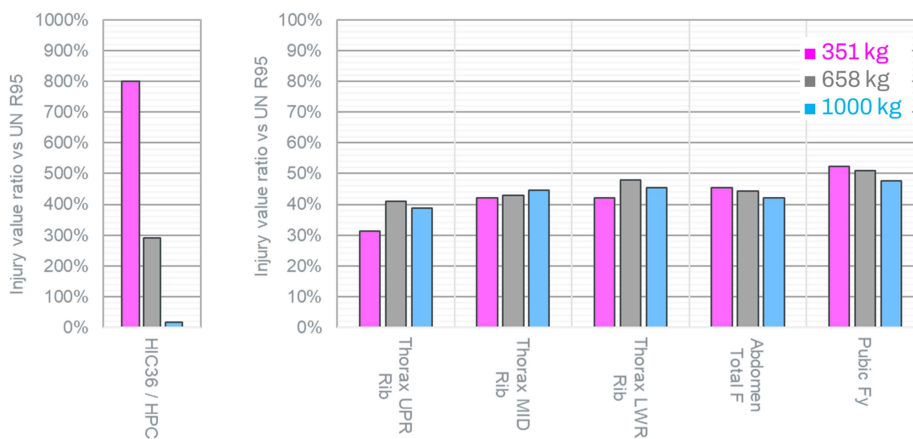*Figure 8. The injury values as percentages of the regulation threshold (IDs#1–3)*

Figure 9. The injury values as percentages of the regulation threshold (IDs#4–6)

Door Velocity

The door velocity was measured at three points to evaluate how the door impacts the ES2 (Figure 3).

The velocity profiles are illustrated in Figure 10. At the left is the microcar Gap case, at the right the K-car case. The red vertical line indicates the timing of the peak injury value. The door UPR graph shows the Chest deflection, door MID shows the Abdomen force, and door LWR shows the Pelvic force. Because the timing was slightly different depending on the Vehicle mass, the line thickness indicates the range from the earliest to latest peak timing of each case. Every UPR, MID, and LWR location resulted in a very similar profile regardless of the Vehicle mass, until the time of the peak injury value. The K-car Gap case produced very similar profiles, regardless of the Vehicle mass.
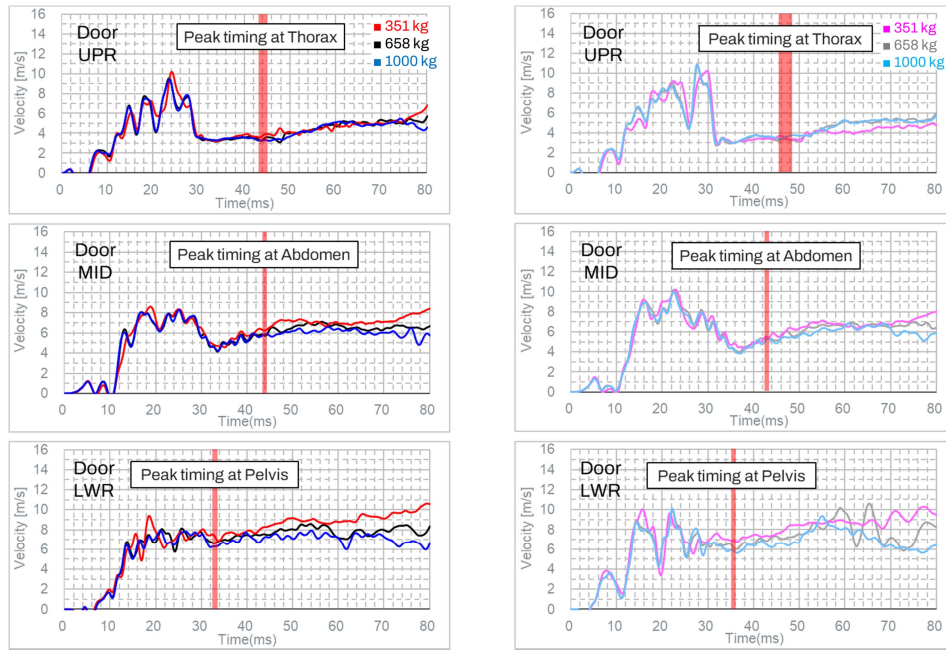
Figure 10. Door Velocity (Left: IDs#1–3, Right: IDs#4–6)
red vertical line indicates range of timing for injury peak

ATD Velocity

Impact severity at the ATD is assessed by measuring its moving velocity. The velocities were measured at T1 (first thoracic vertebra), T12 (twelfth thoracic vertebra), and the Pelvis. The results are illustrated in Figure 11. The velocity profiles were almost the same regardless of the Vehicle mass until the injury value reached its peak, for all three locations. The left graphs in Figure 11 show the results of the microcar gap cases (IDs# 1–3) and those on the right show the K-car gap cases (IDs# 4–6). For the chest (thorax) region, it was confirmed that the impact severity for ES2 did not depend on the Vehicle mass, as stated previously. As in the Door velocity graphs, the thickness of the red vertical line indicates the range from the earliest to latest peak timing of each case.
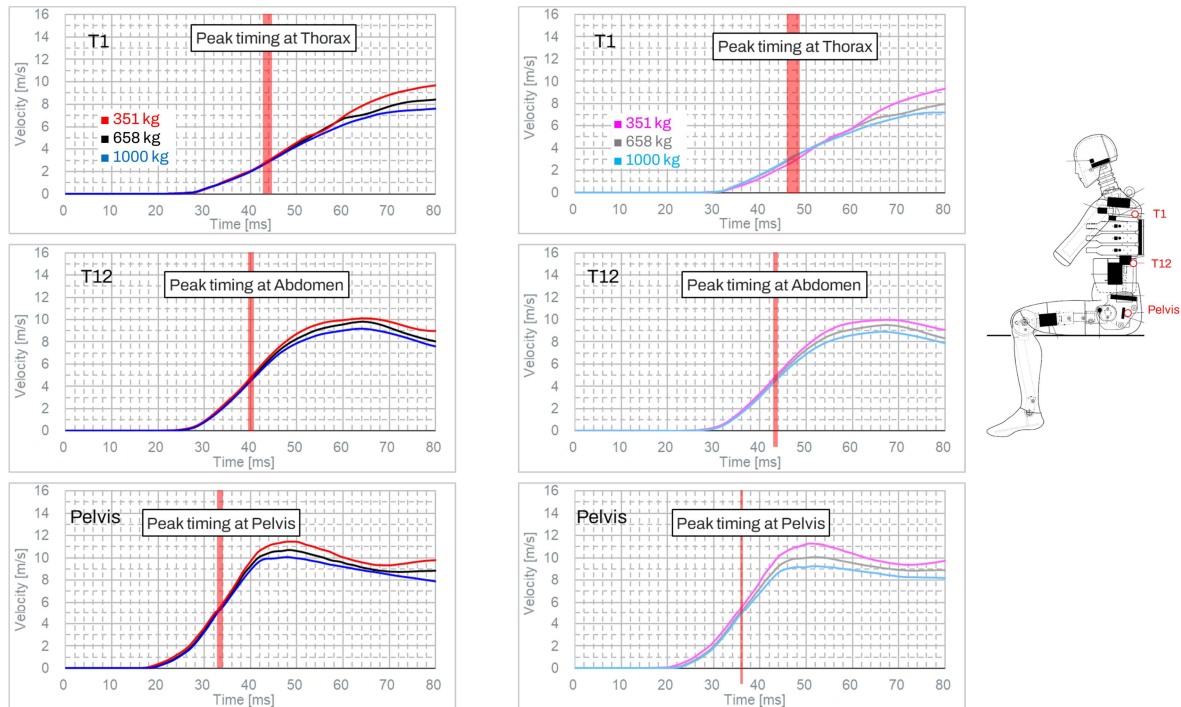

Figure 11. ATD moving Velocity (Left: IDs#1–3, Right: IDs#4–6)
red vertical line indicates range of timing for injury peak

Door intrusion

The door velocity was given in Figure 10 and the Vehicle moving velocity was given in Figure 7. The door intrusion displacement can be calculated as the time integral of the door velocity relative to the Vehicle moving velocity; the peak intrusion results are illustrated in Figure 12. The left is the microcar Gap condition, and the right is the K-car Gap condition. The graphs clearly indicate that the lighter the vehicle, the smaller the door intrusion, and vice versa.
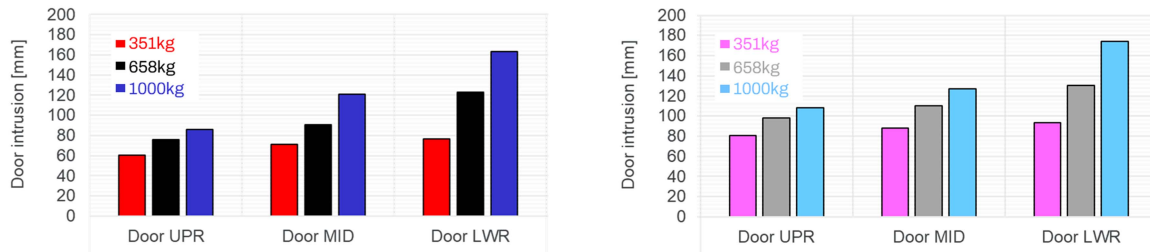

Figure 12. Door intrusion (Left: IDs#1–3, Right: IDs#4–6)

Gap effect

Figure 13 shows the effect of the Gap for each of the Vehicle mass conditions. For the MID and LWR regions, the K-car Gap injury ratios were less than those of the microcar Gap in every Vehicle mass condition.

However, for the HIC36 and UPR regions, the difference between the two Gap distances did not seem to follow a pattern; for example, in the 351kg case, the K-car gap produced a higher HIC36—but in the 658kg case the microcar gap produced a higher HIC36. The reason is that when the side window breaks later, it can restrain the shoulder longer, reducing the head's potential kinetic energy; as a result, head injury can be reduced. It appears that the higher the UPR deflection, the lower the HIC36 injury, and vice versa. Based on this observation, the side window of the 351kg vehicle was broken earlier than its counterpart in the heavier vehicles. Since the lighter vehicle has the larger inertia force in the crash, it leads to quicker and larger deformation of the door.

The direct injury factor of the contact force between the door and ES2 is shown in Figure 14, indicating clearly that the wave shape is similar even in the different gap conditions, although the timing differs. The peak forces of the K-car Gap were a little less than those of the microcar Gap. The graphs in Figure 14 show the 351kg case; the other Vehicle mass cases show the same trend.

The actual timing of the side window's breakage depends on a vehicle's design. However, a generic evaluation of the Gap effect can be made: a larger Gap has the potential to reduce injury levels even in these small cars with tiny door clearance. The potential injury reduction is slight but demonstrable.
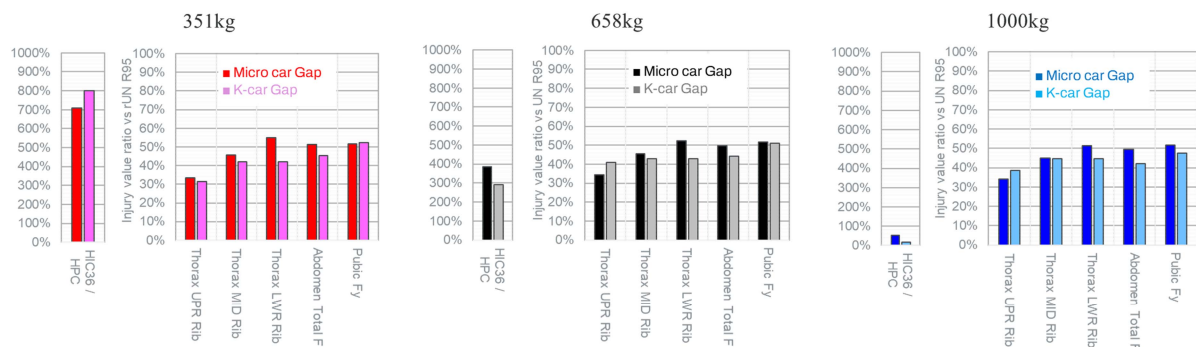

Figure 13. The injury values as percentages of the regulation threshold ; microcar gap vs K-car gap
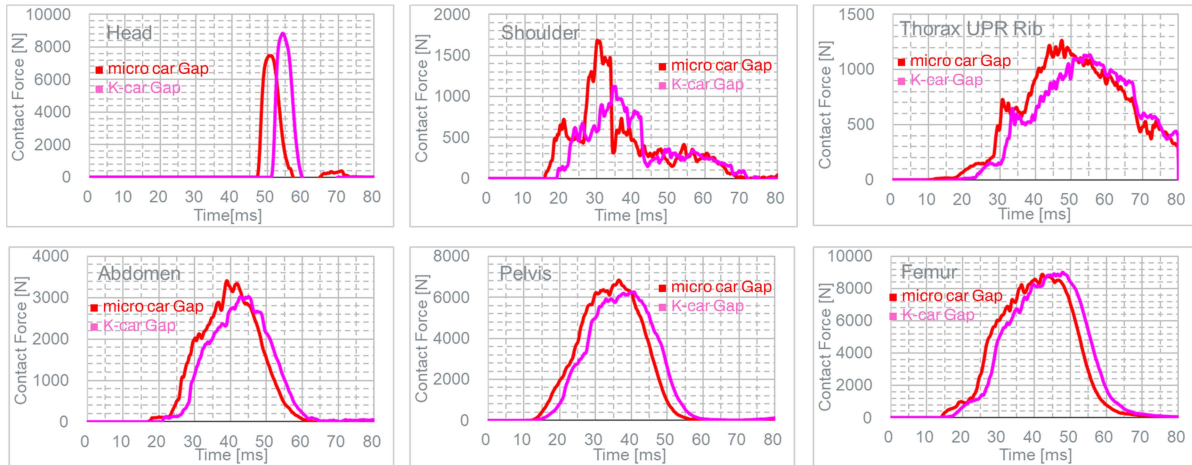
Figure 14. Contact force between door and ATD; microcar gap vs K-car gap (351kg Vehicle mass)

DISCUSSION

Same injury level regardless of the Vehicle mass

Although the head injury level was affected by the Vehicle mass, the chest-to-pelvis region injury level was not affected. The mechanism is explained below. The severity levels at the various regions are related to how the door impacts the side of occupant, and the most reasonable indicator of door impact severity is door velocity. This logic is supported by the work of Sunnevång et al. [12], who compared the occupant protection performance of modern versus older cars, using indicators of Door velocity and chest deflection. The indicators showed good correlation. In our study, the door velocities did not vary, regardless of the Vehicle mass, up until the time of the injury indicator peak.

The MDB velocity profiles were also almost all the same, until the time of the injury indicator peak. The merged final velocity of the MDB and Vehicle complies with the law of conservation of momentum; however, the temporal process was different from our expectation. The velocity of the MDB changed more slowly than that of the Vehicle: the difference can be seen after the injury peak.

Other interior parts have the potential to affect injuries in a crash event, such as the seat and seatbelt, which contact the occupant. The seatbelt applied in our tests did not have a pretensioner, so it could not create effective restraint friction, and the seat was responsible for only a small friction force through the seat cushion.

In summary, an occupant is in contact with the door, seatbelt, and seat in a crash. The most critical factor, the door velocity, remained almost the same because of the slow MDB velocity change; the other factors, seatbelt and seat, could not change very much—that is, the mechanism of injury is the same regardless of the Vehicle mass. This summary applies to the chest-to-pelvis region, not the head region.

A larger Gap has greater safety potential

Although there was almost no effect of Vehicle mass, the Gap parameter demonstrated some effects. As discussed, the biggest injury-causing impact element is the door, and the MDB velocity and Door velocity should be correlated in principle. As seen in Figure 7, the ES2 started to move at 20ms (Figure 11); the MDB velocity (= door velocity) at this point is nearly 13m/s, and the difference between the two Gap conditions is 33mm. The time duration to intrude 33mm is approximately 2ms, so we can calculate the difference in door impact velocity between the two, in this case approximately 0.2–0.3m/s—which can be roughly estimated from Figure 7. Velocity is squared for impact energy calculation, so even a slight difference in velocity can make a big difference in impact. Thus it can be said that the larger Gap definitely contributes to improved side-crash protection performance. The cabin of a microcar does not have any room to spare, but somehow (perhaps with seat layout) the challenge of making a larger Gap should be explored.

As one example of addressing this challenge, the CITROEN AMI (Figure 15) has a unique seat layout: the driver seat and front passenger seat are offset fore and aft, allowing the front seats to be closer than those in other microcars. We expect that this layout creates as large a door clearance as possible while avoiding interaction between occupants' shoulders. This type of innovation is needed to achieve user comfort, acceptable safety, and a reasonable price at the same time.

Figure 15. CITROEN AMI: Seat Layout

Head injury

This study indicated that the head could be impacted by the roof rail, whose velocity is affected by the Vehicle mass: the lighter the vehicle, the higher the impact velocity. As a result, the microcar has more need for head protection than larger, normal passenger cars. The head is an important body region which must be protected to avoid severe injuries. Although it is understood that a microcar will have a super low cost, the risk of head injury has to be reduced as much as possible.

As one solution, a higher roof which could avoid head impact is suggested. This requirement would restrict the design freedom, and some potential for neck injury could be expected instead, but it is just one of many ideas which will hopefully be proposed in the future.

LIMITATIONS

A K-car has a monocoque body structure like a normal passenger car, but a microcar would not normally have that kind of structure, considering the production volume and the tooling cost. It is not easy to determine which body structure would have a safety advantage. While there are many other possible kinds of structure (like ladder frame or pipe frame), this paper is based on a microcar with a monocoque structure.

In addition to the structure, benchmarking the microcar category, the material should be discussed. Microcars use resin a lot rather than metal, which might affect the body and door deformation characteristics.

Finally, the door thickness varies greatly, depending on the make of microcar, but generally microcars have thinner doors than K-cars. This difference means that the door contact timing to ES2 would be earlier than it was in our simulations, so the door impact velocity would be higher than in a K-car. As a result, the severity would be higher than reported in this paper.

CONCLUSION

The remarkable feature of a microcar is its small size and light weight. In this paper, we evaluated how these characteristics affect side-crash protection performance using vehicle mass and door clearance parameters.

The first key finding is that the injury level of chest-to-pelvis is not affected by the struck vehicle mass. In other words, every vehicle mass produced the same door intrusion velocity regardless of the struck vehicle mass. In principle, the door intrusion velocity is correlated to MDB velocity. While the velocities of the MDB and the struck vehicle were both affected by the vehicle mass, the MDB's velocity change was too slow to affect the injury level, which was already determined before the MDB velocity decreased. Secondly, the velocity of the struck vehicle was affected by its mass and this trend appeared from the beginning. The lighter vehicle moved faster. The ES2 head contacted the roof rail in the crash, and the lighter the vehicle the higher the impact speed to the head. Thus a microcar presents a more severe injury risk to the head region than a normal passenger vehicle. Thirdly, a larger gap between an occupant and the door can potentially reduce injuries, even in such a very small car.

Based on these findings, three suggestions can be made. First, acquiring as much door clearance as possible must be a priority, even in a microcar. Second, a microcar should have a door specification equivalent to that of a K-car, which gave an acceptable performance in this study as well as in JNCAP. And as a final suggestion, a head protection system should be prioritized, rather than a chest-to-pelvis protection system.

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