ANALYSIS OF DISPLACEMENT OF A CONCRETE BARRIER ON IMPACT OF A VEHICLE. THEORETICAL MODEL AND EXPERIMENTAL VALIDATION

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Abstract

A vehicle hitting a traffic barrier creates a major threat to traffic safety as a result of displacement of components of the barrier by the forces transferred from the vehicle. We built a theoretical model of the dynamics of such processes and behaviour of concrete barriers set on various types of surfaces.

We calculated the displacement as a function of vehicle impact energy and barrier base. We completed analytical approximation for our calculations and we referred the theoretical results to experimental test results. This validated our model of barrier and vehicle movement dynamics as fully qualified for use in the planning of safer barriers and evaluation of barrier effect on traffic.

Basing on our calculations, we determined that a second-order polynomial can be used for describing the lateral displacement of a barrier placed on various types of surfaces for a wide range of impact energies (actually, from 0 to 120 kJ). The courses of the approximating function represent an efficient model for determining the maximum lateral displacement of a concrete barrier on impact of a B or C segment vehicle.

Keywords: *transport, road transport, road safety, roadside crash, concrete barrier, safety barriers*

1. Introduction

Road infrastructure (in much the same way as vehicles) incorporates active and passive safety devices. The latter group contains various safety barriers. These are important for safety as more than 15% vehicles driving off the road lane collide with such structures [7].

We distinguish permanent and temporary (removable) barriers. The latter are mostly concrete blocks used for temporary traffic re-routing or securing road work sites. Concrete barriers consist of segments connected with couplings featuring high tensile strength. Such combination acts as an articulated joint with limited mobility. By retaining their integrity on impact from a vehicle, the components perform their protective role. There are various types of concrete barriers with different profiles (e.g., New Jersey, STEP, or profile "F") [9].

Although many research institutes perform computer-assisted simulation of car crashes (including collisions with rigid structures), most of them focus on safety features of vehicles and structural aspects of barriers. There are few studies devoted to the practical use of traffic barriers, including barrier behaviour on impact.

Our purpose is to build a practical model for researching certain aspects of such behaviour. We considered various barrier base surfaces and displacements depending on impact energy. We also performed validation calculations based on results of many experiments.

2. Barrier Displacement on Impact of a Vehicle

The collision of a car with a traffic barrier creates great threats resulting from:
- difficult to predict vehicle trajectory after rebounding from or sliding along the barrier,
- barrier component displacement as a result of vehicle impact.

Regarding the former point, barriers are designed and installed so that they return the vehicle back into traffic heading in its original direction (parallel or nearly parallel to the barrier). Typically, such trajectory poses least threat to other vehicles. The other aspect of the problem, lateral displacement of the barrier, is worth considering as another threat, particularly where the barrier defines the outer lane limit or the median.

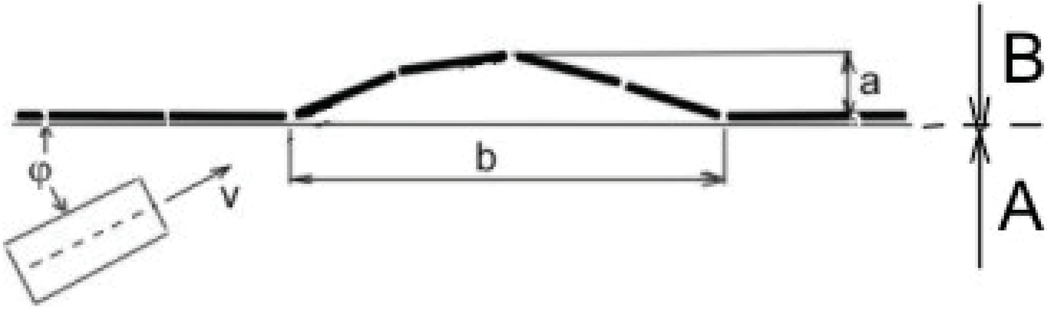

Fig. 1. The following quantities describe such displacement: a - maximum lateral displacement, b - length of the active (movable) section of the barrier, β - angle of vehicle approach to the barrier with velocity v

Letters “A” and “B” in Fig. 1 represent different surface strips with a clear demarcation line.

Lateral barrier displacement on impact of a vehicle, also shown in Fig. 2, is typically observed for a few sections of the barrier (section “b” in Fig. 1). The maximum displacement is also referred to as barrier deflection (letter “a”) or “working width”.

Fig. 2. Concrete barrier displacement on impact of a vehicle [2]

3. Theoretical Model and Selection of Test Conditions

Based on results of traffic monitoring and concrete barrier placement studies, we built a model serving a purpose of describing the movements of the vehicle and barrier segments on collision. An important feature of the model is that it describes the development of situation from the initial contact until disengagement.

The PC Crash application we used for this purpose enables linking structure segments to represent a concrete barrier placed directly on ground. The model addresses the differences between the surfaces in areas “A” and “B” were considered in this model and outlined in Fig. 1. Our mathematical model of the trajectory of the vehicle and the displacement of the barrier components was based on studies [12, 16-18]. We used the Kudlich-Slibar model to describe the collision. [13, 17]. We did not analyze the vehicle deformations described in this paper.

Figure 3 represents a model of collision with a barrier consisting of rigid segments and shows the following:

- outlines of segments 9, 10 and 11 and segment couplings s10 and s11,
- “frozen” vehicle body position,
- vehicle’s centre of inertia trajectory.

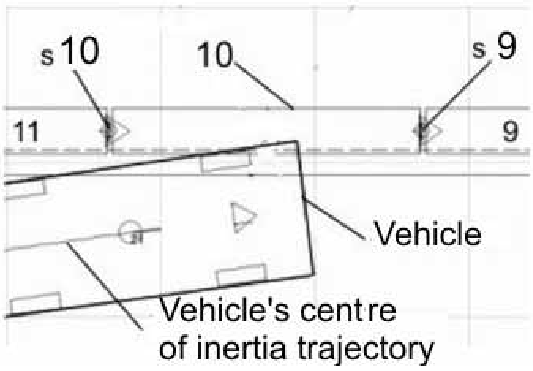

Fig. 3. Momentary vehicle position during collision with a barrier segment (see the description in the body of this paper)

We considered forces and moments acting on barrier segment couplings as external factors affecting each segment individually. The following equation describes the moment of resistance of a coupling calculated for each axis of the local coordinate system,

$$M(\varphi) = (\varphi - \varphi_M) S + \dot{\varphi} D \ \text{ for } |\varphi| > \varphi_M , \tag{1}$$

$$M(\varphi) = 0 \ \text{ for } |\varphi| \le \varphi_M , \tag{2}$$

where:

φ - angle of barrier segment rotation relative to the adjacent segment [^{o}],

φ_M - threshold angle, the exceeding of which results in an increase of the moment of resistance,

S - moment of resistance gain factor in the coupling [Nm/^{o}],

$\dot{\varphi}$ - angular velocity of rotation of adjacent barrier segments,

D - coupling damping coefficient.

Once the segment rotation angle reaches $|\varphi| = \varphi_o$ so that $|M(\varphi_0)| = M_{\max}$, the coupling is broken and from now on $M(\varphi) = 0$. Obviously, $\varphi_0 > \varphi_M$. The maximum moment of resistance of the coupling is limited by the coupling's tensile force limit. The tensile force limit for the coupling used in the model, the exceeding of which ruptured the barrier, was 350 kN (i.e., close to the value declared by manufacturers of reinforced concrete barriers [15]).

The barrier displacement resistance is produced by friction between barrier components and the underlying surface and the moment of resistance acting in segment couplings. We considered the following in our selection of test conditions:

- conclusions from traffic collision studies [13],
- Polish and European standard PN EN 1317,
- possibility of calculation result validation.

4. Model Parameters and Calculations

We accepted the following assumptions and values for the model:

- concrete barrier consisting of 20 segments, 4 m length and 2200 kg weight each (typical for Poland and European Union),
- typical B and C segment vehicles weighing 900 kg and 1500 kg, respectively,
- 80-110 km/h speed on impact,
- 8-24 degrees angle of vehicle approach to the barrier,
- adhesion coefficient $\mu = 0.8$ for the lane ("A" in Fig. 1).

A review of vehicle-barrier collisions demonstrates that 5-10 degrees is the typical approach angle [3, 4, 10]. On the other hand, the Polish standard PN-EN 1317 [15] (defining methods and conditions for traffic barrier testing in Europe) assumes the angle is within the 8-20 degrees range. The impact from a small passenger car approaching at a small angle will not produce an actual displacement of the barrier, so we disregarded such scenarios in our work. However, a heavier vehicle and a 10 degree or larger angle produces a clear barrier displacement, which can pose a threat to the traffic.

The coefficient of friction between the barrier and the underlying surface (strip “B” in Fig. 1) addresses the results of study [5]. We measured the position of the barrier segment from the “idle” state up to the speed of approx. 2.5 m/s and obtained 0.2-0.9 friction coefficient values. The characteristic values observed for the segment moving at 1m/s velocity are as follows:

- ground surface: 0.7-0.75,
- asphalt covered with dry and wet sand: 0.5-0.6.

We used vehicle crash descriptions contained in the PC Crash application’s library of vehicles in our calculations.

In our model, the barrier consisting of a kinematics chain of solids can be displaced by impact. Each segment can move, rotate or turn over.

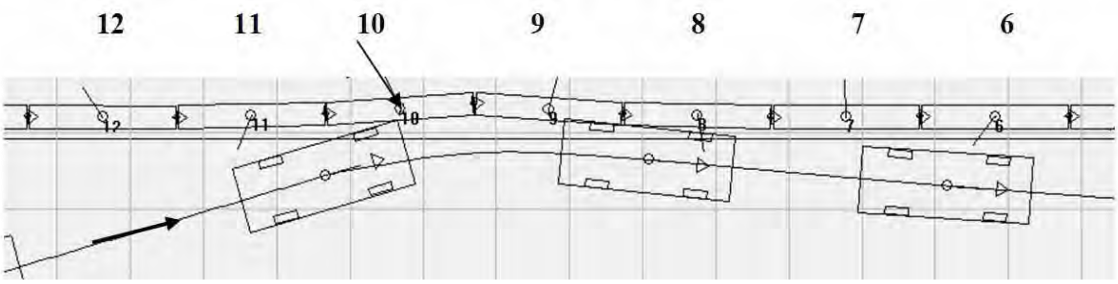

Fig. 4. The position of the barrier hit by the vehicle at a 16 degrees angle, vehicles centre of inertia trajectory and vehicle contours at 0.5 s intervals. The visible part of the barrier consists of segments 6-12

Figure 4 shows some calculation results for the final barrier position and vehicle positions calculated at 0.5 s interval. The maximum barrier displacement is measured from the barrier axis in pre-collision state to the farthest coupling position in the end of the simulation. This distance is measured orthogonally to the original position of the barrier (Fig. 4).

5. Calculation Results. Barrier Displacement vs. Impact Force

We provided a mathematical proof of lateral barrier displacement dependence on impact energy. The energy depends on the weight (m) and speed (v) of the vehicle and the approach angle (β). This energy

$$E_U = \frac{1}{2} m (v \sin \beta)^2, \tag{3}$$

is sometimes used as the Impact Severity (IS) factor [4, 10, 14] to facilitate comparison of barrier behaviour in various scenarios. According to our calculations, the impact energy in the simulations varied widely from 6 to 120 kJ. We found out the barrier was not ruptured in any of our cases. This means the barriers meet the requirements of [15].

While analyzing the results (60 points in Fig. 5), we asked a question whether the effect of friction between barrier segments and the underlying surface on the lateral displacement of the barrier can be reflected in a general and analytical, but also easy to interpret way, for the impact energy range concerned?

The approximate analytical model of the barrier displacement dependence on the impact angle and energy facilitates the following:

- describing general nature of the dependency,
- predicting the dependencies between calculation points and nearby points (to address impact angles outside of the studied range),
- demonstrating convergence of the calculated function course with the results of the calculations.

In the last application, the model is used for evaluating convergence in mean square according to [11].

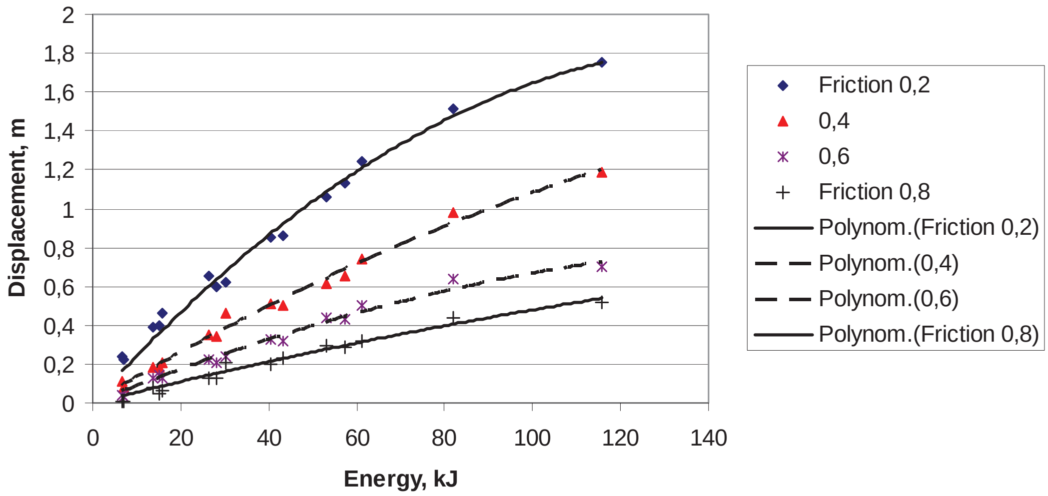

Fig. 5. Maximum Barrier Displacement vs. Impact Energy

Figure 5 compares calculation results for 4 friction f coefficient values: $\mu_B = 0.2; 0.4; 0.6\ i\ 0.8$. We considered a few impact angles (β) ranging from 8 to 24 degrees. Also, we addressed 80-110 km/h impact speeds of cars from commercial segments B and C. The comparison demonstrated that a second-order polynomial depending on the coefficient of barrier friction against the underlying surface can describe the relationship between the displacement and energy. See Tab. 1 for the functions we used to approximate the results shown in Fig. 5.

Tab. 1. List of functions used to approximate the relationship between the maximum lateral barrier displacement ("y" expressed in meters) and the energy of impact ("x" in kJ)

Friction coefficient	Approximating polynomial	R^2 factor
0.2	$y = -0.00009x^2 + 0.025x$	0.988
0.4	$y = -0.00003x^2 + 0.0136x$	0.990
0.6	$y = -0.00003x^2 + 0.0092x$	0.984
0.8	$y = -0.000009x^2 + 0.0057x$	0.974

Convergence factor (R^2) values close to 1 confirm that the combination of functions provides an efficient displacement/energy model for B and C type vehicles.

6. Calculation Result Application for Validation of Barrier Impact Model

We should always try to validate the model by referring it to empirical results. For this purpose we used results of vehicle-barrier crash tests. [6, 10]. Although the literature is abundant, descriptions detailed enough for the purposes of our work are rare.

Table 2 provides the results of two experiments compared with results calculated on the basis of the course of the approximating functions listed in Table 1 above, containing quite detailed descriptions. So compared, the values of the maximum barrier displacement in the experiment to calculation result approximation layout are similar one to another.

Tab. 2. Comparison for validation of calculation results based on experimental research results

Vehicle weights, type	Impact angle, deg.	Impact speed V, km/h	Impact energy, kJ	Barrier; segment length and type	Max. displacement – empirical, m	Max. displacement – calculated using the approximation from Tab. 5	References
Chevrolet Cheyenne 1995 r 2000kg,	25	100	137	3.81m. Type F	0.81 m	0.78-0.79 m	[6]
Suzuki Metro, 910kg	15	78	14	2.5 m . RS	0.21 m	0.14-0.15 m	[10]

Figure 6 shows the results of experiments for many vehicles weighing from 800 to 1200 kg and a wide range of impact speeds (see paper [10]), depending on impact energy. The figure shows also the course of the experiment result approximating function, i.e. lateral barrier displacement dependence on vehicle impact energy.

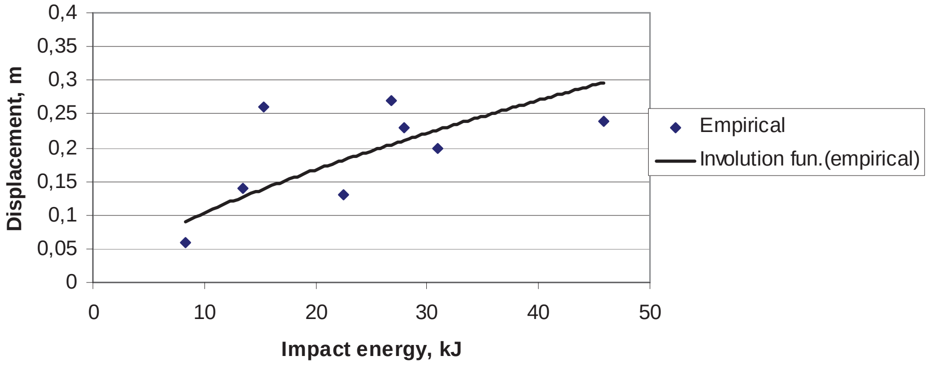

Fig. 6. Experiment results in study [10] and an approximation of the results

Then, Fig. 7 and Tab. 2 compare the course of the approximating function shown in Fig. 6 with approximation of our calculations.

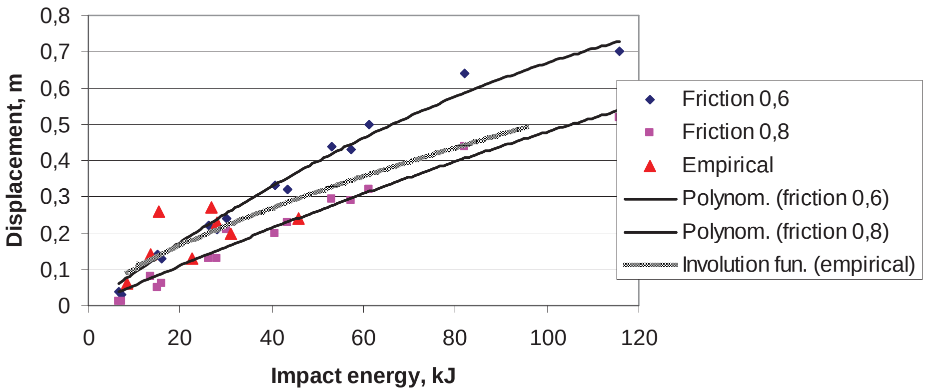

Fig. 7. Empirical results vs. calculation results

Tab. 2. List of approximating functions shown in Fig. 7 and convergence factor values

Data labels	Approximation	R^2 factor
Friction 0.6	$y = -0.00003x^2 + 0.0092x$	0.984
Friction 0.8	$y = -0.000009x^2 + 0.0057x$	0.974
Empirical	$y = 0.021x^{0.693}$	0.544

Figure 7 shows the courses of the two functions from Fig. 5 we used to approximate the calculation results for barrier displacement on the underlying surface with friction factor $\mu_B = 0.6\, i\, 0.8$ (typical for concrete or asphaltic concrete either clean or contaminated with sand). Also, the figure shows the course of the function we used to approximate the empirical results from Fig. 6 (for concrete surfaces). We extrapolated the function for an impact energy range much wider than that shown in Fig. 6. The extrapolated course of approximation also corresponds to our calculation results. It confirms that the theoretical results are consistent with the empirical ones.

7. Conclusion

Our calculations and results demonstrate that our model describing the process of a vehicle collision with a removable concrete barrier is feasible. The results of comparing our theoretical results with the empirical ones confirm, in principle, that the two are consistent, although, the latter originated from multiple experiments.

We demonstrated that lateral barrier displacement depends on vehicle impact energy. This relationship is particularly useful for traffic safety studies since it defines characteristic traffic parameters (vehicle weights and speed). Basing on our calculations, we determined that a second-order polynomial can be used for describing the lateral displacement of a barrier placed on various types of surfaces for a wide range of impact energies (actually, from 0 to 120 kJ). The courses of the approximating function shown in Fig. 5 represent an efficient model for determining the maximum lateral displacement of a concrete barrier on impact of a B or C segment vehicle.

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