

Article

Simulation of the Impact of Tyre Damage on Vehicle Travel Safety

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Abstract

This article presents the results of simulation-based research aimed at assessing the impact of tyre damage on vehicle travel safety. The analysis takes into account various influencing factors, including vehicle speed, load conditions, and road surface condition (dry or wet asphalt). Particular emphasis was placed on the dynamic analysis of the vehicle during collision scenarios, including post-impact vehicle positioning, changes in kinetic energy, and the magnitude of the generated impact force. Simulation results indicate that tyre damage significantly compromises vehicle trajectory stability and, in certain cases, makes vehicle control impossible. The conclusions highlight the critical importance of maintaining proper tyre condition in mitigating the consequences of road collisions and emphasise the need for regular tyre inspections as part of routine vehicle maintenance.

Keywords: vehicle tyres; vehicle operation; road safety; V-SIM software; tyre wear

1. Introduction

Road safety is one of the most significant challenges in contemporary transport engineering and public policy. Due to the rapidly increasing number of vehicles on the roads, the frequency of road incidents has significantly increased, as emphasised in numerous scientific publications, for example [1–3]. Statistical data indicate that despite the continuous development of technologies aimed at reducing the risk of road accidents, the number of fatalities and injuries remains relatively stable year over year, with only a marginal decline observed.

Among the various factors influencing driving safety [4,5], particular attention should be given to the technical condition of vehicles, especially the tyres, as they directly affect both travel comfort and, precisely, travel safety. Tyres play a crucial role in vehicle mobility, and their damage becomes a critical factor affecting driving efficiency [6], adhesion [7], vibration damping, as well as the transmission of both driving and braking forces [8].

The importance of tyres in a vehicle is so significant that even minor damage can lead to a deterioration in vehicle behaviour during travel, particularly at high speeds or on surfaces with variable adhesion. Statistics show that tyre wear is a more serious issue in the case of trucks. During turning, tyres in multi-axle suspension systems are subject to abrasive wear caused by high slip angles resulting from steering geometry [9].

Tyre damage, whether sudden or progressive, represents one of the most common causes of unpredictable vehicle behaviour and may lead to loss of steering control, departure from the intended driving path, or road incidents with other road users.

According to a report from the US Highway Safety Administration, prior to the installation of tyre pressure monitoring systems (TPMSs) in vehicles, tyre bursts resulted



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in 414 fatalities and 10,275 injuries annually. In 78,392 tyre-related accidents, the fatality rate caused by tyre bursts was nearly 100% when a vehicle was travelling at speeds above 120 km/h. It is evident that abnormal tyre failure or bursts during high-speed driving pose a significant challenge to vehicle stability and road safety [10,11].

A Freedom of Information investigation has revealed the scale of Britain's tyre safety crisis, with official government data showing 3.1 million individual tyre defects caused MOT failures in the 13-month period from July 2023 to July 2024. The data shows that 603,416 vehicles were found to have tyres with exposed plies or cords—a catastrophic failure condition that significantly increases the risk of sudden tyre failure at speed. A further 1.16 million vehicles failed due to insufficient tread depth below the legal minimum of 1.6 mm [12].

Due to the critical role of tyres in the vehicle, numerous scientific studies have been conducted, focusing primarily on design aspects, material engineering, and environmental issues. For example, article [13] discusses the mechanisms of tyre wear particle generation, the operational conditions affecting tyre wear (such as inflation pressure, load, road environment, and driving style), as well as measurement techniques and emission assessment methods. The authors of [14] conducted simulations of the tyre inflation process in heavy vehicles and machinery. The authors also carried out a risk analysis related to over-inflation-induced explosions and developed safety models for vehicle operators. In [15], an empirical investigation of tyre abrasion under various conditions was performed, along with an analysis of the influence of operational parameters on the wear rate of tyres. In turn, the authors of [16] used thermal imaging measurements of tyres to assess the appropriate load capacity of trucks. The cause of standing wave formation in radial car tyres was investigated in [17] using dynamic finite element analysis under transient conditions, in order to predict the steady state of free rolling at high speeds.

The literature contains relatively few studies addressing tyre damage in the context of its impact on vehicle dynamics and driving safety. However, this issue is highly relevant from both the vehicle design and operational perspectives.

The aim of this article is to simulate the effect of tyre damage on vehicle driving safety. The study uses the V-SIM 6.0 numerical simulation environment, which enables the reproduction of realistic road scenarios and vehicle behaviour under conditions of partial or complete loss of functionality of one of the wheels.

The results of the simulations not only provide a deeper understanding of the influence of tyre damage on vehicle dynamics but may also serve as a basis for developing road safety procedures and driver training programmes.

2. Operational Conditions and Sample Tyre Damage in Vehicles

Automotive tyres play a critical role in vehicle operation. However, due to the loads exerted on the vehicle's wheels and, consequently, on the tyres, premature wear or damage may occur. The conditions under which tyres operate are highly variable and depend on the forces acting on the wheels at any given moment [18]. Among the loads acting on vehicle wheels, the following can be distinguished:

- Static forces, resulting from the vehicle's weight.
- Dynamic forces, associated with acceleration and braking.
- Lateral forces, generated during turning, which are the result of transverse force transmission.

The distribution of these forces depends on factors such as vehicle speed, turning radius, and road surface adhesion.

Figure 1 presents a schematic diagram of the wheel loads during vehicle operation.

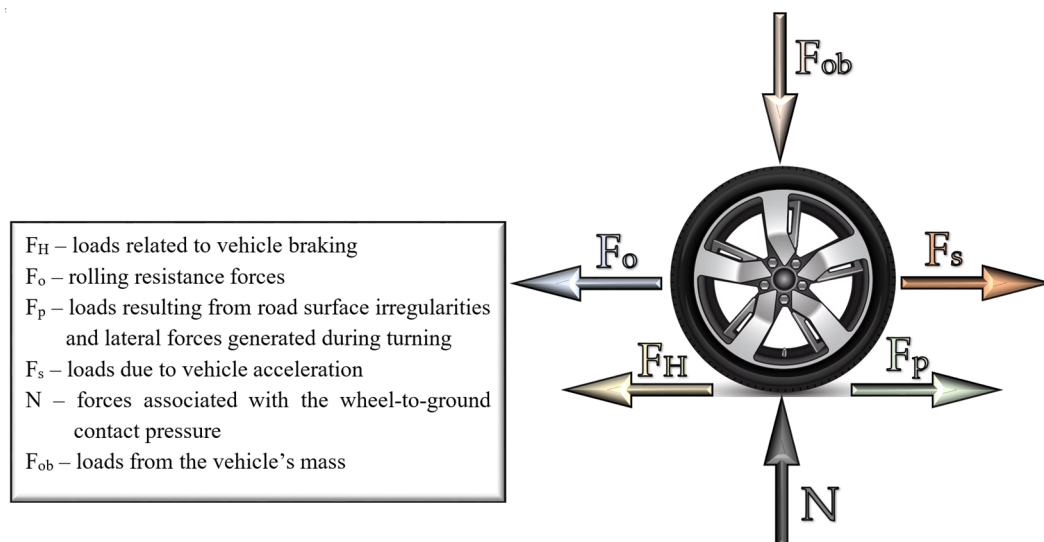


Figure 1. Diagram of vehicle wheel loading.

In addition to the aforementioned factors contributing to tyre damage, several other factors can be identified that also significantly reduce tyre life. Foremost among these is the variation in tyre pressure, which directly affects, for example, the structural stiffness of the tyre and the contact patch with the road surface. Furthermore, tyres are subjected to thermal loads [19,20]. During driving, tyre temperatures can rise to as much as 70–80 °C, or even higher when the vehicle is operating at high speeds [21]. This factor may contribute to the deterioration of rubber material properties, accelerated tread wear, or a sudden loss of adhesion in the event of overheating.

Equally significant, from the standpoint of tyre life, are environmental factors, which occur randomly but, when combined with other loads, amplify the risk of damage. Among others, these factors include

- Ambient temperature.
- Weather conditions, particularly those involving rainfall and snowfall, and the resulting road slipperiness [22].
- Contaminants present on the roadway. Sharp objects are especially hazardous, but even residues left from road de-icing or anti-slip treatments can pose a threat to tyre integrity,
- The type and condition of the road surface. Frequent driving on gravel roads may lead to mechanical damage to the tyres. Similarly, road surface irregularities and contact with kerbs may cause tyre damage.

A significant issue directly related to static forces resulting from the vehicle's mass is the exceeding of the permissible gross vehicle weight, which leads to tyre overloading. Frequent exposure to such conditions may result in mechanical damage and deformation of the tyres, and in extreme cases, may lead to tyre blowouts. There are also situations in which tyres are underinflated while the vehicle is simultaneously overloaded. This combination of adverse operational conditions often accelerates tyre deterioration. The risk of tyre failure in such cases is twice as high as in scenarios involving axle overloading alone.

Another contributing factor is uneven load distribution, which can lead to overloading in places and subsequently to fatigue-related damage.

Road manners also play a non-negligible role in the technical condition and life of the tyres. Aggressive driving, characterised by frequent acceleration and sudden braking, not

only has a negative impact on environmental quality [23], but also contributes to accelerated tyre wear. This issue has been raised in, for example, publications [24,25].

As discussed above, tyres are subjected to a wide range of interacting factors, many of which occur simultaneously. In conclusion, it should be emphasised that the operational conditions of tyres have a decisive impact on their durability, driving safety, travel comfort, and the overall economic efficiency of vehicle operation [26]. Despite being engineered with appropriate mechanical and strength properties, tyres can still suffer damage at times. Figure 2 presents examples of typical tyre damage, which—if not detected in time—may lead to a dangerous situation on the road.

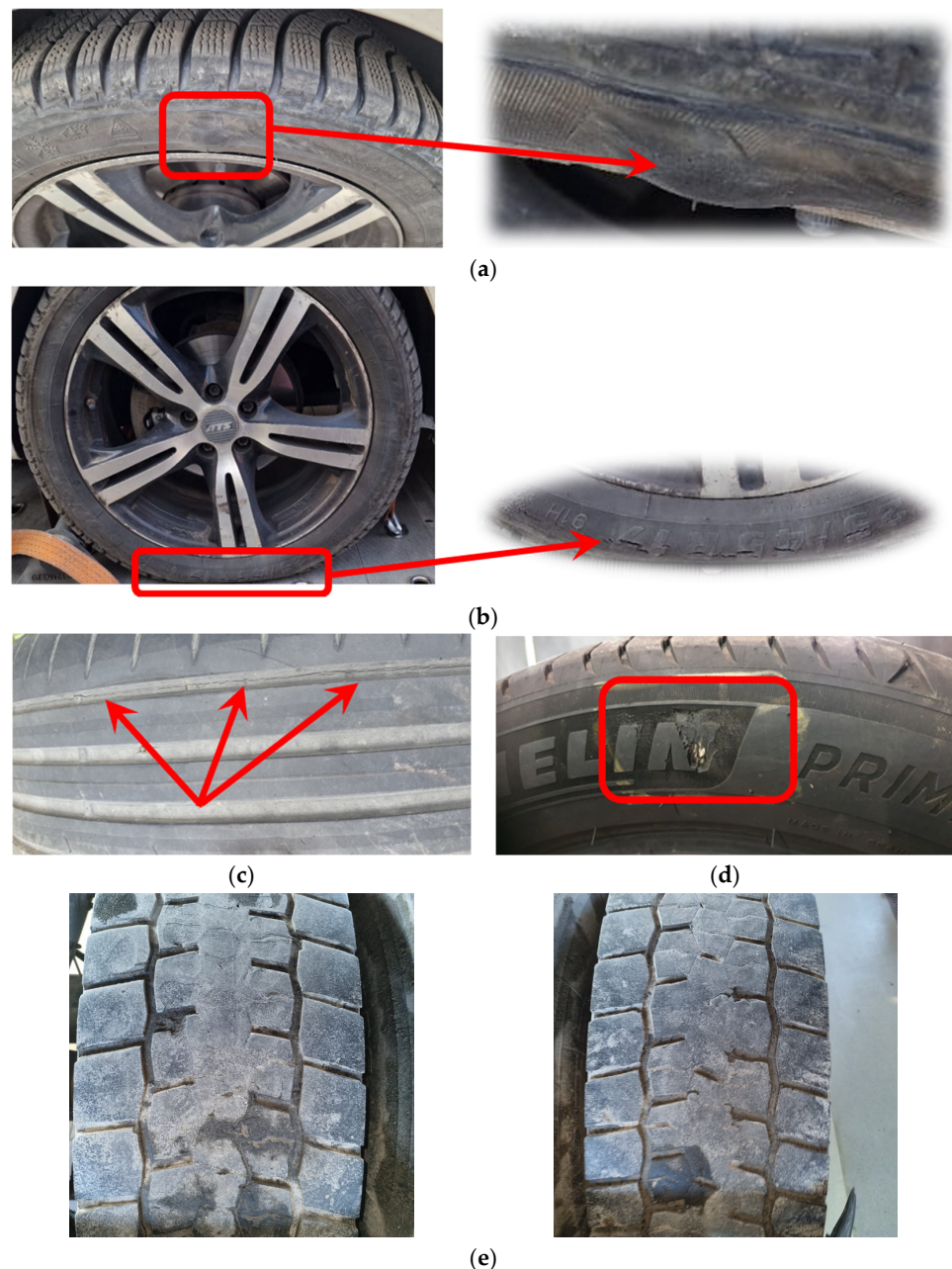


Figure 2. Examples of tyre damage that may pose a potential hazard to road safety, (a) localised bulge on the tyre sidewall; (b) randomly distributed sidewall cracks; (c) cracks located on the tread crown; (d) sidewall damage resulting in the exposure of the carcass; (e) uneven tread wear.

In Figure 2a, a localised bulge on the tyre sidewall is visible. This type of tyre deformation is most commonly caused by a rupture in the cord structure as a result of impact

with a kerb or after driving over a pothole. Another potential cause of such deformation is driving with insufficient air pressure in the tyres.

Cracks are another frequent form of operational tyre damage. They can appear in various locations and vary significantly in size. Figure 2b presents an example of a tyre with randomly distributed sidewall cracks of different dimensions. Figure 2c, on the other hand, shows cracks located on the tread crown, extending around the entire circumference of the tyre. This type of damage can be attributed, among other factors, to material ageing processes or the adverse effects of road salt on rubber quality. Operating tyres despite visible damage can lead to water penetration into the inner layers of the tyre structure, potentially causing progressive corrosion of steel components. Such tyres are also more susceptible to more frequent mechanical damage.

Figure 2d illustrates a localised sidewall damage resulting in the exposure of the carcass (textile layer). This damage most likely occurred as a result of the tyre running onto the kerb edge. Continued use of a tyre with this type of damage is hazardous, as the textile layer is responsible for maintaining the structural integrity of the tyre under internal pressure and for transmitting loads during turning, braking, and acceleration.

Another form of tyre damage encountered during operation is excessive tread wear in the central part of the tyre, along with permanent deformation (Figure 2e), or uneven wear observed on both the inner and outer tread sides. In the first case, the cause of wear is excessive tyre pressure. This phenomenon is frequently observed in trucks or delivery vans. In the second case, tyre damage is primarily caused by improper wheel alignment.

The examples presented above do not exhaust all possible forms of tyre damage in motor vehicles. Other issues include tyre delamination, which may occur due to excessive centrifugal and thermal loads. In some cases, signs of overheating and melting of the inner tyre layer can also be noted. The most hazardous form of tyre failure, most commonly observed in trucks and delivery vans, is a tyre blowout. This event occurs suddenly, and an unprepared driver may lose control of the vehicle. There are numerous potential causes of a blowout—ranging from tyre overloading and mechanical damage to material defects, overheating, or tyre ageing.

The results of the research work [27] indicate that tyre rupture was caused by delamination of the material coatings and corrosion of the steel cord wires. These defects could have arisen due to the earlier cracking of the rubber layer and the ingress of moisture, or as a result of the use of corroded steel cord wires in tyre production.

All types of tyre damage pose a dangerous and pose a potential hazard to road safety, particularly when such defects go unnoticed by the driver and the vehicle is being operated at high speeds [28].

3. Statistical Analysis

The issue related to the technical condition of tyres in many vehicles is also corroborated by data obtained from mandatory inspections conducted at certified vehicle inspection stations. On a daily basis, several vehicles are classified by inspection personnel as unfit for further operation due to non-compliance resulting from deficiencies in tyre condition identified during the inspection process. When interviewed by inspection personnel, drivers admit that they do not perform regular assessments of tyre condition, and only rely on tyre pressure sensors. Instead, drivers typically undertake corrective action only after the detection of abnormal pressure values by the sensors.

Figure 3 presents statistical data obtained from two regional vehicle inspection stations located within the Małopolskie Region (Poland). The data were collected over the period from 2021 to 2025.

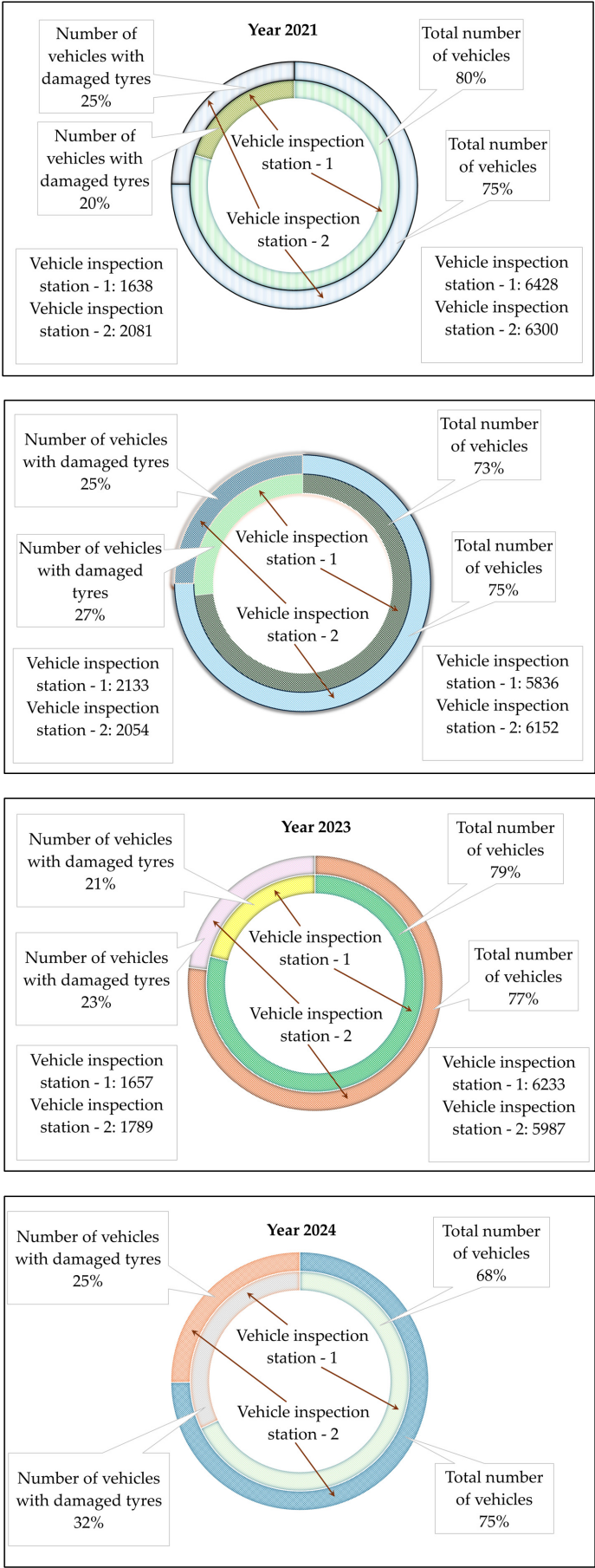


Figure 3. Cont.

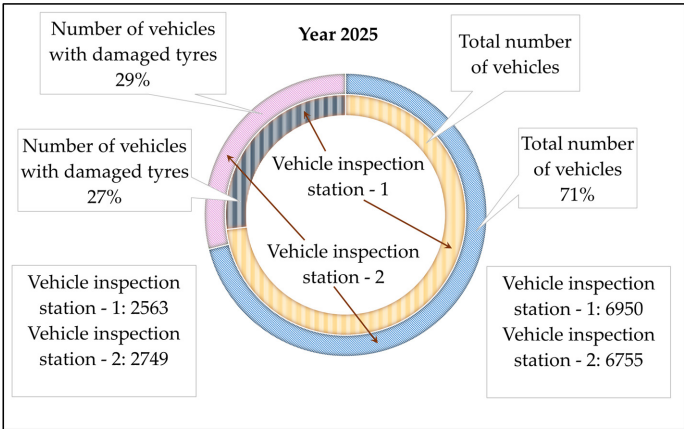


Figure 3. Comparison of the number of vehicles with damaged tyres relative to the number of conducted diagnostic inspections.

The data presented in the diagrams illustrate the significant scale of tyre-related issues in vehicles regularly operated on public roads. Diagnostic test results indicate that approximately 20–30% of vehicles fail inspections each year due to various forms of tyre damage. This represents a considerable concern, as the running gear directly affects travel safety. Any unexpected tyre failure can result in situations where the driver loses control of the vehicle, potentially leading to a traffic incident. An example of such an incident is analysed in the subsequent sections of this article.

Figure 4 presents the number of recorded instances of tyre damage categorised by type of defect. The data were obtained from the same two regional vehicle inspection stations.

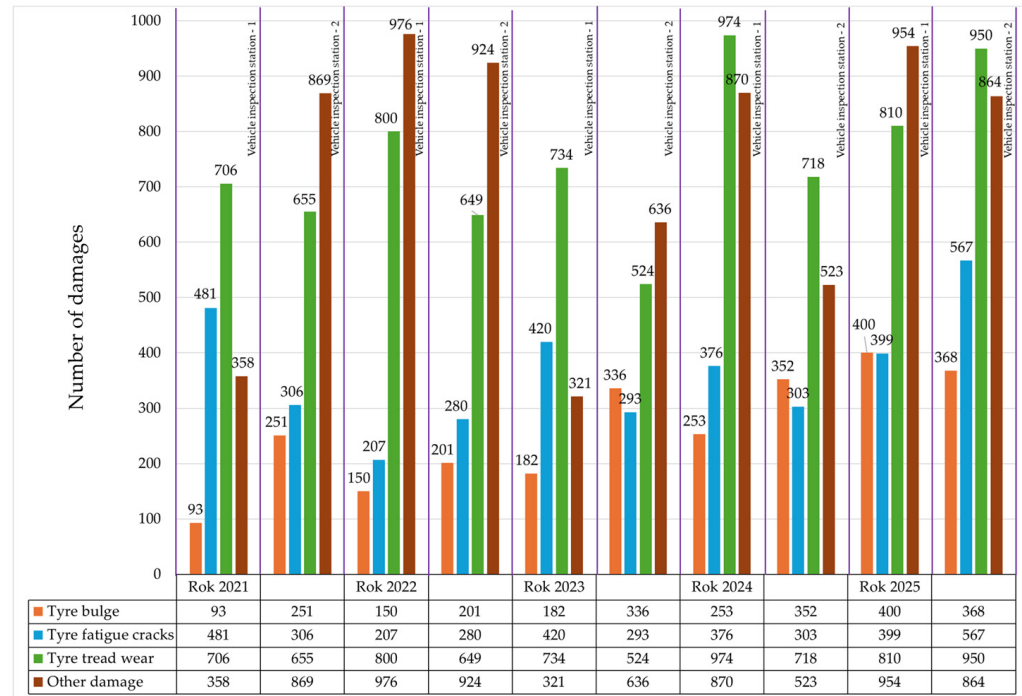


Figure 4. The number of recorded instances of tyre damage by the type of defect.

The analysis of the diagram indicates that the most prevalent issue affecting tyre condition is excessive tread wear. The second most common defect comprises fatigue cracks of varying sizes, located in different areas of the tyre. The location of certain cracks hindered their detection, leaving drivers unaware of their presence, which could eventually lead to unpredictable situations during vehicle operation.

Vehicle inspection personnel also identified tyre bulges as part of the diagnostic process. The annual number of such defects was relatively low; however, even this quantity represents a potential hazard during vehicle operation. Therefore, drivers should exercise increased vigilance and identify such irregularities during routine inspections of their vehicle's technical condition.

Data obtained from vehicle inspection stations were used to forecast the number of tyre-related irregularities likely to be detected in the future. To this end, a linear trend model was applied, with its function expressed by Formula (1).

$$y = at + b \quad (1)$$

where

a —slope coefficient

$$a = \frac{\sum_{i=1}^n [(t_i - \bar{t}) \cdot (y_i - \bar{y})]}{\sum_{i=1}^n (t_i - \bar{t})^2}$$

b —intercept of the trend

$$b = \bar{y} - a \cdot \bar{t}$$

t_i —year

y_i —number of defects

$\bar{t}$, $\bar{y}$ —mean values

Based on the data and the above equations, linear functions were derived for each type of tyre defect, and their corresponding diagrams are presented in Figure 5. For the purposes of the prognostic analysis, the data from the first and second vehicle inspection stations were aggregated and treated as a single input dataset for the calculations.

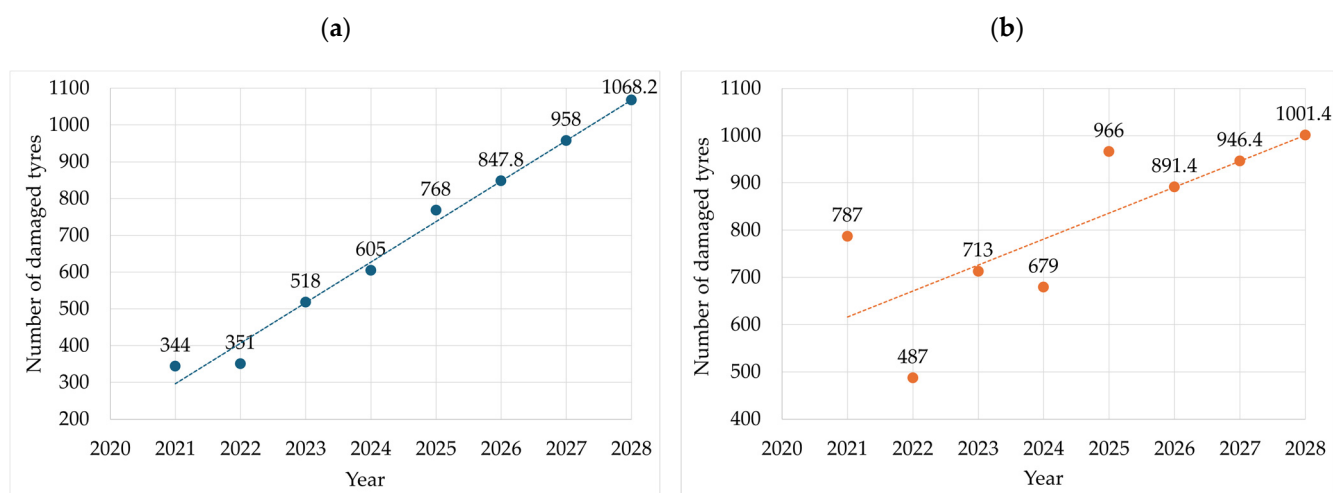


Figure 5. Cont.

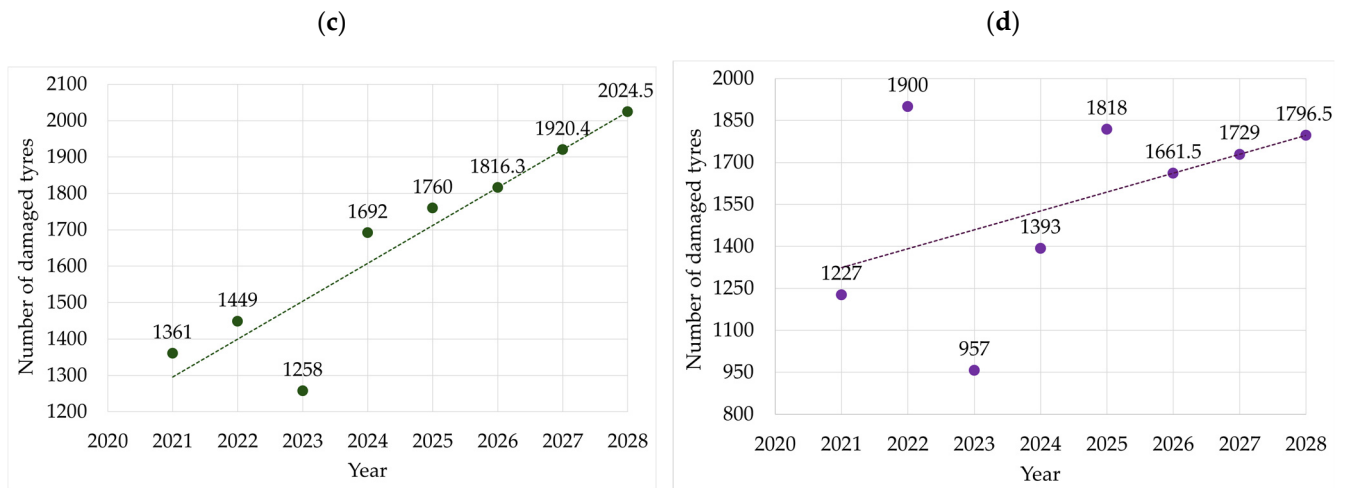


Figure 5. The forecast of the number of damaged tyres by type of damage, (a) tyre bulge, (b) tyre fatigue cracks, (c) tyre tread wear, (d) other damage.

Tyre bulge

$$y = 110.2 \cdot t + 186.6$$

Tyre fatigue cracks

$$y = 55.0 \cdot t + 561.4$$

Tyre tread wear

$$y = 104.1 \cdot t + 1191.7$$

Other damage

$$y = 67.5 \cdot t + 1256.5$$

The tyre damage forecasts presented in Figure 5 indicate a clear and consistent increase in the number of irregularities in the coming years, with the rate of growth depending on the type of damage. The steepest trend line slope is observed for excessive tread wear, suggesting the highest growth rate. It can be inferred that the number of such defects is expected to increase at an estimated rate of approximately 8–12% per year. This phenomenon is particularly concerning, as tread depth directly affects braking distance, resistance to hydroplaning, and vehicle stability during cornering.

A slightly lower, yet still noticeable, upward trend is observed for fatigue cracks. The number of detected cases will increase by approximately 5–7% per year, which could result in a cumulative growth of around 25–35% over several years. Fatigue cracks are particularly hazardous due to the difficulty of detecting them at an early stage and the risk of sudden tyre rupture during operation.

In the case of tyre bulges, despite the relatively low number of occurrences, the forecast indicates a relatively high percentage increase for this category of defects. It is estimated that these values will grow at a rate of approximately 10–15% per year. This figure represents the highest percentage increase among all analysed types of tyre damage. Bulges constitute the most critical type of tyre defect, as they may lead to instantaneous tyre rupture at higher speeds.

The mildest upward trend is observed in the “other damage” category, with an annual growth rate ranging at 2–4%. Although this increase is relatively small, its consistency indicates that even less common tyre defects will occur more frequently, reflecting a general deterioration in tyre maintenance and usage practices among drivers.

Forecasts suggest that, without appropriate action, the number of tyre defects will continue to rise, posing an increasing risk to road safety. An annual growth of 5–12%

across most categories implies that, within a few years, vehicle inspectors will identify a significantly higher number of vehicles with defective tyres, and the scale of the problem will become even more severe than at present.

4. Simulation Conditions

The simulation involved two vehicles. A delivery van (Vehicle 1), which in each simulation run was travelling at a different speed ranging from 50 to 140 km/h, and a car (Vehicle 2), which—immediately prior to the collision—was travelling at a constant speed of 60 km/h in all cases. It is not possible to determine whether the car driver travelled at a constant speed all the time or began to decelerate upon noticing the other vehicle merging into their lane.

The crash simulation considered two vehicle load variants. In the first variant, only the drivers were present in the vehicles, and no cargo was being transported. In the second variant, both vehicles were fully occupied with passengers and carried additional cargo. A detailed description of the vehicle loading conditions is provided in a later section of the article.

4.1. Vehicle Characteristics

Below are the basic technical specifications of the vehicles involved in the road incident. These data were obtained using the V-SIM 6.0 software.

Delivery van (Vehicle 1—Figure 6a):

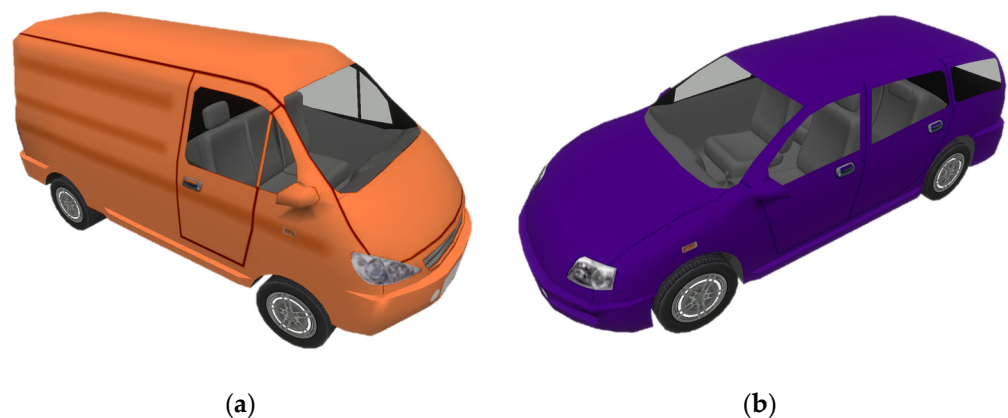


Figure 6. Silhouettes of the vehicles involved in the road incident simulation: (a) the delivery van; (b) the car.

Length $\times$ width $\times$ height: 5077 $\times$ 1996 $\times$ 2385 mm,
 Number of axles: 2,
 Wheelbase: 3000 mm,
 First axle wheel track: 1696 mm, the second axle: 1540 mm,
 Kerb weight: 2070 kg, gross vehicle weight rating: 3500 kg,
 Maximum power: 106 HP at 3300 rpm,
 Tyres: 95 $\times$ 75 R16 107—6 pcs; tyre pressure: 100%,
 Tyre grip coefficient: 0.8 (dry asphalt),
 Tyre grip coefficient: 0.6 (wet asphalt).

Car (Vehicle 2—Figure 6b):

Length $\times$ width $\times$ height: 4823 $\times$ 1861 $\times$ 2385 mm,
 Number of axles: 2,
 Wheelbase: 2816 mm,

First axle wheel track: 1578 mm, the second axle: 1576 mm,
 Kerb weight: 1653 kg, gross vehicle weight rating: 2150 kg,
 Maximum power: 228 HP at 6200 rpm,
 Tyres: 245 × 45 R17 107—4 pcs; tyre pressure: 100%.
 Tyre grip coefficient: 0.8 (dry asphalt),
 Tyre grip coefficient: 0.6 (wet asphalt).

4.2. Traffic Environment and the Vehicle Load

At the time of the collision, road conditions were favourable. The weather was sunny, but sunlight did not dazzle the drivers. Two types of road surface conditions were analysed:

- Dry asphalt with the following parameters:
 - Slide coefficient of adhesion— $\mu_s = 0.75$
 - Rolling resistance coefficient—0.015
- Wet asphalt with the following parameters:
 - Slide coefficient of adhesion— $\mu_s = 0.50$
 - Rolling resistance coefficient—0.015

The quality of the road surface at the collision site and its immediate surroundings was assessed as high. No ruts, surface defects, or other forms of road damage were noted.

The vehicles were travelling on a two-way road with a width of 7 m. On both sides of the roadway, there were hard dirt shoulders, each 1 m wide. Installed along the shoulders were U-14a-type modular safety barriers, designed to prevent road users from veering into the water that bordered the roadway.

Prior to the road incident, both vehicles were moving correctly in opposite directions. At some point, due to the bulge in the left rear tyre of the delivery truck and the high pressure acting on the wheel, it explodes and the pressure in the wheel drops rapidly. Only damage addressed by this article is full deflation of the tyre, and this is simulated in V-SIM by setting a deflation time of 0.10 s.

At the moment tyre damage occurred, the vehicles were 89.3 m apart. Figure 7 presents a visual representation of the traffic environment and road conditions used as the basis for simulating the road collision scenario.



Figure 7. Traffic environment and road conditions used in the road accident simulation.

As mentioned previously, the car accident simulation was conducted for two vehicle load scenarios. In the first scenario, the delivery van was occupied only by the driver, whose body mass was 93 kg, and the vehicle was not carrying any cargo. Similarly, the only car occupant was the driver, whose body mass was 75 kg.

The second simulation scenario assumed full loading of both the delivery van and the car. The delivery van was occupied by the driver, weighing 93 kg, and one passenger weighing 88 kg. There was a cargo load of 1400 kg in the vehicle. The car was occupied by the driver weighing 75 kg and four passengers with a combined body mass of 294 kg. Additionally, luggage weighing 60 kg was transported in the car.

4.3. Road Incident Simulation Software

The road incident simulation was performed using V-SIM 6.0 software, licenced by CYBID sp. z o.o. sp. k., headquartered in Kraków, Poland. V-SIM is an advanced simulation programme designed for road incident reconstruction. The software integrates sophisticated physics and numerical modelling in a 3D environment, and accounts for interactions within the Human-Environment-Vehicle system. The programme enables analysis of vehicle motion and collisions, pedestrian, cyclist, or scooter rider impacts, as well as drivers' and passengers' behaviour. The realistic representation of the traffic environment is supported by compatibility with multiple data formats, built-in drawing tools, and extensive libraries of 2D and 3D graphic objects.

5. Analysis of Simulation Results

5.1. Vehicle Positions at the Moment of Collision, the Course of the Incident and Extent of Vehicle Damage

A sketch of the vehicle positions at the moment of collision forms the basis for assessing the behaviour of the vehicles prior to the accident and aids in understanding its mechanics.

A properly made sketch not only facilitates the determination of fault but also helps to comprehend the mechanism of damage occurrence and the displacement of vehicle components. Depending on the relative positioning of the vehicles, it is possible to identify whether the collision was frontal, side-impact, or oblique. The angle and location of the impact allow for an evaluation of how external forces were distributed across the vehicle body structure and how the kinetic energy was dissipated. Furthermore, it is also possible to assess whether controlled deformation zones were activated, whether structural deformations occurred, and how these factors may have influenced passenger safety.

Sketches are used in road incident reconstruction. In many difficult or disputed cases, they serve as the basis for determining the perpetrator of the accident. Moreover, knowledge of the vehicles' positions at the moment of collision enables the assessment of the collision type. Depending on the impact angle and point of contact, vehicles may come to a stop at the scene, be propelled in different directions, or even overturn or rotate around their own axes. Such phenomena are crucial not only for understanding the course of the accident but also for predicting its consequences. A sketch, combined with the application of principles of dynamics and the conservation of momentum, allows for estimating vehicle speeds, movement directions, and possible post-collision trajectories.

The first stage of the simulations conducted was the assessment of the vehicles' positions at the moment of collision, their post-crash locations, and the extent of body deformation. Figure 8 presents the positions of the vehicles at the moment of collision for selected driving speeds of Vehicle 1 and under varying road conditions, assuming that only the drivers were present in the vehicles and that the vehicles were not additionally loaded.

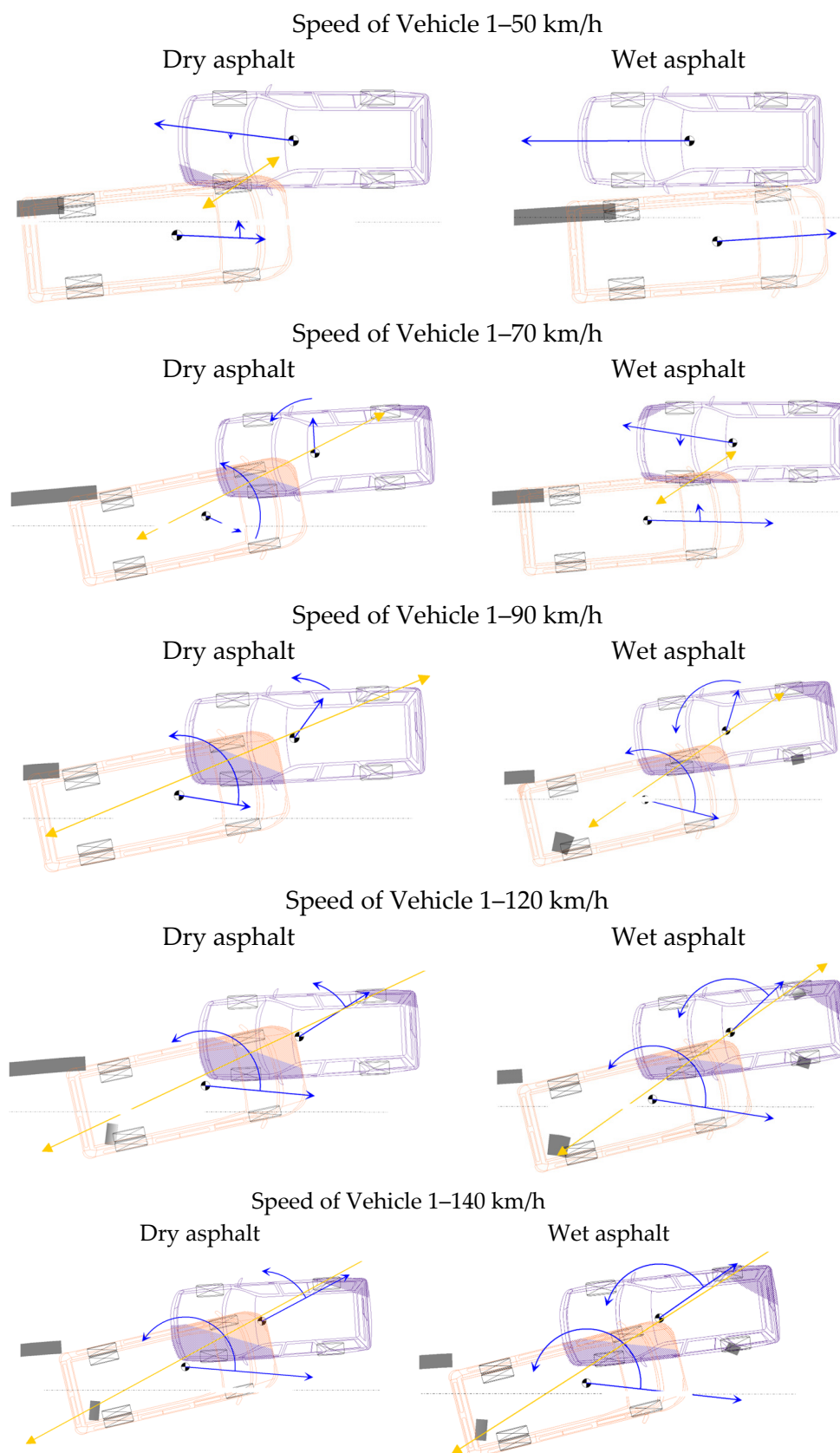


Figure 8. A sketch showing vehicle positions at the moment of collision for various speeds of Vehicle 1—unladen vehicles.

5.1.1. Unladen Vehicles—Dry Asphalt

In the event of tyre damage occurring at Vehicle 1 speed of 50 km/h, the van driver will have approximately 3.14 s to react in order to avoid a collision. This response time appears to be sufficient; however, if—for any reason—the collision cannot be avoided, vehicle impact will occur, and the maximum overlapping volume of the vehicle silhouettes will be 0.24 m³. Following the collision, both vehicles change lanes and continue moving forward. After 5.40 s from the start of the simulation, the delivery van impacts the safety barriers on the same side where the collision occurred. The car subsequently hits the safety barriers at 5.87 s, after which both vehicles are expected to come to a complete stop.

In the scenario where Vehicle 1 travels at 70 km/h on a dry asphalt surface and tyre damage occurs, a collision with the car will take place 2.64 s, and the maximum overlapping volume of the vehicle silhouettes in this case is 0.71 m³. As a result of the impact forces, the car is pushed by the delivery van and hits the safety barrier with the vehicle's rear section. The vehicle then rebounds and strikes the barriers, this time with the vehicle's front-right section. Meanwhile, the delivery van rotates by 184° and comes to a stop in the same lane it was originally travelling in. The total simulation time until the vehicles come to a complete stop is 7.05 s.

The final phase of the collision sequence differs significantly from the previously described scenarios when the impact occurs at delivery van speeds of 90 km/h or higher. The time to first contact between the vehicles is 2.20 s at a speed of 90 km/h, 1.88 s at 120 km/h and 1.63 s at 140 km/h. This is therefore a very short reaction time for either driver. The delivery van collides with the car at an angle of approximately 12°, pushing the car into the safety barrier, which is struck with the right-rear section of the car. The maximum overlapping volume of the vehicle silhouettes at the moment of collision is 1.30 m³ for a delivery van speed of 90 km/h, 1.60 m³ at 120 km/h and 1.62 m³ at 140 km/h. The post-impact forces acting on Vehicle 1, along with the resulting moment of force, cause the vehicle to overturn onto its side, and at higher speeds, a rollover may even occur.

5.1.2. Unladen Vehicles—Wet Asphalt

Additionally, simulations were conducted to assess vehicle behaviour under wet asphalt conditions. Since the accident occurred on a roadway surrounded by a lake, the asphalt in this area is very frequently damp, which significantly affects the coefficient of adhesion. The gradual change in roadway surroundings can reduce driver alertness, leading to a failure to adjust driving speed to the prevailing road conditions in a timely manner.

In such conditions, a driving speed of 50 km/h or even 60 km/h is generally considered safe, and drivers are typically able to maintain control of their vehicles regardless of the situation. However, in the analysed case, the scenario unfolds differently, as the driver of Vehicle 1 veers into the oncoming lane, resulting in an impact with the car. According to the simulation results, this contact leads to minor damage, and the car is able to continue the ride. The maximum overlapping volume of the vehicle silhouettes in this scenario is 0.01 m³. The delivery van subsequently collides with the safety barriers at a speed of 29.4 km/h, causing additional damage to the vehicle. As a result of the impact with the safety barrier, the maximum damage volume of Vehicle 1 increases by an additional 0.05 m³.

At a driving speed of 70 km/h, the consequences of the collision become more severe. The delivery van impacts the car at an angle of 5.1°. The collision causes both vehicles to lose stability. The car first hits the safety barrier with the vehicle's rear-right section, followed by a second impact with the vehicle's front-right section, which leads to the vehicle shifting across to the oncoming lane at an angle of 254.2°. The vehicle then impacts the safety barrier with the vehicle's rear-left section and subsequently returns to its original

lane, hitting the barrier once again with the vehicle's front-right section. At this point, the total kinetic energy of the vehicle has been dissipated, and the car comes to a complete stop after 7.40 s from the start of the simulation. Meanwhile, the delivery van continues to move forward and subsequently impacts the safety barrier with the vehicle's front-left section at an angle of 62.9° . The delivery van rebounds from the barrier and shifts to the oncoming lane, where that vehicle collides with the safety barrier again, this time with the vehicle's rear-left section at an angle of 121° and a speed of 12 km/h. The vehicle subsequently changes lanes again, ultimately coming to a stop when perpendicular to the direction of travel.

A driving speed of 90 km/h for Vehicle 1 leads to significant vehicle structural damage, although it does not result in the delivery van rollover, as was observed in the case involving dry asphalt conditions. In this scenario, the delivery van impacts the car at an angle of 12.3° . The maximum overlapping volume of the vehicle silhouettes is 0.81 m^3 . As a result of the impact, the car loses its front-left wheel and the vehicle's body hits the road surface. Subsequently, the car collides with the safety barrier with the vehicle's rear-right section at a speed of 4.9 km/h, rebounds, and impacts the delivery van once more. The car decelerates and comes to a stop in its original lane, oriented at an angle of 25.5° . During this time, the delivery van rotates by 105.6° and impacts the safety barrier with the vehicle's rear-right section at a speed of 30.0 km/h. As a result of this impact, the delivery van hits the same safety barrier once again—this time with the vehicle's front-left section at an angle of 192.9° and a speed of 18.8 km/h. It subsequently rebounds from the barrier and comes to a stop in its original lane, oriented at an angle of 175.6° relative to the pre-impact direction of travel.

Although a driving speed of 120 km/h is not legally permissible on the type of road analysed in this study, instances of such behaviour do occur, as some drivers tend to disregard speed limits and drive at such a speed. This is mainly due to the fact that drivers are often in a hurry and want to save time, especially when they see a long, straight road section ahead of them. The problem arises when an unexpected event, such as a tyre crack, occurs at such high speeds. Therefore, the simulation included an additional scenario involving a collision with the delivery van travelling at 120 km/h.

Under these conditions, on wet asphalt, the delivery van collides with the car at an angle of 13.4° , occurring 1.88 s after the onset of tyre damage. The maximum overlapping volume of the vehicle silhouettes in this case is 1.12 m^3 . The car is pushed sideways and impacts the safety barrier with the vehicle's rear-right section at a speed of 3.6 km/h, generating an impact force of 383 kN. After rebounding from the safety barrier, the vehicle returns to its original lane and comes to a stop at an angle of 88° relative to the roadway axis.

Following the collision with the car, the delivery van rotates around its own axis and turns over onto its side. While sliding on the asphalt, the vehicle collides with the safety barrier with the vehicle's front section, and remains in that final position. Figure 9a presents the post-collision scenario described above.

If a delivery van is travelling at an extreme speed of 140 km/h for these road conditions, it will strike a properly moving passenger car at an angle of 15.9° . The maximum vehicle coverage volume in this case is 1.17 m^3 . As a result of the collision, the passenger car strikes the guardrail with its rear end and, after rebounding from the guardrail, moves toward the centre of the roadway. During this time, the delivery van overturns and rolls over. The post-accident situation is shown in Figure 9b.

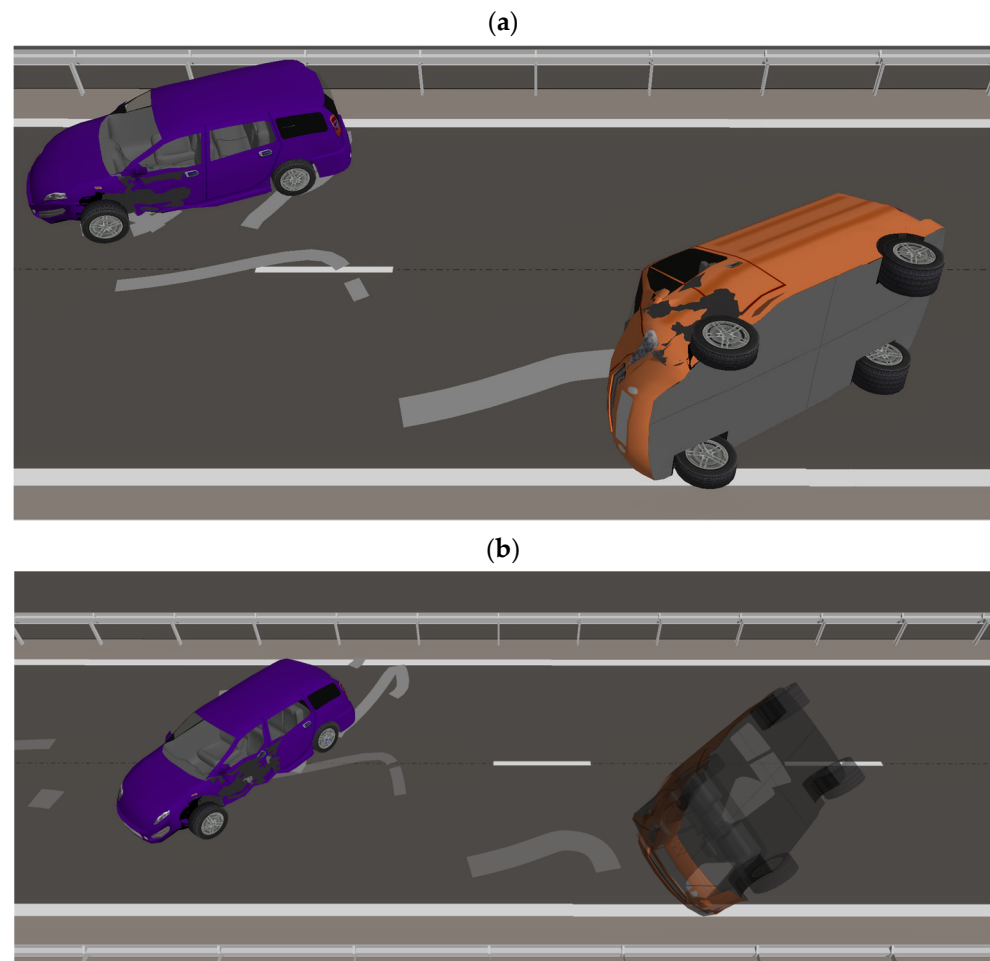


Figure 9. The post-collision scenario. (a) Vehicle 1 speed: 120 km/h, (b) Vehicle 1 speed: 140 km/h; wet asphalt surface.

5.1.3. The Depth of Vehicle Body—Unladen Vehicle

Each of the described road incidents involves varying degrees of damage to the vehicles involved in the accident or collision. A key metric for assessing this damage is the depth of deformation of the vehicle body.

The depth of vehicle body deformation is a parameter widely used across various domains related to the automotive industry, road safety, and accident reconstruction. This metric indicates the extent to which the vehicle's structure has been indented or distorted as a result of a collision or accident. The deformation depth primarily provides insight into the severity of body damage, but it can also serve as a basis for estimating the amount of kinetic energy absorbed by the vehicles during the impact.

Among the aforementioned domains, road accident reconstruction is where vehicle deformation depth is most commonly applied. That parameter is used to determine collision dynamics, including vehicle speeds prior to impact and force directions. When that parameter is supplemented with additional information—such as eyewitness accounts or data from commonly used dashcam recorders—it becomes possible to accurately reconstruct the sequence of events during the road incident. Although less frequently, deformation depth is also used in municipal damage assessment and claims processing. Deformation depth is also useful in estimating vehicle repair costs and in determining whether the vehicle should be classified as a total loss. Knowledge of the extent of vehicle deformation also allows for an estimation of the excessive loads that may have acted on the human body during the

collision. This is particularly important in the assessment of the causes of injuries and the attribution of liability for those.

Table 1 presents the vehicle body deformation depths recorded under varying vehicle speeds and asphalt surface conditions (dry and wet).

Table 1. Vehicle body deformation depth [mm]—unladen vehicles.

Driving Speed [km/h]	Vehicle 1		Vehicle 2	
	Dry Asphalt	Wet Asphalt	Dry Asphalt	Wet Asphalt
50	293	10	273	10
60	654	68	811	78
70	732	312	898	303
80	791	615	957	605
90	820	781	1016	918
100	859	840	1074	986
110	908	889	1113	1055
120	957	938	1152	1104
130	996	986	1201	1152
140	1045	1035	1250	1211

An analysis of the data presented in Table 1, along with the post-collision behaviour of the vehicles, reveals that vehicles tend to sustain less damage when driven on wet asphalt. At lower vehicle speeds, a significant difference in the extent of damage is noted depending on the surface condition. This disparity becomes less pronounced only when Vehicle 1 reaches speeds of at least 80 km/h. Nevertheless, the deformation depth—as an indicator of body deformation—remains lower on wet asphalt, even at higher speeds. This mechanism can be explained by the reduced tyre-to-surface adhesion on wet roads. In accident scenarios, reduced adhesion can cause the vehicle to enter a skid prior to impact, allowing the vehicle to dissipate part of its kinetic energy before the actual collision occurs. As a result, the sliding vehicle reduces its speed, leading to a collision with a lower impact force.

The values presented in the table refer exclusively to the deformation depth of the vehicle bodies at the moment of impact. However, the final extent of damage is greater, as evidenced by the previously described post-collision vehicle behaviour. After the initial impact, vehicles continued to move in an uncontrolled manner, frequently colliding with safety barriers before fully dissipating their kinetic energy and coming to a complete stop. As a result, the car sustained damage in many places, including the front-left, rear-right, and—under certain conditions—front-right sections of the bodywork (as observed, for example, when Vehicle 1 was travelling on wet asphalt at a speed of 70 km/h). A similar pattern was observed for the delivery van, which also struck safety barriers many times, causing additional damage to its body.

The second simulation scenario assumed that both the delivery van and the car were fully loaded. Figure 10 presents the positions of the vehicles at the moment of collision for selected driving speeds of Vehicle 1 and under varying road conditions, i.e., on dry and wet asphalt.

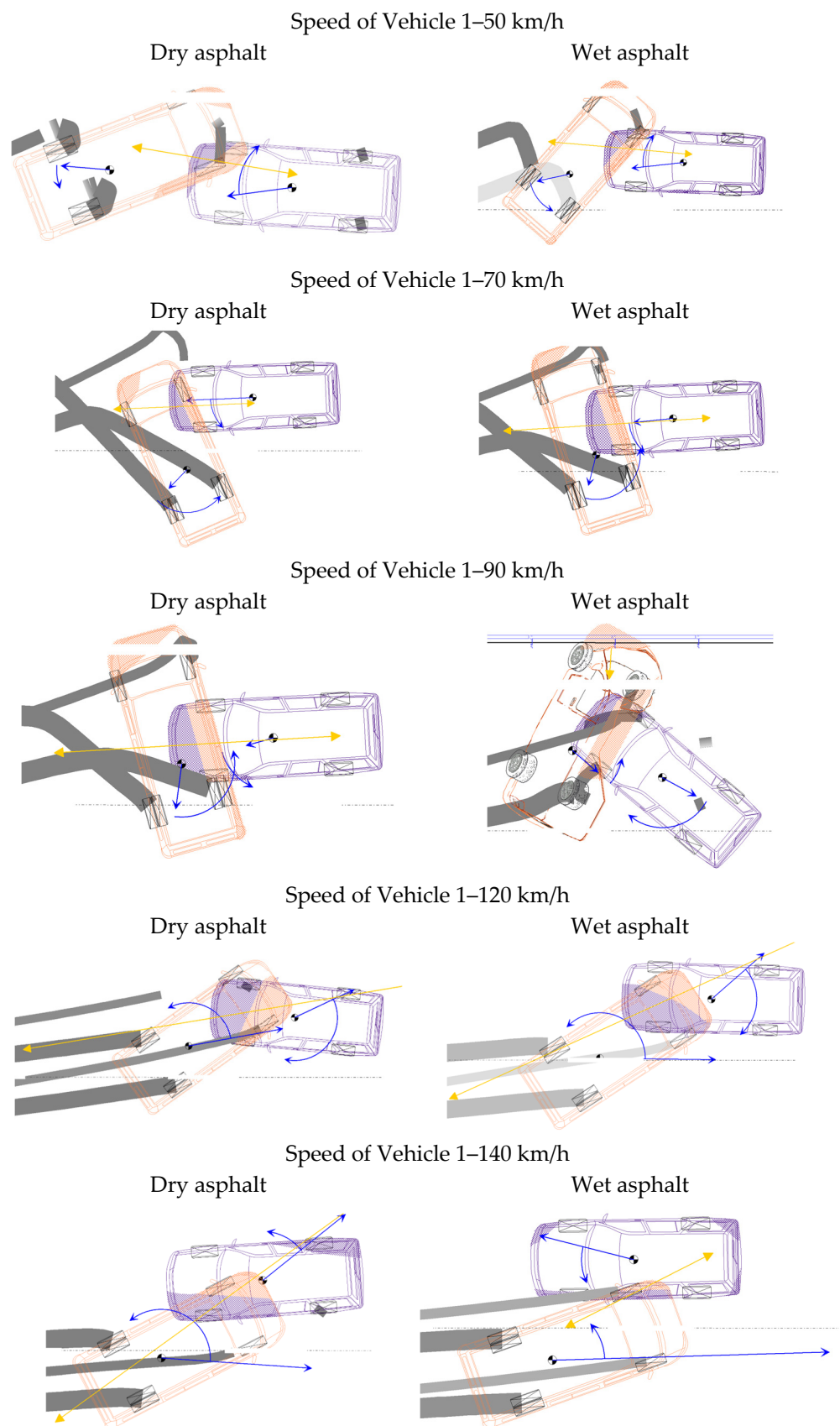


Figure 10. A sketch showing vehicle positions at the moment of collision for various speeds of Vehicle 1—loaded vehicles.

5.1.4. Loaded Vehicles—Dry Asphalt

Figure 10 illustrates schematic representations of the post-impact positions of the vehicles in a scenario where the car was fully occupied by passengers, and the delivery van was loaded to its maximum cargo capacity. At a vehicle speed of 50 km/h on dry asphalt, the delivery van initially impacts the safety barrier, generating a force of 379 kN and releasing 25.5 kJ of kinetic energy. Following the impact, the vehicle rebounds from the barrier and moves toward the centre of the roadway. During this time, the car approaches at the same speed maintained prior to the incident. The reason for the lack of driver reaction in the car remains unclear. Despite an apparently sufficient reaction time of 3.03 s, the driver fails to respond and collides with the delivery van at full speed. The maximum overlapping volume of the vehicle silhouettes resulting from the collision is 0.77 m³. The combination of the car's velocity and the forces acting at the time of impact causes the delivery van to be pushed forward by the car. After several metres, a second collision between the two vehicles occurs. The impact force acting on the delivery van, measured at 30.6 kN, causes the vehicle to begin to turn over onto its side. However, the vehicle does not overturn and remains upright on its wheels. After dissipating its kinetic energy, the delivery van comes to a stop in the middle of the roadway, oriented at an angle of 174.9° relative to its original direction of travel. Meanwhile, the car strikes the safety barrier with the vehicle's front-right section, generating a force of 90.5 kN, rebounds from the barrier, and subsequently impacts the opposite safety barrier with the vehicle's rear-left section at a force of 24.5 kN. Following this impact, the vehicle dissipates its remaining kinetic energy and comes to a stop near the centre of the roadway.

In the scenario where the delivery van is travelling at a speed of 70 km/h, the course of the collision is very similar to the one described above. In this case as well, the delivery van first collides with the safety barrier on the opposite side of the roadway, generating an impact force of 651 kN. The car driver has 2.98 s to react and avoid the collision. This reaction time proves to be insufficient, resulting in a collision. As a consequence of the impact, the maximum overlapping volume of the vehicle silhouettes is 0.83 m³. The crash-induced loads are sufficiently high to cause the delivery van to overturn.

At a travel speed of 90 km/h, the delivery van changes lanes at an angle of 61.7°, and after 2.22 s, it collides with the safety barrier. The vehicle then rebounds and impacts the car. As a result of the second collision, the maximum overlapping volume of the vehicle silhouettes is 1.40 m³. Subsequently, due to momentum, Vehicle 1 hits the safety barrier with the vehicle's front-left section, leading to vehicle rollover.

For vehicle speeds exceeding 90 km/h, the sequence of events is very similar. The initial collision between the vehicles is followed by the rollover of the delivery van. The only variables that change are the magnitude of the loads acting on the vehicles during the impact. A delivery van initially travelling at 120 km/h collides with a passenger car at 48.2 km/h. If the delivery van's initial speed is 140 km/h, the collision occurs at 66.6 km/h. As a result of the collision, the maximum volume of vehicle silhouette coverage is 2.38 m³ for a driving speed of 120 km/h and 1.51 m³ for a driving speed of 140 km/h.

5.1.5. Loaded Vehicles—Wet Asphalt

The sequence of events during a vehicle collision on wet asphalt closely resembles that observed in the scenario involving the vehicles moving on dry asphalt. The only difference lies in the magnitude of the post-collision parameters obtained. When the delivery van travels at a speed of 50 km/h, it impacts the safety barrier with the vehicle's front-left section at an angle of 40.5°, 2.88 s after tyre damage. The impact force on the barrier is 379 kN, resulting in the generation of 25.6 kJ of kinetic energy. After rebounding from the

safety barrier, the vehicle begins to roll backward, obstructing the path of the oncoming car, which subsequently collides with it on its right side. The maximum overlapping volume of the vehicle silhouettes in this scenario is 0.77 m^3 . As a result of the collision, the delivery van rotates and comes to a stop in the centre of the roadway, oriented at an angle of 191.2° relative to its original direction of travel. During this time, the car collides with the safety barriers—first with the vehicle front section, and then with the rear—before coming to a complete stop.

At a travel speed of 70 km/h, the delivery van strikes the safety barrier with the vehicle's front-left section, generating an impact force of 465 kN at an angle of 59.5° . Then the vehicle rebounds from the barrier and hits the car on its left side at an angle of 107.8° . This impact results in the maximum overlapping volume of the vehicle silhouettes of 1.21 m^3 . The car gradually decelerates, but in the process, it pushes the delivery van forward. As a result of the process, the delivery van overturns onto its side.

In the scenario where tyre damage occurs at a delivery van speed of 90 km/h, the vehicle impacts the car with its left side at an angle of 47.8° , while simultaneously hitting the safety barrier with the vehicle's front-left section. As a result of high post-impact loads, the delivery van overturns onto its side, while the car comes to a stop in the centre of the roadway.

At delivery van speeds of 120 km/h and 140 km/h, a side collision with the car occurs. In each case, the collision leads to a loss of stability and subsequent rollover of the delivery van. Simultaneously, the car is subjected to inertial forces, causing it to move uncontrollably along the roadway, during which the car impacts the safety barriers several times.

5.1.6. The Depth of Vehicle Body—Loaded Vehicle

Table 2 presents the vehicle body deformation depths recorded under varying vehicle speeds and asphalt surface conditions (dry and wet).

Table 2. Vehicle body deformation depth [mm]—loaded vehicles.

Driving Speed [km/h]	Vehicle 1		Vehicle 2	
	Dry Asphalt	Wet Asphalt	Dry Asphalt	Wet Asphalt
50	557	459	518	449
60	342	381	420	469
70	361	469	400	557
80	459	635	449	723
90	527	723	653	684
100	684	1055	771	771
110	703	1016	811	1211
120	1201	684	1123	1328
130	742	801	1396	1299
140	898	459	1348	498

The data presented in the table show that during a collision on wet asphalt, the delivery vehicle sustains less deformation than on dry asphalt only at speeds of 50, 120, and 140 km/h. In contrast, the passenger car exhibits less deformation on the wet surface when vehicle 1 was travelling at 50, 130, and 140 km/h. At all other speeds, the damage to both vehicles is greater. This situation results from the trajectory of the delivery vehicle after the tyre failure, which was discussed earlier.

When comparing the depth of deformation between unladen and fully loaded vehicles, clear differences can be observed depending on the road surface and driving speed. The fully loaded delivery vehicle travelling on dry asphalt sustained greater damage during the

collision with the passenger car at speeds of 50 and 120 km/h. In contrast, on wet asphalt, the same vehicle experienced less deformation when its speed was 100, 120, and 140 km/h.

The passenger car, on the other hand, suffered more severe damage on dry asphalt when the delivery vehicle was travelling at 50, 130, and 140 km/h. Smaller deformations of the passenger car were recorded on wet asphalt when the delivery vehicle's speed was 90, 100, and 140 km/h.

5.2. Coefficient of Restitution

One of the fundamental parameters used in road accident reconstruction is the coefficient of restitution. The coefficient describes the relationship between vehicle speeds before and after a collision. Thus, the coefficient indicates the degree to which the impact was elastic or inelastic. The parameter enables a precise estimation of the energy dissipated due to deformation, and aids in determining the collision mechanism. The coefficient of restitution is commonly applied in calculations of kinetic energy loss as well as in estimating the initial speed of vehicles, particularly in cases where no braking marks are present. The coefficient depends on several factors, including the vehicle design, deformation zone stiffness, contact geometry, as well as the impact angle, collision speed, and point of contact.

Figure 11 presents the coefficient of restitution as a function of the pre-collision speed of the delivery van, vehicle loading conditions, and road surface conditions.

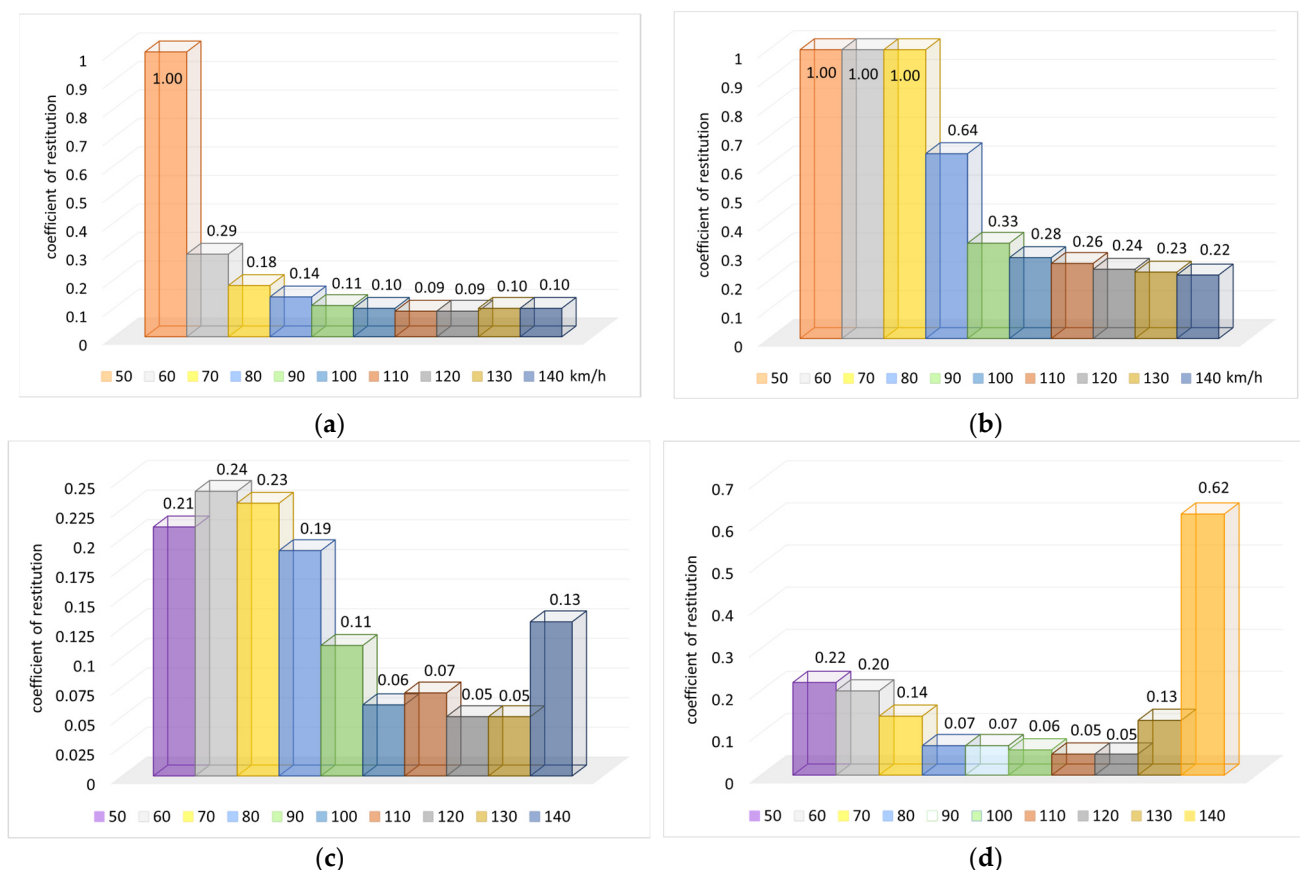


Figure 11. Coefficient of restitution: (a) unladen vehicles, dry asphalt, (b) unladen vehicles, wet asphalt, (c) loaded vehicles, dry asphalt, (d) loaded vehicles, wet asphalt.

5.2.1. Unladen Vehicles—Dry Asphalt

The road collision simulation demonstrated that dry asphalt surfaces provide a high coefficient of adhesion between the tyres and the road surface, which limits skidding and allows for the effective transmission of forces without additional losses. Moreover, unladen

vehicles have a lower total mass, which results in a reduced moment of inertia and limited structural deformation during impact. A collision at a delivery van speed of 50 km/h exhibits an elastic nature, whereas at 60 km/h, the collision becomes partially elastic. At higher speeds, the collision demonstrates a predominantly plastic nature.

5.2.2. Unladen Vehicles—Wet Asphalt

In the case of a wet road surface, the key factor influencing collision dynamics is the reduced coefficient of friction between the tyres and the asphalt. The moment of body contact remains physically comparable to the previously discussed scenario; however, the presence of surface moisture significantly affects the final outcome of the road incident. A potential delay in the timing of vehicle contact, resulting from microskidding, combined with energy redistribution due to lateral and rotational motions, leads to elastic or partially elastic collision behaviour at lower speeds of the delivery van. Only when the vehicle speed exceeds 90 km/h does the collision exhibit a plastic nature.

5.2.3. Loaded Vehicles—Dry Asphalt

An additional vehicle load increases the total system mass, and consequently, the amount of kinetic energy transferred during impact. This added mass amplifies deformation within the deformation zones and influences suspension and damping system performance, leading to greater energy absorption by the vehicle body. An important aspect in this scenario is that the delivery van initially impacts the energy-absorbing barrier, and only subsequently collides with the car. This sequence of impacts significantly reduces the coefficient of restitution. At lower delivery van speeds on dry asphalt, the collision retains a partially elastic nature, whereas at higher velocities, a larger portion of the energy is converted into permanent deformations.

5.2.4. Loaded Vehicles—Wet Asphalt

In the final simulation variant, a combination of effects typically associated with loaded vehicles operating on a wet surface is noted. In this case, a cumulative damping effect is noted, resulting from two key factors: the high kinetic energy associated with vehicle mass and the loss of tyre-road adhesion, which leads to uncontrolled lateral displacements that absorb part of the collision energy. Due to the increased plastic deformations and the limited potential for post-collision motion, the coefficient of restitution for each analysed speed of the delivery van is the lowest among all examined scenarios.

5.3. Kinetic Energy

Kinetic energy is a basic parameter used to assess the consequences of a road incident. In road accident reconstruction, knowledge of this value facilitates the determination of the vehicle speeds prior to the accident.

5.3.1. Unladen Vehicles

Figure 12 presents a diagram illustrating the variation in kinetic energy for unladen vehicles involved in the incident, as a function of the delivery van's speed at the moment of collision with the car.

Simulation results indicate that an unladen delivery van travelling at 50 km/h on dry asphalt generates a kinetic energy of 77.5 kJ at the moment of impact with a car. The corresponding energy in the car is 148.8 kJ. In the case of a collision occurring on wet asphalt, the energy values are 236.8 kJ and 154.6 kJ, respectively. These values are high enough for the consequences of the accident to be noticeable to a person. To illustrate the magnitude of these values, the lowest of them may be compared to a scenario in which a person weighing 80 kg falls from a height of 100 metres. It should therefore be borne in mind that

the kinetic energy of a vehicle at the moment of collision directly translates into the forces acting upon the vehicle's structure and its passengers. For this reason, the vehicle design, particularly the deformation zone, is of critical importance. According to the definition of kinetic energy, it increases linearly with the vehicle's mass and quadratically with the speed. This means that even a relatively small increase in speed results in a significant rise in kinetic energy, which in turn greatly influences the severity of the consequences of accidents.

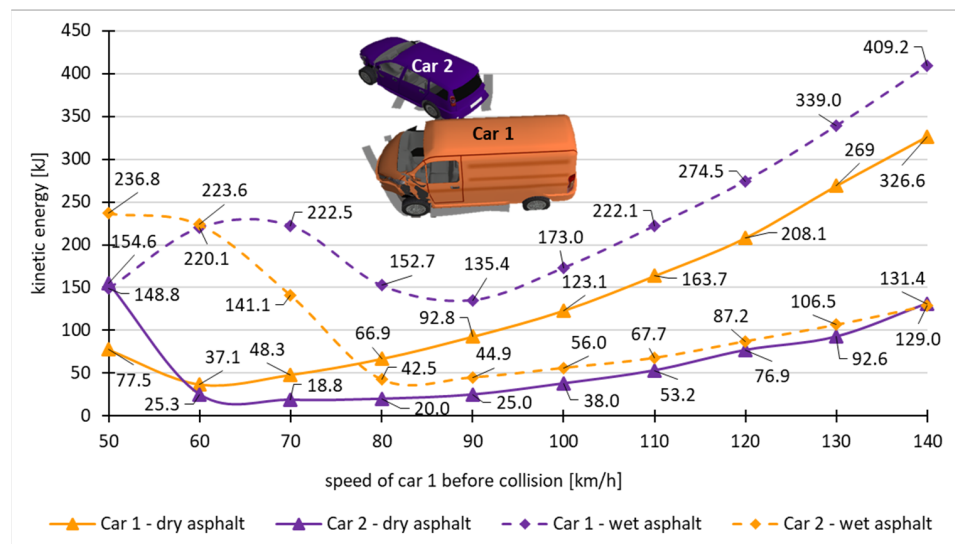


Figure 12. Kinetic energy variation as a function of Vehicle 1 speed—unladen vehicles.

An analysis of the data presented in the diagram confirms that kinetic energy increases exponentially with speed. However, the rate of this increase is also dependent on the point of impact of one vehicle into the other. At the moment of collision, the energy is primarily dissipated through vehicle deformation and the displacement of objects.

5.3.2. Loaded Vehicles

Figure 13 presents a diagram illustrating the variation in kinetic energy for unladen vehicles involved in the incident, as a function of the delivery van's speed at the moment of collision with the car.

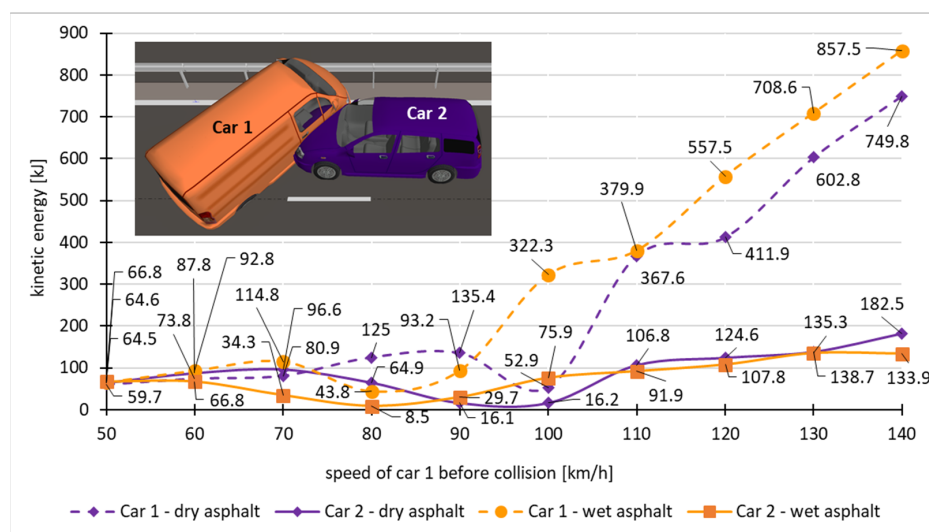


Figure 13. Kinetic energy variation as a function of Vehicle 1 speed—loaded vehicles.

An additional load carried on the vehicle has a significant impact on both the total kinetic energy and the vehicle's dynamic behaviour during the accident. The vehicle load substantially raises the amount of kinetic energy, which directly correlates with the severity of injuries during the collision. Statistically, a loaded vehicle with four passengers may release up to twice the kinetic energy during an accident compared to an unladen vehicle. A greater amount of energy to be dissipated results in higher forces acting during the collision, which in turn can cause more extensive vehicle body deformation and lead to post-impact trajectories that are difficult to control.

The difference in kinetic energy accumulation between loaded and unladen vehicles is clearly noticeable in the diagram above. This disparity becomes particularly evident at vehicle speeds of 100 km/h and above. It is at that speed that the vehicles collided with each other. Below that speed, the delivery van—following tyre damage—first collided with roadside safety barriers before being subsequently hit by the car. This sequence of events causes a partial dissipation of the energy.

As illustrated by the corresponding diagram, wet asphalt acts as an additional factor contributing to increased kinetic energy release during collision. At speeds up to 60 km/h, the differences in energy accumulation during a vehicle collision are not significant, a substantial increase—up to two- or threefold—is noted as the speed rises to 90 km/h. Above 90 km/h, the kinetic energy of Vehicle 1 increases many times, resulting in severe damage scenarios, including the delivery van rollover.

5.4. Resultant Force During the Accident

The magnitude of the force generated during a road incident, further referred to as the resultant force, is a key parameter for determining the extent of vehicle body deformation, as well as the acceleration and speed of the vehicles prior to the collision. This section presents the variation in collision force values as a function of vehicle speed (for both unladen vehicles in Figure 14 and fully loaded ones in Figure 15), in order to illustrate the loads acting on the vehicles and on the occupants inside them. The V-SIM simulation software enables modelling of the forces involved during a collision and the analysis of its consequences. The simulations are based on mathematical models that take into account both the resultant force and the moment of force.

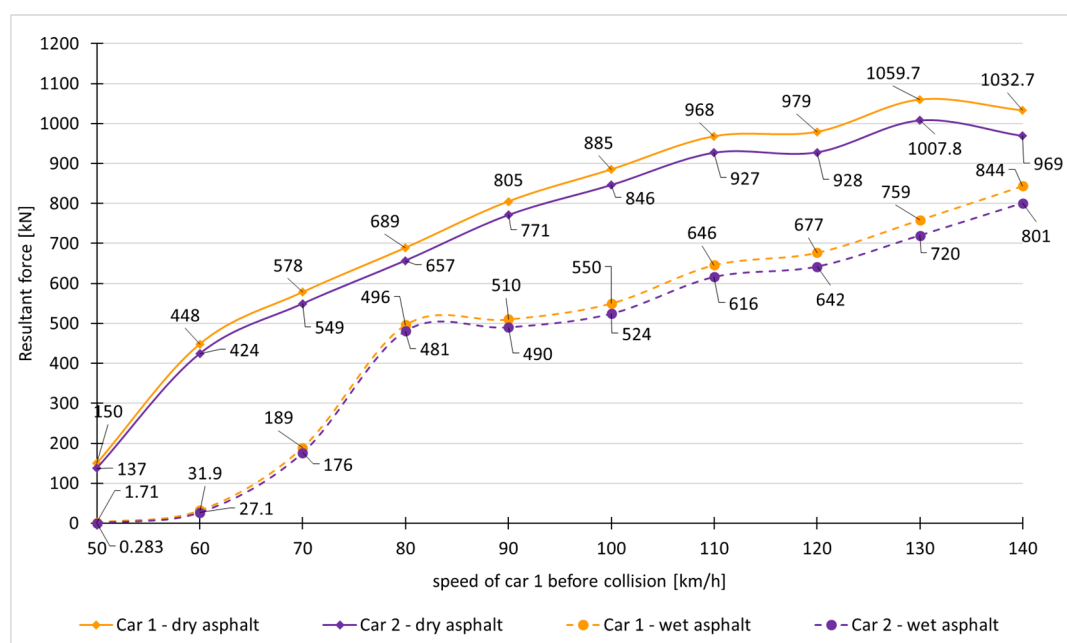


Figure 14. Variation in the resultant force with Vehicle 1 speed—unladen vehicles.

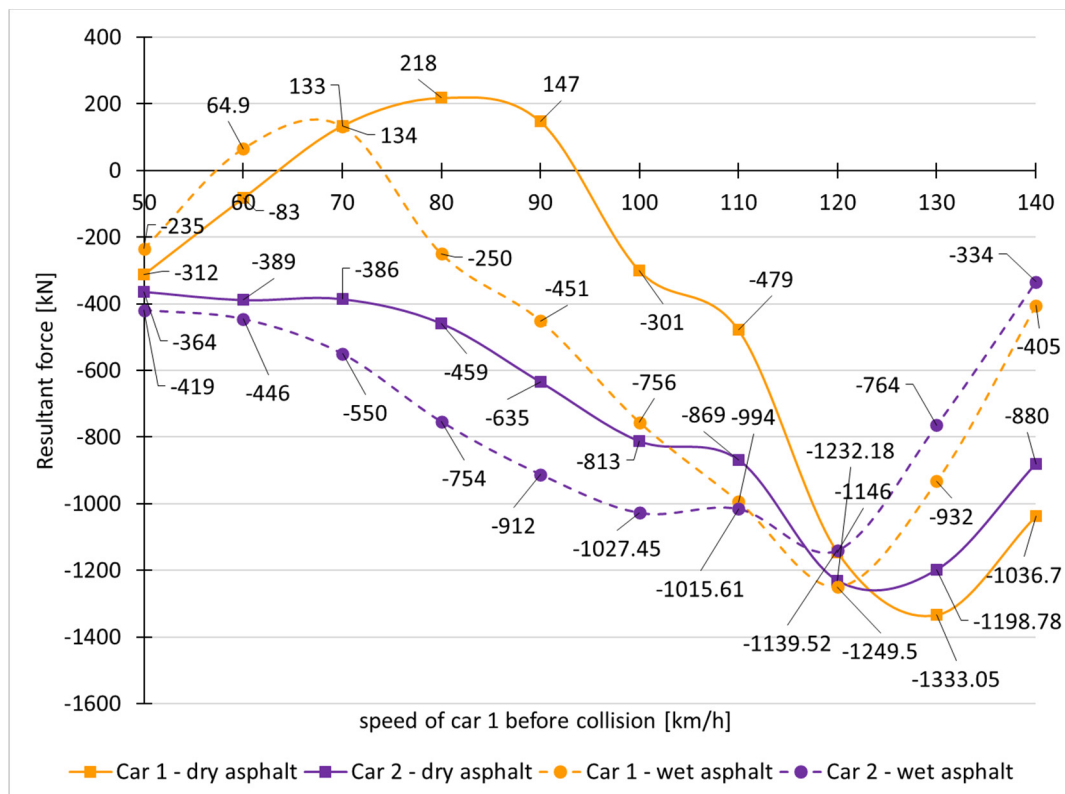


Figure 15. Variation in the resultant force with Vehicle 1 speed—loaded vehicles.

5.4.1. Unladen Vehicles

For unladen vehicles driving on dry asphalt under the simulated conditions, the resultant collision force generated during an impact involving a delivery van travelling at 50 km/h ranges between 137 and 150 kN. These are considerable values for a collision occurring at such a relatively low speed, as they correspond to pressures of approximately 14,000–15,000 kg. Therefore, during a road accident, the collision configuration and the effectiveness of deformation zones in absorbing the kinetic energy associated with such high levels of force are of critical importance.

Further analysis of the diagram indicates that a collision at a vehicle speed of 60 km/h results in force values approximately three times greater than those recorded at the speed discussed previously.

At higher delivery van speeds, the value of the impact force increases in a linear way; however, the differences in magnitude are no longer as significant, with the force increasing by approximately 100 kN for each subsequent speed increment.

For unladen vehicles driving on wet asphalt under the simulated conditions, the resultant collision force generated during an impact involving a delivery van travelling at 50 km/h ranges between 0.3 and 1.7 kN. This represents a significant difference, up to a hundredfold, compared to the force magnitudes observed for analogous speeds on dry asphalt. The force values recorded for other speeds are also lower, with a maximum value not exceeding 900 kN at a speed of 140 km/h. In the vehicle speed range of 50 to 80 km/h, the resultant forces generated during the collision increase by a factor of three to four. It is only beyond a delivery van speed of 90 km/h that these forces begin to increase by approximately 10% each time.

5.4.2. Loaded Vehicles

Loaded vehicles behave entirely differently during a collision, as previously demonstrated. The resultant forces varying with the speed of Vehicle 1 also exhibit an irregular pattern in this case, as illustrated in Figure 15.

The magnitude of resultant forces generated during a collision involving loaded vehicles, whether driven on dry or wet asphalt, is significantly greater compared to the forces observed in collisions involving unladen vehicles. The minimum recorded value of the resultant force for Vehicle 1, travelling at 50 km/h, is 235 kN and is noted for the vehicle driven on wet asphalt.

An analysis of the diagram reveals that Vehicle 2 consistently exhibits negative resultant force values, regardless of the examined speed of Vehicle 1 or road conditions. In contrast, the delivery van demonstrates such resultant force values only at speeds below 60 km/h and above 95 km/h when driven on dry asphalt, and below 58 km/h and above 75 km/h when driven on wet asphalt.

The negative force values observed in the diagram result from the post-collision direction of vehicle motion. A negative sign indicates that, immediately after the impact with the other vehicle, the given vehicle moved in the direction opposite to its initial trajectory under the influence of the dynamic reaction to a sudden stop or a high-intensity collision. This phenomenon is commonly referred to as the recoil force.

6. Summary

The aim of this article was to assess the impact of sudden tyre failure on road safety and on the dynamics of vehicles involved in a traffic incident, with particular emphasis on driving speed, road surface condition, and vehicle load.

Simulation results demonstrated that sudden tyre failure leads to an immediate loss of vehicle stability and a rapid deviation from the intended trajectory, with the driver's available reaction time depending on speed. At 50 km/h, this reaction time was approximately 3.14 s, whereas at 140 km/h it decreased to just 1.63 s, practically preventing effective evasive action and collision avoidance. As vehicle speed increased, the severity of the collision also rose significantly, as reflected by the volume of vehicle silhouette overlap, which increased from 0.24 m³ at 50 km/h to over 1.60 m³ at speeds of 120–140 km/h. Such high values indicate a substantial level of deformation in the load-bearing structures of the vehicles.

Road surface conditions had a significant influence on the course of the incident. On wet asphalt surfaces, particularly at lower speeds, smaller depths of vehicle body deformation were observed. This phenomenon resulted from the earlier onset of skidding of the delivery vehicle and the partial dissipation of kinetic energy prior to contact with the other vehicle. At the same time, however, a wet surface led to a more unpredictable course of the incident, with multiple changes in travel direction and repeated impacts with energy-absorbing barriers. This increased the extent of secondary damage and may contribute to the occurrence of subsequent collisions.

Full vehicle loading resulted in increased kinetic energy and higher forces acting during the collision. The additional load caused an increase in body deformation of up to as much as 25–30% compared to unladen vehicles, particularly on a dry road surface. Under these conditions, the delivery vehicle frequently overturned onto its side or rolled over, clearly indicating the extremely hazardous nature of such events.

The values of kinetic energy and collision forces further confirmed the scale of the hazard. For unladen vehicles on a dry surface at 50 km/h, the collision force ranged from 137 to 150 kN, while at 60 km/h that force increased nearly threefold. In the case of loaded vehicles, these values exceeded 650 kN at 70 km/h and reached levels above 1 MN at

the highest speeds. Such high loads imply a substantial risk of severe occupant injuries and total vehicle destruction. Furthermore, the analysis of the coefficient of restitution demonstrated that, with increasing vehicle speed and mass, collisions rapidly assume a highly plastic character, indicating the dominance of permanent deformations and significant energy losses.

The analysis of statistical data obtained from regional vehicle inspection stations confirms that improper tyre technical condition is a widespread and growing problem in everyday vehicle operation. Diagnostic test results from 2021 to 2025 indicate that each year, approximately 20–30% of vehicles inspected at these stations fail to pass technical inspections due to various types of tyre damage. The most frequently identified irregularity was excessive tread wear, which significantly exceeded the occurrence of other defects such as fatigue cracks, tyre bulges, and other structural damage.

7. Conclusions

The conducted simulations confirmed that tyre technical condition is a critical factor for driving safety, and that sudden tyre failure represents one of the most hazardous road incident scenarios. At speeds exceeding 90 km/h, loss of vehicle control becomes nearly inevitable, and the consequences of such events—particularly under full vehicle load and on surfaces with reduced adhesion—are catastrophic in nature.

The research findings clearly indicate the necessity for regular and thorough tyre inspections, not limited to pressure checks but also encompassing the detection of cracks, bulges, and tread wear. According to the statistical analysis, these defects constitute one of the primary causes of road traffic hazards.

Projections based on linear trend analyses indicate a consistent increase in the incidence of detected tyre defects over the coming years, with the growth rate varying according to defect type.

Tyre damage that is routinely identified during technical inspections may, under real-life operational conditions, precipitate traffic incidents with severe consequences, particularly at vehicle speeds exceeding 80–90 km/h. Simulations have demonstrated that even a single, ostensibly localised tyre defect can induce sudden vehicle instability, resulting in frontal or side-impact collisions and a potential rollover, directly aligning with the defect patterns documented by vehicle diagnostic technicians. This indicates that statistical data from vehicle inspection stations not only serve as indicators of vehicle technical condition but also provide a realistic reflection of the level of risk present in road traffic.

Accordingly, it is appropriate to underline a need to enhance preventive measures and increase vehicle users' awareness regarding tyre inspection. The test results suggest that reliance solely on tyre pressure monitoring systems is insufficient, as these systems do not detect tyre damage.

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