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Kinetic energy dissipation by a portable concrete traffic barrier

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S u m m a r y

The article presents an energy balance analysis which makes it possible to evaluate the kinetic energy of an automotive vehicle, dissipated by a portable concrete traffic barrier during the collision period. This provides a possibility of indirect assessment of vehicle driver's and passengers' safety because the greater kinetic energy part that is converted into the work of friction of the moving barrier segments and the vehicle body, the lower deformation of the vehicle body and the lower probability of intrusion into the survival space. In the example illustrating how to use the procedure proposed, information taken from report No. FHWA/TX-02/4162-1 published in the Internet was used as the input data for the calculations. The analysis was carried out for the experiment described in the first part of the report (test No. 441621-1) [1, 2].

Major symbols used:

A, B	– coefficients defining the vehicle body stiffness curve
a_B	– average vehicle deceleration when rubbing against the lateral face of the barrier
b	– width of the barrier segment
C	– deformation of the vehicle body
d	– length of the distance of contact of the vehicle with the barrier
E_k	– initial kinetic energy of the vehicle when hitting the barrier
E_{swob}	– energy related to the free movement of the vehicle from the loss of contact with the barrier to the standstill
g	– standard gravity
h	– height of the barrier segment
L	– length of the barrier segment
$M(\alpha)$	– moment of the force at the connection between barrier segments
m	– complete vehicle kerb weight
m_{Bi}	– mass of the *i*-th barrier segment
s_B	– length of the distance covered by the vehicle when remaining in contact with the barrier
s_i	– displacement of the centre of mass of the *i*-th barrier segment
v	– vehicle velocity
V_s	– volume of the barrier segment
$W_{\alpha i}$	– work related to the rotation of the *i*-th barrier segment
w_0	– width of deformation of the front part of the vehicle body
W_B	– work of friction of the vehicle moving along the lateral face of the barrier
W_D	– energy dissipated during deformation of the vehicle body

W_{BC} – total work related to the deformation of the barrier
W_{Pi} – work done at the *i*-th connection between barrier segments
W_{Si} – work of friction related to the translation of the *i*-th barrier segment
α_1 – angle of rotation at which the barrier segment's rotation begins
α_2 – angle of rotation at which the barrier segment's rotation stops
α_{P0} – angle of rotation at which the moment at the connection between barrier segments begins increasing
α_{P1} – angle of rotation at which the moment at the connection between barrier segments stops increasing
α_{P2} – angle of rotation at which the barrier segments stop rotating in relation to each other
α_i – angle of rotation of the *i*-th barrier segment
β – angle defining the direction of velocity v of the vehicle when hitting the barrier
γ – mass density of concrete
θ – angle of impact of the vehicle against the barrier segment
μ_0 – static coefficient of friction of the concrete barrier segment against the ground (roadway)
μ_P – sliding coefficient of friction

1. Portable concrete barriers

One of the main purposes of concrete traffic barriers is to prevent a vehicle from going outside of the edge of its traffic lane. From the safety point of view, it is important to estimate what part of the kinetic energy of a vehicle will be dissipated by the barrier. The greater kinetic energy part that is dissipated, the smaller deformation of the vehicle body and the higher probability of avoiding intrusion into the survival space (i.e. the space where deformation of the vehicle body should not result in any contact with vehicle parts that would be dangerous for the driver and passengers).

The task to dissipate energy may be well fulfilled by portable concrete barriers, which consist of segments connected with each other by articulated joints but not permanently fastened to the ground The segments may move over the road surface.

Modern portable concrete barriers should be so designed that the vehicle having hit the barrier should not loose its stability in result of the collision, it should move along the lateral face of the barrier for a certain distance, and it should return to the proper direction of motion after the collision. In this case, a part of the kinetic energy of the vehicle is converted into work of the friction forces acting between the vehicle body and the lateral face of the barrier. At the same time, the articulated joints between barrier segments make it possible for the segments to slide, with individual segments pulling those adjacent to them; thus, the system causes the conversion of a part of the kinetic energy of the vehicle into work of friction between the barrier and the ground. Such an effect, sometimes referred to as the “chain effect,” may be obtained if individual segments of the portable concrete barrier have appropriate dimensions and weight and are connected together by means of flexible coupling links. Moreover, the system of portable barriers reduces the maximum vehicle deceleration value. Obviously, this value should not exceed the level above which the airbag is operated. Simultaneously, the probability of vehicle rollover decreases as well.

The barrier performance may depend on a variety of parameters, e.g.:

– Segment cross-section shape;
– Segment height;
– Value of the friction force between the barrier segment and the road surface;
– Barrier deflection caused by the vehicle impact.

In most cases, the barriers have cross-sections shaped according to the F or New Jersey profiles. For such cross-sections, if the vehicle runs onto the barrier base at a small angle (below 10°) then a reaction of the vehicle suspension system takes place but the vehicle body does not hit the lateral face of the barrier (Fig. 1). At a greater impact angle, the vehicle may hit the lateral face of the barrier.

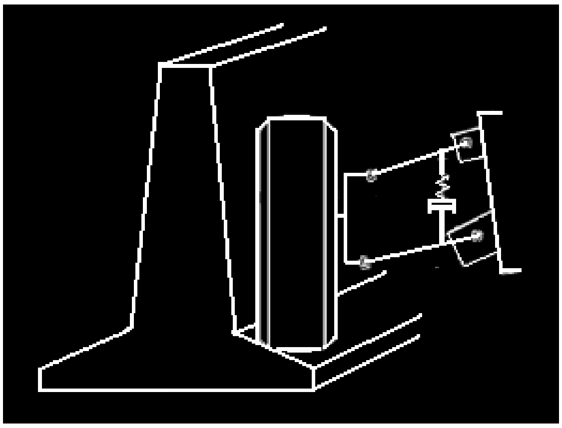

Fig. 1. Reaction of the suspension system when the vehicle runs onto the barrier base.

A matter of particular importance is the correct engineering of the barrier segment connection system because the structural characteristics of this system have direct impact on the magnitude of lateral displacement and the rotation of barrier segments. The connection of inappropriate flexibility may cause excessive deformation of the vehicle body and barrier deflection greater than acceptable.

In the European Union countries (Poland inclusive), the DELTA BLOCK system is used. It meets the requirements of Polish Standards PN-EN 1317-1 and PN-EN 1317-2. Every segment is symmetrical and has identical fastening elements at both ends, thanks to which the barrier assembling is easier. Apart from reinforcement mesh, the DELTA BLOCK segments are provided with coupling strips embedded in them during the production process. Thanks to the strips, the segments may be easily connected with each other and the accident damage may be quickly repaired by simple replacement of individual segments without the overall barrier performance being affected. The segments are connected together by means of the J-J Hooks system, which makes the connecting of individual segments of the portable barrier easy and quick. The system consists of two identical J-shaped steel hooks (hence the name).

2. Dissipation of the vehicle energy by the portable concrete barrier

From the road traffic safety point of view, it is important to determine what part of the kinetic energy E_k of the vehicle will be dissipated in result of the contact of the vehicle with the barrier. The decisive role in this process will be played by the dimensions and mass of the barrier segments and the design of the segment connections because these factors have an influence on the translation and rotation of each of the moving units. Simultaneously, a part of the kinetic energy of the vehicle is dissipated in result of friction of the vehicle body against the lateral face of the barrier. The other part of the energy is converted into the work related to the deformation of the vehicle body. If the sum of these energies is lower than the initial kinetic energy of the vehicle then the vehicle having lost its contact with the barrier will keep moving as long as to the standstill.

The energy balance equation has the following form:

$$E_k = \sum_i W_{\alpha i} + \sum_i W_{Si} + \sum_i W_{Pi} + W_B + W_D + E_{swob} \tag{1}$$

where:

E_k – initial kinetic energy of the vehicle when hitting the barrier;

$W_{\alpha i}$ – work of friction related to the rotation of the *i*-th barrier segment;

W_{Si} – work of friction related to the translation of the *i*-th barrier segment;

W_{Pi} – work done at the *i*-th connection between barrier segments;

W_B – work of friction of the vehicle moving along the lateral face of the barrier;

W_D – energy dissipated during deformation of the vehicle body;

E_{swob} – energy related to the free movement of the vehicle from the loss of contact with the barrier to the standstill;

$i = 1, \ldots n$ – number of the barrier segments having been displaced.

The following assumptions have been made in the further part of this study:

- All the barrier segments have identical dimensions and are made of identical material.
- The barrier segments having been displaced did not tip over and remained in contact with the ground during the entire process of collision with the vehicle.
- The work related to damage to barrier segments is very small and may be ignored in the energy balance.

3. The work related to the rotation of the *i*-th barrier segment

Let us assume that the barrier segment is represented by a parallelepiped of dimensions $b \times h \times L$, where:

b – width of the barrier segment;

h – height of the barrier segment;

L – length of the barrier segment

In result of the vehicle impact, the *i*-th barrier segment rotates by an angle α_i around the connection with the adjacent element (Fig. 2).

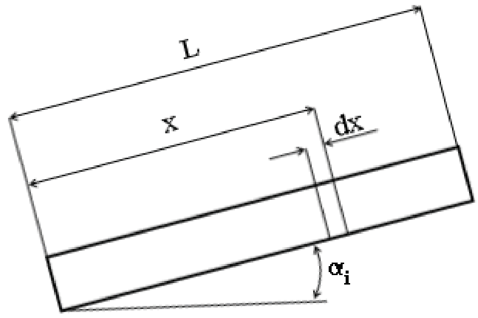

Fig. 2. Rotation of the barrier segment by an angle α_i.

During the rotation of the barrier segment, a friction force *T* depending on the coefficient of friction develops between the bottom surface of the segment and the road surface. This force reaches its maximum value for static friction. It is equal, in terms of its value, to the maximum force that would act in the possible direction of motion without causing the object to move. It may be determined from a formula $T=\mu_0 \cdot N$, where *N* is the pressure force exerted by the object onto the ground and μ_0 denotes the coefficient of static friction.

In most cases, an assumption is made that when an object has been set in motion then the friction force value does not depend on the object velocity and that the coefficient of sliding friction μ_P is lower than the static coefficient of friction μ_0 is. This means that the value of the coefficient of friction drops from that of the static friction to that of the sliding friction.

The value of the coefficient of friction between the concrete barrier segment and the road surface depends on the type of the latter. The numerical values of the coefficient of friction are shown in Table 1.

Table 1. Values of the static coefficient of friction between the barrier segment and ground of various types

	μ_0	Source
Concrete – soil/rock	0.30	http://www.supercivilcd.com/FRICTION.htm
Concrete – dry concrete	0.65	http://www.supercivilcd.com/FRICTION.htm
Concrete – dry concrete	0.61	http://www.aspbase.com/doc/testing
Concrete – dry concrete	0.7	http://www.concrete.org.uk/forum
Concrete – wet concrete	0.57	http://www.aspbase.com/doc/testing
Concrete – dry clay	0.40	http://www.supercivilcd.com/FRICTION.htm
Concrete – wet clay	0.20	http://www.supercivilcd.com/FRICTION.htm
Concrete – wet sand	0.40	http://www.supercivilcd.com/FRICTION.htm
Concrete – wet sand	0.35 ÷ 0.50	http://www.concrete.org.uk/forum
Concrete – dry sand	0.50 ÷ 0.60	http://www.supercivilcd.com/FRICTION.htm
Concrete – sand	0.60	http://klub.chip.pl/jizdeb/tablice
Concrete – dry gravel	0.50 ÷ 0.60	http://www.supercivilcd.com/FRICTION.htm
Concrete – gravel	0.87	http://klub.chip.pl/jizdeb/tablice
Concrete – dry rock	0.60 ÷ 0.70	http://www.supercivilcd.com/FRICTION.htm
Concrete – wet rock	0.50	http://www.supercivilcd.com/FRICTION.htm
Concrete – concrete	0.75	Concrete construction magazine; Sept. 1, 1992 (according to manufacturers' data)
Concrete – concrete	0.80	Concrete construction magazine; Sept. 1, 1992 (according to Precast/Prestressed Concrete Institute's Handbook)

The friction coefficient curve is shown in Fig. 3.

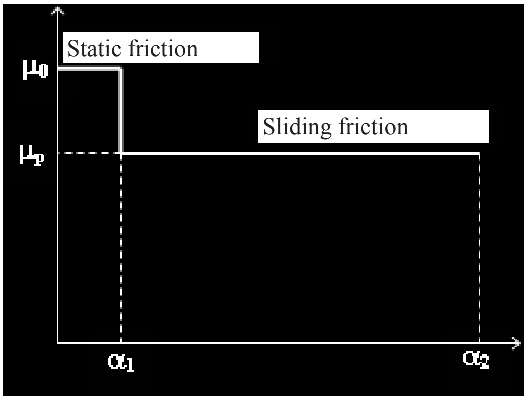

Fig. 3. Changes in the friction coefficient values during a rotation of the barrier segment.

The changes in the friction coefficient values shown in Fig. 3 are described by the following function:

$$\mu(\alpha) = \mu_0 \quad \text{for } \alpha \le \alpha_1$$
$$\mu(\alpha) = \mu_p \quad \text{for } \alpha_1 < \alpha \le \alpha_2 \qquad (2)$$

where:
α_1 – angle of rotation at which the barrier segment's rotation begins;
α_2 – angle of rotation at which the barrier segment's rotation stops.

The mass of an element of the *i*-th barrier segment, with a width of *dx*, is $dm_{Bi} = \gamma \cdot b \cdot h \cdot dx$, where γ – mass density of concrete.

The work of friction done during the displacement of the *i*-th barrier segment along a path of $\alpha_i \cdot x$ length (where the α_i angle is expressed in radians) is:

$$W_{\alpha i} = \gamma \cdot b \cdot h \cdot g \cdot \alpha_i \int_0^L x \cdot dx \int_0^{\alpha 2} \mu(\alpha) \cdot d\alpha = \gamma \cdot b \cdot h \cdot g \cdot \alpha_i \cdot \frac{L^2}{2} \cdot \int_0^{\alpha 2} \mu(\alpha) \cdot d\alpha \qquad (3)$$

The mass of the *i*-th barrier segment is:

$$m_{Bi} = \gamma \cdot b \cdot h \, L \qquad (4)$$

hence:

$$W_{\alpha i} = 0{,}5 \cdot m_{Bi} \cdot g \cdot L \cdot \int_0^{\alpha 2} \mu(\alpha) \cdot d\alpha \qquad (5)$$

4. The work related to the translation of the *i*-th barrier segment

The work required for a translation of the barrier segment depends on the value of the force of friction between the bottom surface of the segment and the road surface. This work is equal to the product of the barrier segment weight and the coefficient of friction. As it is in the case of segment rotation, the difference between the static friction and the sliding friction must be taken into account. The shape of the curve representing the changes in the friction coefficient values is almost identical to that of Fig. 3, with the difference lying in the fact that the variable represented by the horizontal axis is now the linear velocity of the centre of mass of the barrier segment.

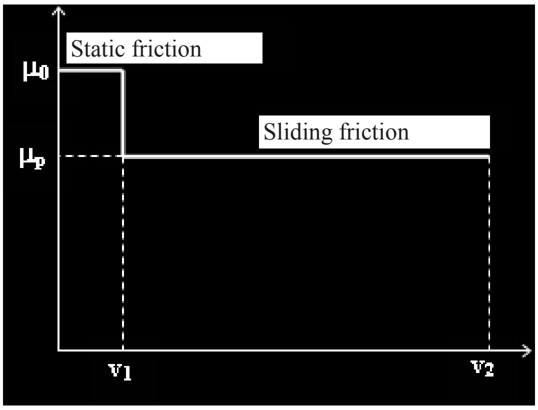

Fig. 4. Changes in the friction coefficient values during a translation of the barrier segment.

The changes in the friction coefficient values are described by the following function:

$$\mu(v) = \mu_0 \quad \text{for } v \le v_1$$
$$\mu(v) = \mu_p \quad \text{for } v_1 < v \le v_2 \tag{6}$$

where:

v_1 – velocity of the centre of mass of the barrier segment at which the barrier segment's translation begins;

v_2 – velocity of the centre of mass of the barrier segment at which the barrier segment's translation stops.

The work of friction W_{Si} required for the translation of the *i*-th barrier segment is

$$W_{Si} = m_{Bi} \cdot g \cdot s_i \cdot \int_0^{v2} \mu(v) \cdot dv \tag{7}$$

where:

s_i – displacement of the centre of mass of the *i*-th barrier segment.

The mass of the *i*-th barrier segment is defined by formula (4).

5. The work done at the connection between barrier segments

The work W_{Pi} done at the *i*-th connection between barrier segments is defined as follows:

$$W_{Pi} = \int_{0}^{\alpha P2} M(\alpha)d\alpha \tag{8}$$

The characteristic curve representing the performance of the connection between barrier segments is related to the angle of relative rotation of adjacent segments and it may be defined as the function of the value of moment M vs. the angle of rotation α, i.e. $M(\alpha)$. The initial rotation related to the play in the joint will take place at a zero value of the moment. Following the initial movement within the play, the moment will increase to its maximum value. The work done at the connection between the segments depends on the value of the angle at which the rotation of barrier segments stops.

The curve representing the moment values vs. the angle of rotation is shown in Fig. 5.

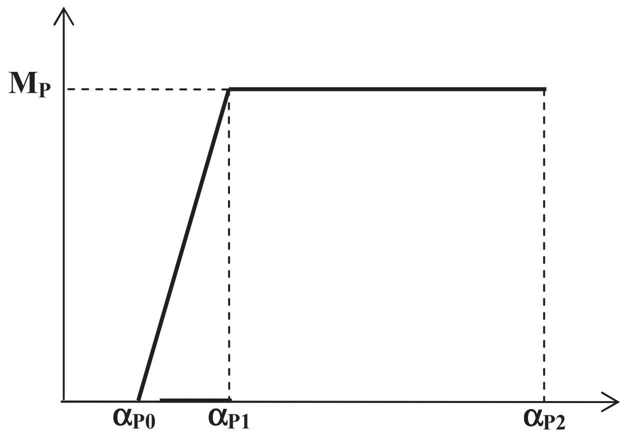

Fig. 5. Changes in the values of the moment at the connection between barrier segments.

Symbols used in Fig. 5:

α_{P0} – angle of rotation at which the moment at the connection between barrier segments begins increasing;

α_{P1} – angle of rotation at which the moment at the connection between barrier segments stops increasing;

α_{P2} – angle of rotation at which the barrier segments stop rotating in relation to each other.

The changes in the moment at the connection between barrier segments are described by the following function:

$$M(\alpha) = 0 \qquad \text{for } \alpha \le \alpha_{P0};$$
$$M(\alpha) = M_P/(\alpha_{P1}-\alpha_{P0})\cdot\alpha \qquad \text{for } \alpha_{P0} < \alpha \le \alpha_{P1}; \qquad (9)$$
$$M(\alpha) = M_P \qquad \text{for } \alpha > \alpha_{P1}$$

6. The work done by the vehicle moving along the lateral face of the barrier

If the vehicle having hit the barrier does not rebound but moves along the lateral face of the barrier then the force of friction between the vehicle body and the barrier will cause a reduction of the vehicle motion velocity. This force might be estimated if the pressure force exerted by the vehicle body onto the lateral face of the barrier and the coefficient of friction between the side of the vehicle body and the barrier face were known. However, this pressure force is difficult to be determined. Therefore, it will be easier to determine the friction work L_B done during this motion by measuring the average vehicle deceleration a_h and the length of the distance of vehicle contact with the barrier. In this case:

$$W_B = m\cdot a_B\cdot s_B \qquad (10)$$

where:
- m – vehicle mass;
- a_B – average vehicle deceleration when rubbing against the lateral face of the barrier;
- s_B – length of the distance covered by the vehicle when remaining in contact with the barrier.

7. The work of deformation of the vehicle body

According to the energy balance equation (1), the work of deformation of the vehicle body is:

$$W_D = E_k - (\sum_i W_{\alpha i} + \sum_i W_{Si} + \sum_i W_{Pi} + W_B + E_{swob}) \qquad (1a)$$

where:
- E_k – initial kinetic energy of the vehicle when hitting the barrier;
- $W_{\alpha i}$ – work of friction related to the rotation of the *i*-th barrier segment;
- W_{Si} – work of friction related to the translation of the *i*-th barrier segment;
- W_{Pi} – work done at the *i*-th connection between barrier segments;
- W_B – work of friction of the vehicle moving along the lateral face of the barrier;
- W_D – energy dissipated during deformation of the vehicle body;
- E_{swob} – energy related to the free movement of the vehicle from the loss of contact with the barrier to the standstill;

$i = 1, \ldots n$ – number of the barrier segments having been displaced.

For the work of deformation of the vehicle body to be estimated, the value of the angle of impact of the vehicle against the barrier should be determined. If the vehicle not only moves with a linear velocity but also rotates around its vertical axis, then angle β, which defines the direction of the resultant vehicle velocity v, differs from angle θ, which defines the position of the vehicle body in relation to the lateral face of the barrier (Fig. 6). In practice, however, this difference is very small, i.e. $\beta \approx \theta$. Therefore, this difference was ignored at further analysis.

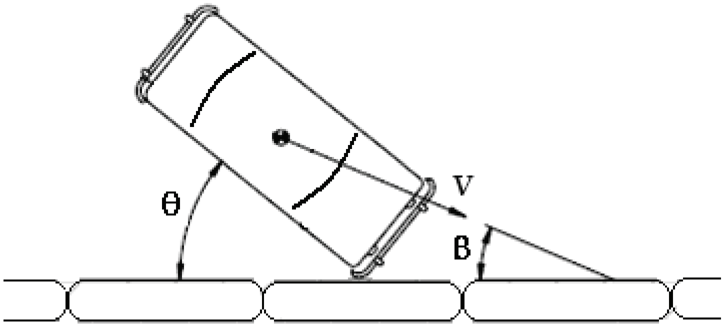

Fig. 6. Angles of impact of the vehicle against the barrier.

For the determining of the work W_D of deformation of the vehicle body, the model devised by Campbell [3] and further developed by McHenry [5] may be used. It is important to assume here that the force $F(C)$ that causes deformation C of the vehicle body may be described by a linear equation in the following form:

$$F(C) = A + B \cdot C \tag{11}$$

where:
A, B – coefficients defining the vehicle body stiffness curve;
C – deformation of the vehicle body.

The work of deformation of the vehicle body is:

$$W_D = \int_0^{w0} \int_0^{C} F(C) \cdot dC \cdot dw \tag{12}$$

where w_0 denotes the width of deformation of the front part of the vehicle body (Fig. 7).

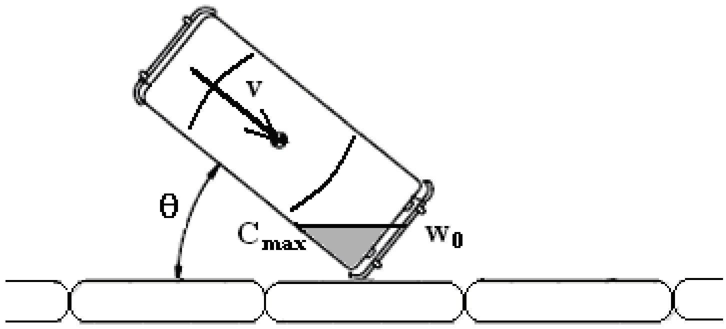

Fig. 7. The vehicle body deformation area after the completion of the collision phase.

For the amount of energy dissipated during the deformation of the vehicle body to be determined, the dimensions defining the deformation area should be known. It is not important whether the deformation resulted from a collision with a rigid or flexible barrier or with another vehicle.

When substituting formula (11) for *F(C)* to equation (12), we will obtain:

$$W_C = \int_0^{w0}\int_0^{C} (A + B \cdot C) \cdot dC \cdot dw = \int_0^{w0} \left(A \cdot C + \frac{1}{2} B \cdot C^2 \right) \cdot dw \qquad (13)$$

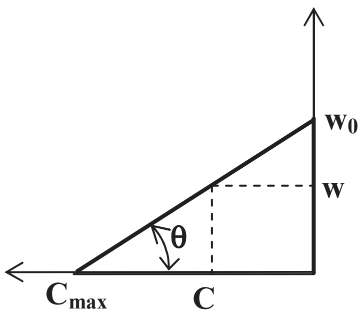

Fig. 8. Geometrical relationships used to determine deformation depth *C*.

The following relationships can be seen when analysing Fig. 8:

$$w_0 = C_{max} \cdot tg\theta \qquad (14)$$

$$C = C_{max} - \frac{w}{tg\theta} \qquad (15)$$

When taking the above into account, we will obtain:

$$
\begin{aligned}
W_D &= \int_0^{w0}\left[A\cdot\left(C_{max}-\frac{w}{tg\theta}\right)+\frac{1}{2}B\cdot\left(C_{max}-\frac{w}{tg\theta}\right)^2\right]\cdot dw \\
&= \int_0^{w0}\left[A\cdot C_{max}-\frac{A}{tg\theta}\cdot w+\frac{1}{2}B\cdot C_{max}^2-\frac{B\cdot C_{max}}{tg\theta}\cdot w+\frac{B}{2tg^2\theta}\cdot w^2\right]\cdot dw \\
&= A\cdot C_{max}\cdot w_0-\frac{A}{2tg\theta}\cdot w_0^2+\frac{1}{2}B\cdot C_{max}^2\cdot w_0-\frac{B\cdot C_{max}}{2tg\theta}\cdot w_0^2+\frac{B}{6tg^2\theta}\cdot w_0^3
\end{aligned}
\tag{16}
$$

The applying of formula (14) to the above will result in the following:

$$
\begin{aligned}
W_D &= A\cdot C_{max}^2\cdot tg\theta-\frac{A}{2tg\theta}\cdot(C_{max}\cdot tg\theta)^2+\frac{1}{2}B\cdot C_{max}^3\cdot tg\theta \\
&-\frac{B\cdot C_{max}}{2tg\theta}\cdot(C_{max}\cdot tg\theta)^2+\frac{B}{6tg^2\theta}\cdot(C_{max}\cdot tg\theta)^3 \\
&=\frac{1}{2}A\cdot C_{max}^2\cdot tg\theta+\frac{1}{6}B\cdot C_{max}^3\cdot tg\theta
\end{aligned}
\tag{17}
$$

This means that if the value of the maximum deformation C_{max} is known then, having estimated the values of coefficients A and B, we will be able to calculate the work of deformation of the vehicle body W_D.

The method of determining the magnitude of deformation for any deformation type has been described in the operation manual of the *Cash 3 Analyzer* software and in many publications dedicated to collisions of automotive vehicles. The source publication dealing with this issue is the one specified in the list of references as item [5].

The values of coefficients A and B may be estimated with taking results of experimental research as a basis. The information on the A and B values may be chiefly obtained from the results of crash tests published by the US organisation NHTSA (*National Highway Traffic Safety Administration*) on its website. Such data may also be found in *Accident Reconstruction Journal*. The A and B values averaged for specific vehicle categories may also be used.

The A and B values for passenger cars categorised according to the US system as mini, subcompact, compact, intermediate, and vans, are given in Table 2 [11].

Table 2. The *A* and *B* coefficient values

Description	Mini	Subcompact	Compact	Intermediate	Vans
Wheelbase [m]	2.05÷2.40	2.40÷2.58	2.58÷2.80	2.80÷2.98	2.76÷3.30
Wheel track [m]	1.29	1.38	1.49	1.57	1.71
Length [m]	4.05	4.44	4.98	5.40	4.66
Width [m]	1.54	1.70	1.84	1.95	2.00
Mass [kg]	1 000	1 386	1 610	1 928	1 952
FI – *A* [N/m]	52 900	45 400	55 500	62 300	67 100
FI – *B* [N/m^2]	320 000	300 000	390 000	230 000	870 000
RI – *A* [N/m]	64 100	68 500	71 800	62 500	52 500
RI – *B* [N/m^2]	260 000	280 000	300 000	90 000	380 000
SI – *A* [N/m]	13 500	24 500	30 300	25 000	–
SI – *B* [N/m^2]	260 000	460 000	390 000	340 000	–

FI – frontal impact, RI – rear impact, SI – side impact

8. Comparative analysis of specific types of the energy dissipated during a vehicle impact against the portable concrete barrier

The calculations given below have been presented to show the method of compiling the energy balance of a vehicle impact against the portable concrete barrier.

For the analysis, the experimental data published in report No. FHWA/TX-02/4162-1 were used. The analysis was carried out for the experiment described in the first part of the report (test 441621-1) [1, 2].

A 1996 Chevrolet 2500 pickup truck of 2105 kg gross kerb weight was used for the test. The impact resulted in a rotation of two barrier segments (Fig. 9).

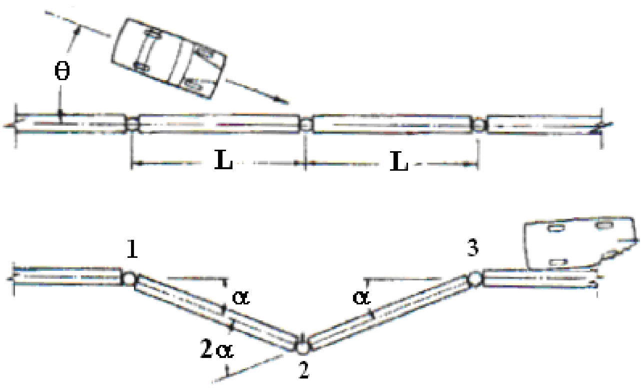

Fig. 9. Schematic diagram of the displacement of barrier segments.

The mass of a barrier segment was determined from its dimensions and mass density of concrete. The overall length of each segment was *L*=9.14 m (30 ft). The dimensions of the barrier segment cross-section are shown in Fig. 10.

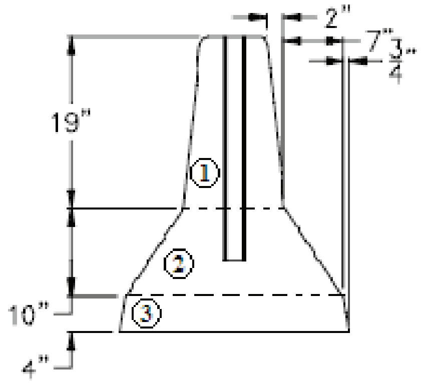

Fig. 10. Dimensions of the barrier segment cross-section (in inches) [1, 2]

The width of the barrier base, although not shown in the illustration but necessary to calculate the segment cross-section area, was estimated with taking as a basis the other dimensions as well as an assumption made that the actual proportions have been maintained in the illustration. Thus, the barrier base with was assumed as 24.5', i.e. 0.62 m. The cross-sectional area was determined as the sum of three trapeziums ①, ②, and ③, which totalled A_s=0.25 m^2. The length of each segment was L=9.14 m (30 ft); hence, the volume of a barrier segment was V_s=2.29 m^3. The mass of the i-th barrier segment was estimated by multiplying the segment volume by the mass density of concrete, from which the barrier segment was made. At an assumption that the mass density of concrete was γ=2 500 kg/m^3, the segment mass was determined as $m_{Bi}=\gamma \cdot V_s$=2 500 kg/m$^3\cdot$2.29 m^3=5 722 kg.

The vehicle impact against the barrier caused energy dissipation related to the displacement of barrier segments, friction in the connections between barrier segments, friction between the vehicle body and the lateral face of the barrier, and deformation of the vehicle body.

According to Fig. 9, the following constituents of the energy balance should be determined:

- W_α – work of friction related to the rotation of two barrier segments;
- W_{P123} – work done at the 1st, 2nd, and 3rd connections between the barrier segments;
- W_B – work of friction of the vehicle moving along the lateral face of the barrier;
- W_D – work of deformation of the vehicle body.

The work of friction related to the rotation of the i-th barrier segment was calculated with the use of formula (5). The parameters of the friction function $\mu(\alpha)$ shown in Fig. 3 were assumed as follows. Based on the data given in Table 1, the friction coefficients were estimated at μ_0=0.7 and μ_p=0.5. Both of the barrier segments rotated by an angle of α_2=12°. Moreover, a value of α_1=0.5° was taken for the calculations. Thus, the changes in the friction coefficient values are now described by the following function: $\mu(\alpha)$=0.7 for $\alpha \le 0.5°$ and $\mu(\alpha)$=0.5 for $0.5° \le \alpha \le 12°$. In result of the calculations made, the work of friction of the two segments was determined as W_α=54 906 J.

The work W_{P123} done at the 1st, 2nd, and 3rd connections between the barrier segments was determined from formula (8).

The parameters of the moment function $M(\alpha)$ shown in Fig. 5 were assumed as follows:

- angle of rotation at which the moment at the connection between barrier segments begins increasing (i.e. the angle of initial rotation related to the play in the joint): α_{P0}=2° (for each connection);
- angle of rotation at which the moment of resistance at the connection between barrier segments reaches it maximum: α_{P1}=3° (for each connection);
- angle of rotation at connections 1 and 3: $\alpha_{P1,3}$=12°;
- angle of rotation at connection 2: α_{P2}=24°.

Thus, the changes in the moment at the connections between barrier segments are now described by the following function: $M(\alpha)=0$ for $\alpha \le 2°$; $M(\alpha)=M_P/1°$ for $2° < \alpha \le 3°$; $M(\alpha)=M_P$ for $\alpha > 3°$.

The value of moment M_P was estimated as follows. Assuming the angular stiffness of the connection k_α=1 000 Nm/1°, we obtain $M_P = k_\alpha \cdot (\alpha_{P1} - \alpha_{P0})$=1 000 Nm/1°·(3°–2°)=1 000 Nm. In result of the calculations made, the work done at the 1st, 2nd, and 3rd connections between the barrier segments was determined as W_{P123}=720 J.

The work of friction of the vehicle moving along the lateral face of the barrier was determined from formula (10), with the gross kerb weight of the vehicle being taken as m=2 105 kg.

The average vehicle deceleration before the vehicle's loss of contact with the barrier was determined experimentally as a_B=0.6g=5.88 m/s^2. Since $a_B \approx \Delta v/\Delta t$, the decrement of vehicle velocity resulting from the friction against the lateral face of the barrier was $\Delta v = a_B \cdot \Delta t$. According to the experimental data, the time of vehicle's contact with the barrier was $\Delta t \approx 1.6$ s. Based on the estimated values of vehicle deceleration and time of vehicle's contact with the barrier, the decrement of vehicle velocity during the vehicle's contact with the barrier was calculated as $\Delta v = a_B \cdot \Delta t$=5.88 m/s^2·1.6 s=9.4 m/s.

The vehicle velocity when the vehicle began to rub against the lateral face of the barrier was v=28.16m/s. Hence, the vehicle velocity after a time of Δt was $v_k = v - \Delta v$=28.16 m/s–9.4 m/s=18.76 m/s.

The average vehicle velocity during the contact with the barrier was $v_{śr} = 0.5 \cdot (v + v_k)$=0.5·(28.16+18.76) m/s=23.46 m/s. Hence, the distance covered by the vehicle during the same time Δt was $s_B = v_{śr} \cdot \Delta t$=23.46 m/s·1.6 s=37.5m.

Based on the above data, the work of friction of the vehicle moving along the lateral face of the barrier was $W_B=m \cdot a_B \cdot s_B$=2 105 kg·5.88 m/s^2·37.5 m=46 4152 J.

The work of deformation of the vehicle body was calculated from formula (17). Based on experimental data [1, 2], the following values were determined:

- angle of impact of the vehicle against the barrier: θ=25.2°;
- maximum deformation of the vehicle body: C_{max}=0.8 m;
- coefficients of the collision model (according to Table 2): A=25 000 N/m; B=340 000 N/m^2.

The result of the calculations made was W_D=3 627.6 J.

A comparison of the values of specific types of the energy dissipated is presented in Fig. 11.

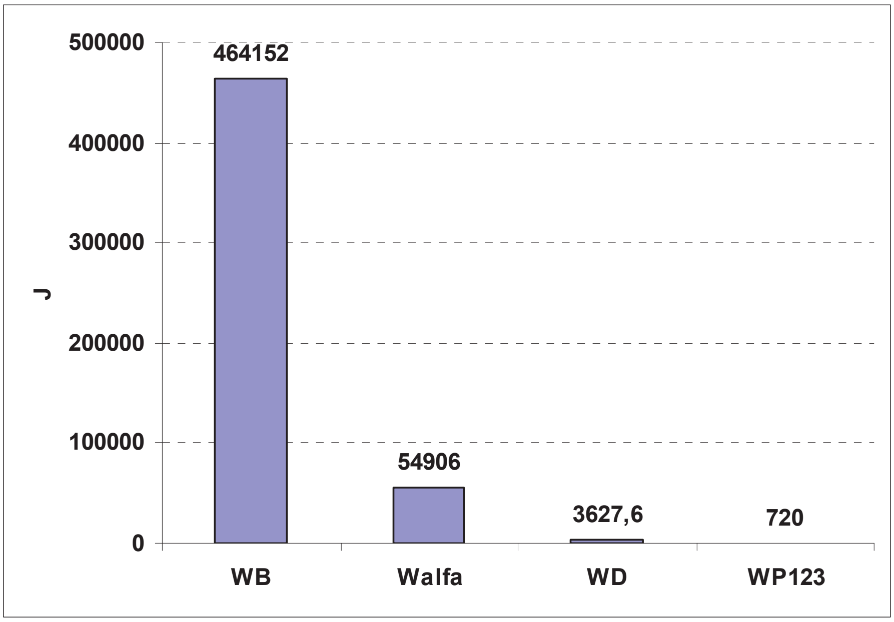

Fig. 11. Comparison of the values of specific types of the energy dissipated

9. Conclusions

The formulas given in this paper make it possible to estimate the values of individual constituents of the balance of the energy dissipated during the impact of a vehicle against a portable concrete barrier. Calculations made for the data obtained from the research work described in report No. FHWA/TX-02/4162-1 have revealed the following:

- The work of friction of the vehicle moving along the lateral face of the barrier makes a predominating part of the total energy dissipated. This shows that an important objective to be pursued when engineering the segments of a portable concrete barrier is to prevent the rebounding of vehicles from the barrier after the impact. This is closely related to the correct engineering of the connection between individual barrier segments in order to obtain the "chain effect."

- The slidable barrier segments dissipate a significant part of the vehicle impact energy, which confirms the reasonability of the use of portable concrete traffic barriers.
- The share of vehicle body deformation in the energy balance is of minor importance. It should be remembered, however, that the pattern of vehicle body deformation is important for the vehicle driver and passengers. The vehicle body should be so engineered that the possibility of intrusion into the "survival space," which is identical with the passenger compartment in the case of passenger cars, should be reduced to a minimum.
- The amount of energy dissipated in the connections between barrier segments is negligible. This means that the most important feature of a well-engineered connection is the enabling of continuous contact of the vehicle body with the lateral face of the barrier, i.e. the causing of the "chain effect." This effect strongly influences the work of friction of the vehicle body while the value of this work predominates in the balance of the energy dissipated.

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