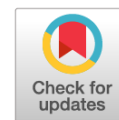


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Expert Methods for Determining the Speed of a Vehicle at the Moment of Collision With a Pedestrian: Current State of the Issue (A Review)

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ABSTRACT

Knowing the vehicle's speed at the moment of collision with a pedestrian is essential for investigators and law enforcement officers to lawfully and accurately interpret the driver's actions and contributing factors during a traffic accident. However, only a few objective methods for determining vehicle speed are applicable in expert practice.

This article examines the current state of this issue based on a review of contemporary Russian and international scientific sources. Existing methods are examined based on their core principle. It is shown that objective assessment of a vehicle's speed at the moment of impact with a stationary obstacle (a pedestrian) is a complex task that requires the use of several approaches with varying degrees of applicability. Further research is needed into the morphological analysis of the conditions and circumstances of traffic accidents involving a moving vehicle and a stationary pedestrian, taking into account the design features of modern vehicles. This will contribute not only to a more thorough and objective investigation of road traffic accidents, but also to the advancement of forensic medicine.

Keywords: traffic accident; vehicle; pedestrian; collision; speed; diagnostics; review.

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Экспертные методы установления скорости движения автотранспортного средства в момент столкновения его с пешеходом: современное состояние вопроса (обзор)

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АННОТАЦИЯ

Знание скорости транспортного средства в момент столкновения его с пешеходом необходимо сотруднику органов следствия и дознания, для того чтобы юридически верно интерпретировать действия водителя в дорожно-транспортном происшествии и факторы, к нему приведшие. Вместе с тем существует лишь небольшое число объективных методов установления скорости движения автомобиля, применимых в экспертной практике.

В статье на основе анализа современной отечественной и зарубежной литературы приведён анализ состояния указанной проблемы. Существующие методы рассмотрены в соответствии с главным принципом, положенным в основу каждого из них. Показано, что объективная оценка скорости транспортного средства в момент столкновения с неподвижной преградой (пешеходом) представляет сложную задачу, требующую применения множества разнообразных подходов, обладающих различной степенью применимости. Сделан вывод о необходимости проведения дальнейших исследований в области «морфологической» диагностики условий и обстоятельств дорожно-транспортных происшествий, связанных со столкновением движущегося автомобиля со стоящим пешеходом, с учётом актуальных конструктивных особенностей современных автотранспортных средств. Это будет способствовать не только всесторонней объективизации расследования дорожно-транспортных происшествий, но и дальнейшему развитию судебно-медицинской науки.

Ключевые слова: дорожно-транспортное происшествие; автомобиль; пешеход; столкновение; скорость; диагностика; обзор.

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机动车在与行人碰撞瞬间行驶速度的鉴定方法：问题的现状综述

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摘要

在机动车与行人发生碰撞的道路交通事故中，明确碰撞瞬间的车辆行驶速度对侦查和调查人员依法准确判断驾驶员行为及事故成因具有重要意义。然而，目前适用于鉴定实践的客观测定车辆速度的方法数量有限。

本文基于对俄罗斯及国外文献的综合分析，评述了该问题的研究现状。现有方法根据各自所依据的基本原理进行了分析。研究指出，客观评估车辆在与静止障碍物（如行人）碰撞时的速度是一个复杂任务，需综合运用多种适用性不同的方法。指出有必要在“形态学”诊断领域开展进一步研究，以考虑现代机动车的结构特点，明确与静止行人碰撞的道路交通事故的条件与情形。这不仅有助于实现交通事故调查的全面客观化，也将推动法医学研究的进一步发展。

关键词：道路交通事故；机动车；行人；碰撞；速度；鉴定方法；审查。

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INTRODUCTION

Forensic medical evaluation of traffic accident victims, both surviving and deceased, is a major part of everyday practice for forensic experts.

Specific expertise is essential for an objective preliminary investigation, as well as for obtaining and expanding evidence [1]. Therefore, a timely forensic examination with high quality maintained at all stages is critical for the investigation to reconstruct a traffic accident and understand the circumstances of the death. Given the extensive published data and advancements in forensic medicine, investigatory tasks such as assigning cause of death, determining the association between detected bodily injuries and the traffic accident, and identifying a specific injury type (traffic accident injury or other) are typically not difficult for forensic experts [1].

However, determining the vehicle's speed during a traffic accident is far more challenging. This is especially relevant in cases of collision of a moving vehicle with a stationary pedestrian, which frequently results in the death of the latter. The second person involved, as an interested party, may attempt to evade responsibility and mislead the investigator by reducing the vehicle's speed in their statement.

Official statistics in Russia confirm the relevance of this issue. According to the 2023 State Report,¹ 25% (3543) of fatal traffic accident victims were pedestrians. Of these, two-thirds (63.7%) died at the scene before the ambulance arrived. Furthermore, every fourth pedestrian victim is a child.

Such accidents typically last for fractions of a second (0.729 s on average), further complicating accurate and objective traffic accident reconstruction [2, 3]. Therefore, even if witnesses are present, their statements may be inaccurate due to individual perceptions and specific traffic accident conditions, such as lighting, distance to the object, weather, and personal involvement. At the same times, witnesses frequently perceive their statements as completely reliable, despite potential inaccuracies [4]. For example, during the first recorded fatal pedestrian accident, which occurred in London in 1896, witnesses stated that the car went at great speed, when it actually did not exceed 8 miles per hour (12.8 km/h) [5].

Therefore, witness statements cannot be considered objective, and a mandatory confirmation is required. For a successful traffic accident investigation, the vehicle's speed during the collision with a pedestrian must be accurately determined using evidence-based methods [4].

Automotive forensic examination findings are used for this purpose. However, available forensic techniques are limited, and their practical use necessitates an extensive search in numerous publications detailing them.

Therefore, this review was conducted to summarize available scientific evidence that can be used in forensic examinations to objectively determine the vehicle's speed in cases of collision with a stationary pedestrian.

SEARCH METHODOLOGY

The search was performed in the *Medline (PubMed)* and *Scopus* electronic databases. The following search terms were used:

- *car speed determination* (43,966 publications);
- *car speed during car accident* (11,776 publications);
- *vehicle speed during collision* (10,840 publications);
- *car speed road traffic accidents* (5751 publications), and
- *car-pedestrian collision* (80 publications).

Each set of search results was screened for relevant publications. Full-text versions of the identified publications were assessed (where available). Publication without full text access were excluded, because the available abstracts lacked the required descriptions of specific techniques and formulas for calculating vehicle speed during a collision with a pedestrian.

The search for publications in Russian was conducted in the *eLIBRARY.RU* database. The following search terms were used:

- *скорость автомобиля / car speed* (104,288 publications);
- *определение скорости автомобиля / car speed determination* (89,612 publications);
- *автомобильная травма / motor vehicle injury* (16,872 publications);
- *наезд автомобиля / car-pedestrian collision* (11,192 publications), and
- *повреждения пешехода при наезде / pedestrian injuries* (2431 publications).

Furthermore, a search was conducted in the electronic research library of the Izhevsk State Medical Academy and the research library of the Department of Forensic Medicine with a course in forensic histology of the Academy's Faculty of Advanced Training and Professional Retraining. The search methodology was similar to that for international publications.

The review identified and systematized techniques for determining the moving vehicle speed during a collision with a stationary pedestrian, which may be useful in forensic examinations.

For convenience, we assigned all methods discussed in the review to conditional groups based on their key characteristics. This grouping provides more structured information, facilitating its comprehension and subsequent practical use.

¹ State Report on Road Traffic Safety in the Russian Federation [presentation]. Moscow: Main Directorate for Traffic Safety of the Ministry of Internal Affairs of Russia, Research Center for Road Traffic Safety of the Ministry of Internal Affairs of Russia, 2023. Available at: <https://госавтоинспекция.рф/original/downloads/gd2023.pdf>. Accessed on: February 15, 2025.

DETERMINING VEHICLE SPEED BASED ON BRAKING DISTANCE

If the case files contain data on braking tracks and their length, the vehicle's speed prior to collision can be calculated [6]. However, this method only estimates the minimal vehicle speed immediately before braking. An accurate calculation requires objective information that allows determining the vehicle's kinetic energy consumption from braking to a complete stop [7].

We identified nine methods for determining vehicle speed based on braking distance in available publications [8]. All these methods have long been used with sufficient efficacy; however, only one of them allows calculating a vehicle's speed at the moment of impact with a stationary obstacle:

$$S_T = S_{IO} + \frac{V_a \times T_3}{7,2}, \quad (1)$$

where S_T is the distance traveled by the vehicle from braking to collision with the obstacle, m; S_{IO} is braking track length, m; V_a is the vehicle's speed before braking, km/h; T_3 is deceleration time in emergency braking, s;

$$V_y = \sqrt{V_a^2 - 25,92 \times S_T \times j}, \quad (2)$$

where S_T is the distance traveled by the vehicle from braking to collision with the obstacle, m; V_a is the vehicle's speed before braking, km/h; j is deceleration during braking, m/s²; V_y is the vehicle's speed during collision, km/h.

In this case, a calculation requires specific, reliable information obtained directly at the traffic accident scene. The distance traveled by the vehicle from braking to collision with a stationary obstacle (S_T) and braking track length (S_{IO}) must be known [8].

Another formula also uses the braking track length to calculate the vehicle's speed before braking [9, 10]:

$$V = \sqrt{254 \times \varphi \times S}, \quad (3)$$

where V is the vehicle's speed before collision with the obstacle, km/h; 254 is vehicle speed conversion factor; φ is tire-to-surface friction coefficient; S is braking distance, m.

This method does not take into account the car model, weight, and axle load distribution. However, the calculations will only be reliable if the vehicle has brakes acting on all wheels, braking is continuous until a complete stop, and it occurs strictly in the horizontal plane. This formula is only applicable for calculating vehicle speed during a collision with a pedestrian when the energy absorbed by the latter is negligible [9, 10].

The proposed methods are not infallible, and their efficacy depends on the design features of modern vehicles and a specific traffic accident. Specifically, if a vehicle has an anti-lock braking system, which has become a mandatory safety requirement in recent years, it may leave no braking tracks at the traffic accident scene. Furthermore, braking

tracks may be absent when the road is wet or covered in snow. Prolonged, heavy precipitation or other vehicles may destroy evidence at a traffic accident scene. Finally, drivers do not always brake before a collision [6]. In such cases, calculating the vehicle's speed is impossible due to a lack of the necessary numerical values.

DETERMINING VEHICLE SPEED BASED ON COLLISION-INDUCED DEFORMATIONS

This method is based on the physical laws of impact theory. The results depend on the geometry of vehicle components, mechanical properties of the materials, and the type and degree of collision-induced deformations. Furthermore, the method only applies to the vehicle [11].

To calculate the vehicle's speed at the moment of collision, it is essential to know the amount of kinetic energy that is released during impact and expended on the deformation of vehicle components. This is determined by the nature of mechanical damage induced by collision with an obstacle. If this condition is met, the vehicle's speed before collision with an obstacle is calculated as follows [11]:

$$V = 0,5t_3 \times j + \sqrt{2S \times j + \frac{2U}{m - \Delta m} + 19,5 \times \varphi \times S}, \quad (4)$$

where V is the vehicle's speed before collision with the obstacle, km/h; U is potential energy of deformation of vehicle body components, %; m is the vehicle's weight, kg; Δm is the portion of the vehicle's weight that does not influence kinetic energy changes during impact, kg; φ is tire-to-surface friction coefficient; S is the path length of the vehicle's center of mass after collision, m; t_3 is deceleration time in emergency braking under examined road conditions, s; j is maximum deceleration in emergency braking under examined road conditions, m/s².

This method for calculating vehicle speed during collision with an obstacle, like the previous one, has certain drawbacks. The primary limitation is the need for precise information on the geometry of vehicle body components prior to collision-induced deformation, as well as their stiffness and coefficient of restitution. This condition significantly limits the method's applicability because these parameters can only be precisely known for a brand-new car. This method cannot be used in cases of corrosion caused by long-term use or vehicle body components restored following previous traffic accidents, because detecting changes in structural characteristics becomes extremely difficult [11].

VIDEO RECORDING METHODS

Video recording methods have become available owing to the widespread use of surveillance cameras, personal dashboard cameras, and camera phones used by witnesses to capture traffic accidents. Video records enable direct vehicle speed determination based on the immediate perception of the captured traffic accident and laws of dynamics [12].

The vehicle's speed is determined by calculating its movement over a distance equal to its length. The video record is used to determine the car model and technical specifications (length). During subsequent video footage analysis, a fragment is selected where the vehicle crosses a stationary object, which serves as a landmark. When selecting a landmark, it must be possible to determine its precise dimensions. These will be used later to assess the vehicle's movement relative to the selected stationary object. The number of frames required for a moving vehicle to completely cross the landmark is calculated. The video record's frame rate is then used to calculate the moving vehicle speed [12]:

$$V = L \times \frac{f_k}{n}, \quad (5)$$

where V is the vehicle's speed before collision with the obstacle, km/h; L is the vehicle's length, m; f_k is the frame rate of the video record; n is the number of frames required for the vehicle to travel its length.

One modification of this method is calculating vehicle speed based on dashboard camera footage [13]. In this case, the vehicle movement between two stationary objects is assessed by visual analysis of the video footage:

Object 1: a road infrastructure component, a stationary vehicle, or a tree by the roadside;

Object 2: the pedestrian, who can be considered a stationary object, because they frequently move perpendicular to the vehicle (e.g., when crossing the road); therefore, the pedestrian's speed is equal to zero relative to the vehicle. To do a calculation, the video record duration and frame rate (frames per second) must be determined.

The distance (S) between stationary objects in the video footage must be measured at the traffic accident scene. The subsequent video footage analysis determines the number of frames (n) required for the vehicle to travel the distance between these objects.

If the frame time (t) is known, the formula by Tarasov (6) can be used to calculate the vehicle's speed [13]:

$$V = 3,6 \times \frac{S}{n} \times t, \quad (6)$$

where V is the vehicle's speed, m/s; S is the distance between objects, m; t is frame time, s; n is the number of frames required for the vehicle to travel between the captured stationary objects.

PAL², the most widely used video record standard globally, has a frame rate of 25 frames per second and a frame time of 0.04 s [14]. To convert m/s to km/h, the result must be multiplied by 3.6.

These are fairly simple calculation methods; however, they are not perfect either, because video recording at the traffic accident scene is not always the case. Furthermore, weather

and lighting conditions may limit the quality of traffic camera footage, which provides valuable information on traffic accidents [15].

DETERMINING VEHICLE SPEED BASED ON ELECTRONIC CONTROL MODULE DATA

Data indicating the vehicle's speed before collision can be collected from airbag control modules [6, 16], tachographs, navigation systems and GLONASSGPS-based equipment [17], and the electronic engine control unit [18].

Electronic control modules, such as the airbag control unit (ACU) [16] and the engine control module (EMC) [18], store information on vehicle movement parameters at the time of recording a trouble code during a traffic accident.

These electronic units have long-term memory elements to save multiple parameters that are essential for car engine operation, taking into account changes in external and internal conditions. These parameters include the vehicle's speed at a specific time point. If specialized technical means are available, a forensic expert can extract and analyze data from the vehicle's control modules.

However, this method is not infallible as well, because the vehicle may be absent at the scene or damaged to the point where data extraction from control modules is impossible (e.g., in cases of vehicle fire).

Therefore, all vehicle speed determination methods described above have certain limitations. Furthermore, their use is limited to automotive forensic examination.

However, the second person involved in the traffic accident, the pedestrian who was injured in the collision with the vehicle, must also be considered.

DETERMINING VEHICLE SPEED BASED ON TRAFFIC ACCIDENT INJURY CHARACTERISTICS

Forensic evaluation of vehicle speed based on the type and severity of pedestrian injuries is challenging due to a lack of appropriately developed techniques [19]. Specialist scientific publications contain data on vehicle speed parameters relative to the severity of pedestrian injuries and fatal outcome, as well as some data that enable determining vehicle speed by the site, type, and morphology of traffic accident injuries. However, these data are inconsistent, which prevents definitive conclusions [20].

According to Smirenin et al. [21], pedestrian injuries typically occur at a relatively low speed (25–50 km/h). Lastovetsky et al. [22] assume that a pedestrian can survive if the vehicle's speed does not exceed 15–20 km/h, whereas a speed of 60 km/h almost always results in a fatal outcome.

² Phase Alternating Line (PAL) is a color encoding system for analog television that is used in the majority of countries in Europe (including Russia), Asia, Africa, and other regions.

Bazanov et al. [23] assessed the probability of fatal pedestrian injuries based on the car's speed during the collision. The authors reported a direct association between the speed of a vehicle with a known weight and the severity of pedestrian injuries, including fatal outcome. A car's speed of 5 km/h during a collision with a pedestrian results in a 1% probability of fatal injuries, which increases exponentially with speed, reaching 100% at a speed of 90 km/h.

Losev [24] proposes the following formula for calculating car speed during a collision with a stationary pedestrian:

$$V = \sqrt{V_a^2 - 26j \left[S_a - (t_1 + t_2 + 0,5t_3) \frac{V_a}{3,6} \right]}, \quad (7)$$

where V is the vehicle's speed during collision with the obstacle, km/h; j is the vehicle's deceleration, m; t_1 is differential driver reaction time, s; t_2 is standard delay time of the vehicle's brake actuator, s; t_3 is standard deceleration time, s; V_a is the vehicle's speed at the time the hazard occurred, km/h; S_a is the distance between the vehicle and the collision site at the time the hazard occurred, m.

According to the author, the hypothetical vehicle speed during a collision with a pedestrian calculated by this method can be later used by investigators for an objective legal assessment of the driver's actions. This assessment is possible in the presence or absence of a causal relationship between the driver's actions during the traffic accident and the resulting pedestrian injuries [24].

Povertovsky [25] proposes calculating vehicle speed based on the force of impact:

$$V_k - V_p = \frac{F \times t}{m}, \quad (8)$$

where F is force, kgf; $V_k - V_p$ is deceleration per 0.0015 s, m/s; m is weight, kgf×s²/m; t is deceleration time (0.0015), s.

The method assumes that the force of impact is equal to the product of the object's weight and acceleration (deceleration time is the time interval between the initial and final speeds) over a period of 0.0015 s [25]. However, it does not always allow determining vehicle speed during a collision with a pedestrian, because it is typically impossible to assess the deceleration within 0.0015 s.

Gromov et al. [26] proposed the following formula for determining the traumatic force (9), which enables calculating vehicle speed (10):

$$T = (1 - K^2) \times \frac{mv_{x_0}^2}{2}, \quad (9)$$

where T is impact work, kgf×m; K is coefficient of restitution; m is head weight, kgf×s²/m; v_{x_0} is impact speed, m/s;

$$V = \sqrt{\frac{2T}{(1 - K^2) \times m}}, \quad (10)$$

where V is vehicle speed, m/s; T is impact work, kgf×m; K is coefficient of restitution; m is head weight, kgf×s²/m.

However, this method only applies to calculating object (victim) speed during impact with a stationary obstacle (e.g., in forensic medical evaluation of in-vehicle injuries). This

is because the force of impact was calculated in experiments using crash test dummies, which were put in motion for a subsequent impact with a stationary obstacle [26].

According to Dürwald [27], a vehicle's force of impact is proportional to the weight of the colliding bodies and the square of the speed, and inversely proportional to the distance the victim's body is thrown. Therefore, the square of the vehicle's speed is the quotient of the product of the distance the body is thrown by the force of impact and the weight:

$$V = \sqrt{\frac{2 \times F \times S}{m}}, \quad (11)$$

where V is vehicle speed, m/s; F is force of impact, kgf; S is distance the victim's body is thrown, m; m is weight, kgf×s²/m.

However, this method can only be used if the distance the pedestrian's body is thrown after impact is known.

Steshin [28] determined the traumatic force F_{oep} (the fraction of impact energy needed to produce injury) using the known speed, as well as the vehicle and pedestrian weight. If braking tracks of the offending vehicle are present at the scene, its speed can be calculated as follows:

$$v = V_0 \sqrt{1 - \frac{x}{S}}, \quad (12)$$

where V is the vehicle's speed during collision with the stationary obstacle (pedestrian), m/s; V_0 is the initial vehicle speed, m/s; x is the distance from braking to collision with the obstacle, m; S is braking distance, m.

Based on the established vehicle speed, the force that caused deformation of vehicle components and pedestrian injuries can be calculated:

$$F_{oep} = K \times \frac{G \times v^2}{254}, \quad (13)$$

where G is vehicle weight, kgf×s²/m; v is vehicle speed, m/s; K is the ratio of pedestrian weight to the sum of pedestrian and vehicle weights; 254 is vehicle speed conversion factor (m/s to km/h, taking into account gravitational acceleration [3.62×g×2]).

In this case, the relationship between the severity of pedestrian injuries and vehicle speed can be determined by comparing the known vehicle speed, corresponding traumatic forces, and the type and severity of pedestrian injuries, taking into account the vehicle and pedestrian weights.

However, the author calculated the traumatic force using the known vehicle speed, rather than the minimum possible speed that can result in a specific injury. Therefore, the same injury may be caused by a vehicle moving at a lower speed [28].

Furthermore, this method only applies when the vehicle was braking during the accident, as indicated by the vehicle speed conversion factor of 254, which converts m/s to km/h, taking into account gravitational acceleration (g, 9.8 m/s). Gravitational acceleration (g) is not taken into account when a vehicle moves uniformly and linearly on a horizontal surface

without braking. This follows from the Newton's second law, according to which the acceleration is directly proportional to the acting force, or, as Newton originally stated: "The change of motion of an object is proportional to the force impressed; and is made in the direction of the straight line in which the force is impressed" [29]. If the vectors of acting forces are perpendicular to each other, their combined action is equivalent to a single resultant force acting along a specific straight line. Therefore, when a solid object moves in a specific field, its effect is limited to the action of a single force applied at a point with a radius vector. For example, in a uniform gravity field, the constant vector is gravitational acceleration (g), whereas in horizontal motion, the vector is speed (V) [30]. When an object moves uniformly and linearly in a horizontal plane (a vehicle moving at a constant speed), the gravity vector is inversely proportional to the support reaction force vector and perpendicular to the object's movement direction. Therefore, the gravitation work equals to zero: it is perpendicular to the movement direction ($\cos(90^\circ) = 0$), hence the gravitational acceleration is also zero [31]. Thus, if the vehicle did not brake before collision, the vehicle speed conversion factor of 254 is not applicable, and the formula (13) is not acceptable for objective assessment of constant vehicle speed (without deceleration).

Furthermore, the absence of braking tracks at the scene prevents definitive conclusions on whether the driver was braking before a collision with a pedestrian.

Determining vehicle speed during a collision with a stationary pedestrian is challenging and requires a comprehensive forensic examination involving forensic medical experts, forensic specialists, and automotive forensic examination specialists. This examination aims to reconstruct a traffic accident by assessing the scene. Experts reconstruct the traffic accident based on the tracks and damage to both the vehicle and the pedestrian [32]. Definitive, objective conclusions on the investigator's inquiries are only possible if all aspects of the traffic accidents are thoroughly, accurately, and objectively examined [33].

CONCLUSION

Existing methods for determining vehicle speed during a collision with a pedestrian primarily rely on technological advancements in objective recording of the circumstances of a traffic accident. However, the biological aspects of the issue remain understudied. Available approaches are based on pedestrian injury analysis and determination of the external force required to inflict these injuries, which is then compared to the offending vehicle's characteristics and speed. They currently do not provide sufficient accuracy and objectivity of the required calculations.

Further research is needed into the morphological analysis of the conditions and circumstances of traffic accidents involving a moving vehicle and a stationary pedestrian, taking into account the design features of modern vehicles.

This will contribute not only to a more thorough and objective investigation of road traffic accidents, but also to the advancement of forensic medicine.

ADDITIONAL INFORMATION

Author contributions: A.Yu. Vavilov: conceptualization, writing—review & editing; D.N. Vasilev: conceptualization, investigation, writing—original draft; M.I. Timerzyanov: investigation, writing—review & editing. All the authors approved the version of the manuscript to be published and agreed to be accountable for all aspects of the work, ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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