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Surface Transportation Engineering Technology

IMPROVING THE ACCURACY OF STIFFNESS COEFFICIENT CALCULATION WHEN ESTIMATING THE KINETIC ENERGY SPENT ON VEHICLE DEFORMATION

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Abstract

Introduction: The paper addresses a method to estimate the kinetic energy spent on deformations and the vehicle speed equivalent to such value during the reconstruction of road accidents. **Purpose of the study:** The study is aimed at improving coefficients used in the method and affecting the vehicle speed at the instant of a collision. **Methods:** The damage analysis algorithm measures the vehicle deformation to estimate the energy required to produce the measured vehicle damage, with regard to the principle of momentum conservation. **Results:** The stiffness coefficients used were developed long before the appearance of modern vehicles. Therefore, the authors propose to substitute the stiffness coefficients used for those considering modern trends in the automobile industry and ensuring much simpler and more direct calculation. It saves us the trouble to reduce experimental results to the formulation of force deflection and makes it possible to simulate damage behavior directly. The authors also describe the scope of application for the proposed coefficients, and restrictions of their use.

Keywords

Vehicle speed, road accident, road accident reconstruction, kinetic energy, vehicle stiffness, vehicle stiffness coefficients.

Introduction

The existing method for the reconstruction of road accidents (CRASH3) includes two separate and independent algorithms based on:

1) analyzing the trajectory of a vehicle involved in the accident (trajectory analysis);

2) analyzing vehicle deformations (damage analysis).

Both algorithms assume that the impact is instantaneous and that at some instant of time during the impact both vehicles reach a common velocity. Due to these assumptions, the CRASH3 method cannot be used to reconstruct road accidents involving rollovers, multiple impacts to the same area (superposition of deformations), towing of a trailer or another vehicle (Dobromirov and Evtyukov, 2016).

The trajectory analysis algorithm is based on work–energy relationships for the spinout trajectory and the principle of conservation of linear momentum for the collision. The velocity is estimated using data on the final rest location, skid marks, friction coefficient, and point of impact. Then, momentum equations are used to calculate the impact speed and the difference between the vehicle speeds (Lan, Crawford and Xin, 2006).

In case of impacts, where the line of action of the collision force is not perpendicular to the involved side, the algorithm uses the spinout trajectory and the principle of conservation of linear momentum to calculate the impact speeds and the difference between the vehicle speeds. The damage analysis algorithm is also used for such calculations. The difference between the vehicle speeds obtained using these two algorithms is rarely the same (Evtyukov and Vasilyev, 2015). However, it can be assumed that the difference between those two estimates is satisfactory when the results differ in not more than 4 km/h or 10% (Evtyukov and Golov, 2019).

Due to the fact that a considerable amount of time passes between the accident and the beginning of the expert examination, and most pieces of evidence, e.g. tire marks (besides, vehicles equipped with an anti-lock braking system (ABS) usually do not leave clearly visible skid marks at the accident site), cannot be recorded, experts rarely use this trajectory analysis algorithm.

Subject, tasks, and methods

During damage analysis, the vehicle deformation is measured to estimate the energy required to produce the vehicle damage, with regard to the theory of momentum conservation.

At first, stiffness coefficient A is determined based on crash test results and using the following equation:

$$\mathrm{A} = \frac{m_t \times v_{min} \times b_1}{3.6^2 \times L_t}, \quad (1)$$

where:

m_t is the actual vehicle mass before its use in the crash test, kg;

L_t is the width of the measured area of the test vehicle volumetric deformation, m;

V_{min} is the minimum speed of the vehicle hitting a deformable barrier when the volumetric deformation still does not occur, km/h;

b_1 is the share of speed distribution over the contact area, (km/h)/m.

Then, stiffness coefficient B is determined based on crash test results:

$$B = \frac{m_t \times b_1^2}{3.6^2 \times L_t}. \quad (2)$$

The share of speed distribution over the contact area is calculated by the following equation:

$$b_1 = \frac{v_t - v_{min}}{C_{AVERT}}, \quad (3)$$

where:

V_t is the test vehicle speed at the moment of hitting a deformable barrier (according to NCAP crash test requirements related to a head-on collision with a barrier), $V_t = 35$ *mph;*

C_{AVERT} is the statistically average value of C_i damage depth measurements within the system of six measurement points (n = 6), with regard to the test vehicle.

To determine the statistically average value of test vehicle damage depth measurements, the following equation can be used:

$$C_{AVERT} = \frac{\frac{C_1}{2} + \sum_{i=2}^{n-1} C_i + \frac{C_n}{2}}{n-1}, \quad (4)$$

where:

C_i is the depth of the volumetric deformation in the i[th] point (where n = 6), according to the results of measuring the test vehicle damage profile, m (an example of measuring the damage depth is given in Figure 1).

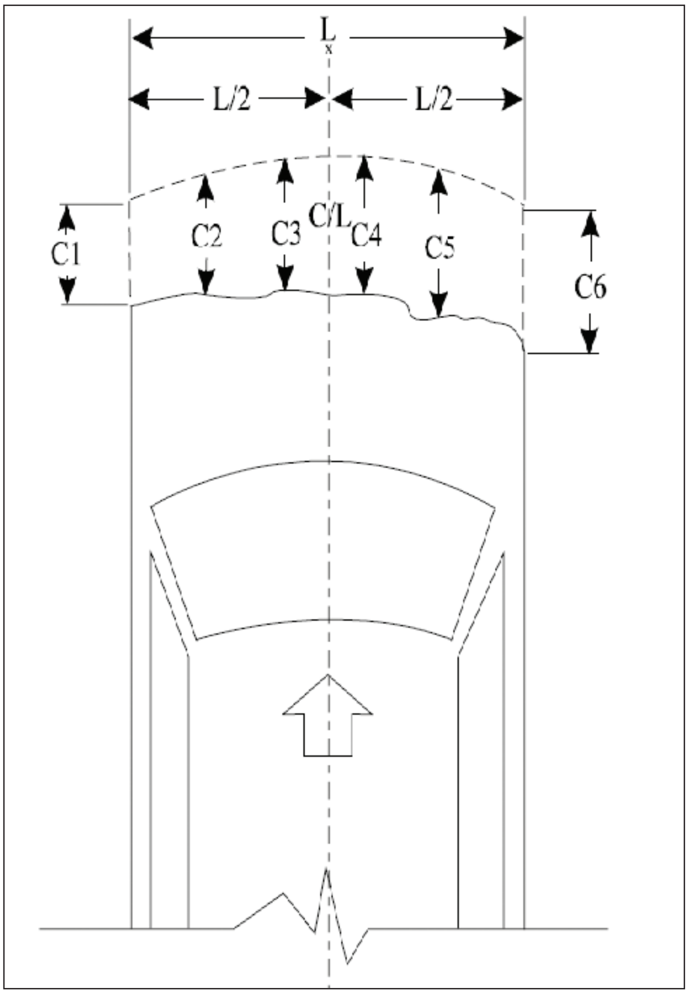

Figure 1. Linear surveying to measure the damage depth and referencing of measurements in case of a head-on collision.

At this stage of selecting coefficients when determining the kinetic energy spent on the vehicle deformation in a road accident, it is required to calculate stiffness coefficients G:

$$G = \frac{A^2}{2 \times B}. \quad (5)$$

Then, the length of the measured section in meters is determined:

$$w_i = \frac{L_t}{n-1}. \quad (6)$$

Based on the selected and calculated coefficients, it is possible to determine the work of forces with regard to the deformation and obtain the average deformation volume:

$$E_D = \sum_{i=1}^{n-1} w_i \times \left(\begin{array}{l} \frac{B}{6} \times \left(C_i^2 + C_i \times C_{i+1} + C_{i+1}^2\right) \\ + \frac{A}{2} \times \left(c_{i+1} + c_i\right) + G \end{array} \right) \times \left(1 + tan^2\theta\right), \quad (7)$$

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where:

Ө is the angle of the deformation force (along the momentum vector) with account for the results of inspection regarding the vehicle involved in the road accident under consideration, degrees.

The result—the equivalent speed of the vehicle spent on the volumetric deformation—is calculated by the following equation:

$$V_D = 3.6\sqrt{\frac{2 \times E_D}{m}} \quad (8)$$

where:

m is the vehicle mass with account for the load at the instant of the collision, kg.

The CRASH3 damage analysis algorithm is based on an assumed linear relationship between the impact speed and crush as well as data on crash tests performed with the use of old (1971–1974) four-wheel drive vehicles manufactured by General Motors. Vehicles of later model years have a unified body and significant changes in materials and design. Therefore, it is necessary to refine the coefficients used in the CRASH3 algorithm (National Highway Traffic Safety Administration, 2019). The present paper addresses stiffness coefficients that are either calculated according to the method presented above or selected based on unified values. In particular, we suggest substituting A, B, and G stiffness coefficients used in CRASH3 for β_0 and β_1. New coefficients ensure much simpler and more direct calculation. It saves us the trouble to reduce experimental results to the formulation of force deflection and makes it possible to simulate damage behavior directly. Stiffness coefficients β_0 и β_1 can be transformed into CRASH3 coefficients A and B as follows:

$$A = \beta_0 \times \beta_1 \quad (9)$$

$$B = \beta_1^2 \quad (10)$$

If β_0 и β_1 stiffness coefficients are used, stiffness parameters of light motor vehicles shall be classified in accordance with the wheelbase and general structural characteristics of a vehicle.

Using the NHTSA's crashworthiness database, which includes New Car Assessment Program (NCAP) and crash test data, we can assume that the front, side, and rear of a vehicle are characterized by uniform stiffness. Based on NHTSA results, it is proposed to divide vehicles into eight categories corresponding to eight sets of stiffness coefficients (β_0, β_1) (National Highway Traffic Safety Administration, 2019; US Department of Transportation, 1986).

Results

Stiffness coefficients for vehicles can be divided into six categories for light motor vehicles (categories 1–6) according to the wheelbase (see Table 1) and two categories for vans (category 7) and off-roaders (category 8). General stiffness coefficients are given in Table 1.

Table 1. Vehicle stiffness coefficients by categories

Category	Wheelbase, cm	Head-on collision	
		β_0	β_1
1	≤ 240.8	91.4	6.7
2	240.8–258.0	97.0	7.22
3	258.0–280.4	102.1	7.25
4	280.4–298.4	107.0	6.36
5	298.4–312.9	109.6	6.18
6	> 312.9	116.0	5.75
7 (vans)	276.8–330.2	109.7	8.51
8 (off-roaders)	–	105.7	7.98

In case of head-on collisions involving vehicles with a front-wheel drive (FWD), it would be reasonable to have a separate category as larger vehicles usually have a rear-wheel drive and smaller vehicles are more often equipped with an FWD. However, the absence of such a category for FWD vehicles can be explained by the fact that FWD distinctive features are counter-balanced by various wheelbase ranges.

Since the automobile industry is constantly developing, and each model year has different stiffness characteristics, stiffness coefficients shall be updated (refined) at least once a year based on crash tests (Sharma et al., 2007).

Lately, a new vehicle class (sport utility vehicles, SUV) has appeared. The calculated average stiffness coefficients for SUV relatively match the stiffness coefficients for category 7 (vans). However, in the long run, this class would require a separate category.

Since the basic body structure of a particular vehicle model does not change every year, it is possible to use the same stiffness coefficients during those years when no changes are introduced. The stiffness coefficients for vehicles tested can be applied to corresponding "cloned" models (Kirkpatrick et al., 1999).

Discussion

It shall be noted that the stiffness coefficients given have statistically average values with regard to the indicated wheelbase range. It is obvious that the stiffness properties of some vehicles may significantly differ from the data presented.

Besides, β_0 и β_1 coefficients cannot be applied for all types of collisions (e.g. for a collision involving a vehicle with a significantly different clearance).

The algorithm under consideration shall be used in the reconstruction of road and traffic conditions that match crash test conditions as closely as possible. Collisions with displacement, side swipes, and collisions in motion shall be studied more thoroughly. This algorithm may not be used as a uniform method to estimate accident severity in terms of speed changes (Consolazio et al., 2003).

Conclusions

The authors analyzed the stiffness coefficients used and proposed to substitute them for those considering modern trends in the automobile industry and ensuring much simpler and more direct calculation. The authors also described the scope of application for the proposed coefficients, and restrictions of their use.

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ПОВЫШЕНИЕ ТОЧНОСТИ ОПРЕДЕЛЕНИЯ КОЭФФИЦИЕНТОВ ЖЕСТКОСТИ ПРИ ОПРЕДЕЛЕНИИ ЗАТРАТ КИНЕТИЧЕСКОЙ ЭНЕРГИИ НА ДЕФОРМАЦИЮ АВТОМОБИЛЯ

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Аннотация

В статье изучается методика определения доли затрат кинетической энергии на развитие деформаций и эквивалентную данным затратам скорость автомобилей при технической реконструкции ДТП. **Цель исследования.** Совершенствование коэффициентов, используемых в методике и влияющих на значение скорости транспортного средства в момент столкновения. **Методы.** Алгоритм анализа повреждений использует измерение деформации ТС для оценки энергии, необходимой для нанесения ТС измеренного ущерба с использованием принципа сохранения импульса. **Результаты.** Используемые коэффициенты жесткости были разработаны задолго до появления современных транспортных средств, в связи с чем предлагается новые коэффициенты жесткости и указывается их область применения. Используемые коэффициенты жесткости, предлагается заменить на новые, концептуально более прямые и простые, а также учитывающие современные тенденции в автомобильной промышленности. Это избавляет от необходимости сводить экспериментальные результаты к формулировке отклонения силы и напрямую моделирует поведение разрушения. Также раскрывается область и ограничения применения предлагаемых к использованию коэффициентов.

Ключевые слова

Скорость транспортного средства, дорожно-транспортное происшествие, реконструкция ДТП, кинетическая энергия, жесткость автомобиля, коэффициенты жесткости автомобиля.