Analysis and mathematical modeling of cable barrier mechanics during car impact

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Abstract. The article discusses the mechanics of the response of cable barriers used in Russia. The first part of the article describes the general mechanics of the barriers. The second part describes the mechanics of the open-type posts, the most commonly used type worldwide. In the third part, accidents with closed-type posts are classified. The latter are unique structures that were developed in Russia to significantly reduce the deflection of barriers (by 35-50%). Understanding the principles of their response is not required for the further development of their structure only but also for the creation of their digital models since accurate models can only be developed if key physical processes are taken into account.

1. Introduction

Problems with passive road safety become clearer if we evaluate them in terms of fatalities per 1 billion kilometres traveled by vehicles. Such estimate gives more explicit information about the car-road infrastructure interaction period and the total number of cars than the death rate in road accidents per 100 thousand people. According to this indicator, in 2018 15.7 people per 1 billion km of car mileage were killed in Russia, 7.0 in the USA, 6.7 in Japan, 6.8 in Germany [1], which shows that the country falls significantly behind from developed countries.

The main way to reduce the severity of road accidents is road barriers, and one of the types are cable barriers (Figure 1). All cable barriers are similar in design and consist of cables, posts, anchor blocks, tension straps, and sleeves [2].

Figure 1. Cable road barriers
Since real-life testing is quite expensive, computational modelling has become the main tool for the analysis of road barriers. The models are built on the basic equations of continuum mechanics and perform many operations automatically, nevertheless, none of them is fully automated yet. The most difficult part is the selection of kinematic constraints, as well as the choice of the equation of state, and the constitutive equations of the material; also the choice of models of the main structural elements of barriers (usually, these are finite element spatial models) is a complex task. This cannot be done without understanding the mechanics of the object and defining the most difficult issues for modelling.

2. Operating principles of cable barriers

The response of the barrier comprises three successive stages. At the first stage, the vehicle begins to deflect the cable of the barrier (Figure 2a), generating stress \(T\) in the cable, which is transmitted to the vehicle itself, as well as to the posts nearest to the active zone (Figure 2b). The friction forces of the wheels with the pavement \(F_w\) and \(F_{rw}\) at the beginning of the impact prevent the vehicle from turning, hence, it continues to move in the initial direction, increasing the cable deflection.

![Figure 2. Interaction between the vehicle and the barrier: (a) the initial moment of impact, (b) free-body diagram of the vehicle](image)

With an increase in the strain of the cable and overcoming of the friction forces, the second stage begins: the vehicle turns around the centre of gravity (G). The turn takes place until the vehicle body is parallel to the cable (Figure 3).

![Figure 3. The second stage of vehicle – barrier interaction](image)

As the vehicle turns, the stresses in the cable reach values sufficient to deform the posts of the barrier. At this stage, the further development of events is almost completely determined by the type of posts of cable barriers. Therefore, let us take a closer look at the mechanics of their response.

3. The response of the posts of cable barrier during the impact

The cable barriers are divided into two large groups: open-type and closed-type (For more details, see. ODM 218.6.018-2016). During the impact, the open-type posts only limit the transversal displacement of the cable, imposing almost no constraints to the vertical movement. The closed-type posts remain fully or partially connected to the barrier throughout the entire impact and cannot move vertically relative to the cable without destruction.
3.1. Open-type posts

3.1.1 Operating principle

When the vehicle hits the barrier, the forces in the cable reach values high enough to form a plastic hinge at the base of the post (Figure 4). The post is gradually pressed to the ground (Figure 4b) and, after complete deformation, ceases to bear any load or hinder the movement of the vehicle.

![Diagram](image1.png)

**Figure 4.** Open-type posts operation mechanics: (a) diagram, (b) test results

The deformation of the posts leads to an increase in the active zone of the cable and a decrease in the angles between the cable and the posts of the barrier (angles $\alpha$, $\beta$; Figure 3). A decreased angle results in a decreased stress impacting the next post, therefore it begins to limit the working zone of the cable until the deflection of the barrier and the increasing stress in the cable increase the angle enough to cause a complete deformation of the post. This process repeats until the vehicle turns in the direction opposite to the direction of impact, or the energy accumulated in the cable is high enough to overcome the frictional forces and force the vehicle back to its lane.

If the posts stiffness is low, when the vehicle gets closer to the post, the post has already partially or completely deformed. Therefore, there isn’t any significant damping of speed in the longitudinal direction, deformations of side members and other load-bearing body elements, separation of parts (Figure 5). This ensures a constant geometry of the vehicle and the barrier in the contact area and stability of the collision process. After the interaction with these barriers, the vehicle is restorable, and the accelerations at the impact that determine the injury index are relatively small.

![Damage](image2.png)

**Figure 5.** Damage to vehicles after collision with a road barrier. Open-type posts: (a) low stiffness, (b) high and medium stiffness

With an increase in the stiffness of the posts, the loads on the car body increase, which leads to increased accelerations that affect the passengers and can cause significant deformations of the car body and the loss of the collision stability. It should be noted that a decrease in the stiffness of the posts leads to an increase in the deflection of the barriers.

3.1.2 Energy absorption structure in barriers with open-type posts
From an energy point of view, the collision is a process of converting the kinetic energy of a vehicle into the internal energy of cables, the work of friction forces in contact pairs, and the work of forces causing plastic deformation of the posts, as well as losses due to internal friction in structural elements.

The structure of these responses and the components of the absorbed energy, as well as their influence on the behaviour of the vehicle and the barrier, were experimentally studied in [3], using 3 full-scale tests of a pickup-car collision. Table 1.1 shows the results of the study. Frictional energy losses were determined from the marks on the barrier and the pavement; since this determination method is not very accurate, the values are presented in ranges.

**Table 1.1. Energy losses at the vehicle - cable impact [3]**

| Test No. | Vehicle energy, kJ | Posts deformation response, kJ | Friction forces, kJ | Energy in the cable, kJ |
|----------|-------------------|-------------------------------|--------------------|------------------------|
| Initial  | Final             | Tyres-road | Vehicle-barrier |                               |
| 1        | 770.4             | 318.8     | 86.0            | 135.3 – 238.9           | 63.9-95.7  |
| 2        | 862.9             | 743.2     | 24.5            | 13.4-20.2              | 41.6       |
| 3        | 850.5             | 540.2     | 64.4            | 118.9-217.7            | 56.0-84.1  |

The results of the study showed that the barrier can absorb up to 60% of the kinetic energy of the vehicle, of which: up to 13% is transformed into plastic deformation of the posts, up to 31% is spent on friction in a pair tyre-road, up to 15% - on friction in a vehicle-barrier pair, up to 10% is transformed into the internal energy of the cable, of which, according to the authors' estimates, up to 3% is dissipated by the cable. It should be noted that the structure of energy absorption requires further research due to the small sample used in the study and the inaccuracy of estimation of some values. A more accurate energy absorption study can be carried out using computational modelling methods, which would allow not only to analyze various design options but also to estimate energy losses due to friction more accurately.

**3.2. Closed-type posts**

The characteristic feature of closed-type posts is that they do not disconnect from the cable during deformation, in part or completely. Closed-type posts act similarly to the open-type posts until they form a plastic hinge. After the hinge has formed, the post starts rotating around the hinge towards the road (Figure 3b).

![Figure 5. Closed-type barrier posts: (a) before impact, (b) at the initial moment of impact, (c) after impact. Damaged post, (d) A post severed from the road after impact.](image)

Since the cables stay rigidly connected to the post, they, unlike the cables of the open structures, cannot maintain their vertical position and continue moving towards the surface of the road together with the post (Figure 5b). This generates a surface comprising cables and posts and inclined to the...
surface of the road that the vehicle can cross to drive onto the barrier. We will call this inclined surface of cables and posts that a vehicle can use to drive onto a barrier a "ramp". Some designs provide mechanisms for the release of the cables, such as zones of planned destruction (Figure 5c) or shallow positioning of the posts (Figure 5d), which allows the posts itself to move relative to the road without restricting the vertical movement of the cable, thus reducing the ramp effect. In all available designs, the vehicle comes into direct contact with the post, which can cause different consequences depending on the strength of the car body, the initial collision angle, and the collision speed.

If the car body and suspension are stiff enough not withstand deformation and destruction on contact with the post, the vehicle itself will press the cables against the road, forming a ramp that allows the vehicle to climb the barrier (Figure 6). In most cases, the vehicle's energy is not enough for a complete crossing of the barrier, and the vehicle ends up "hanging" on the cables without crossing to the wrong lane. This shall be considered a positive outcome, since staying on the oncoming lane significantly reduces the severity of an accident.

![Figure 6. Partial crossing of the barrier (the vehicle is "hung" on the fence): (a) a passenger car, (b) an off-road vehicle, (c) a lorry](image)

This happens most often with the vehicles with a high centre of gravity (off-road vehicles) and heavy vehicles (vans and trucks). In all cases the height of the barrier decreases and the posts are pressed to the road according to the mechanism described in Figure 5.

For passenger vehicles, the most important impact parameters are: angle and speed of collision, as well as the place of impact. If the approach angle is small and the impact occurred close to the post, the vehicle will not be able to deflect the cable enough to form a ramp. This will prevent crossing to the wrong lane, but will lead to a collision with the barrier post. If the initial speed of the vehicle was low, then the impact energy will not be enough for severing and deformation of the suspension. Therefore, the vehicle will start rotating relative to the contact zone formed by the deformed wing of the car, the suspension and the post (Figure 7a, b). After the vehicle turns 90 degrees, it suffers a second impact from the collision with the barrier with its front part, however, due to the high stiffness of the barrier, the vehicle only slightly crosses to the oncoming lane. If the speed of the vehicle and the energy are high enough, then the front suspension of the vehicle can completely detach from the vehicle, a partial turn occurs, and the vehicle continues sliding along the barrier, with repeated collisions of much lower energy (Figure 7a).

Comparing to other barrier types, a disproportionality of damage to the vehicle relative to the impact energy should be noted. For rail-type and parapet barriers, if the impact occurs with a low angle or energy, the vehicle will exit tangentially without significant damage. In cable barriers, even at very low angles and high speeds, a car wing will be crushed or the suspension detached, which significantly damages the vehicle.
Figure 7. A vehicle after a collision: (a) a vehicle turns without destruction of the suspension, (b) the suspension is completely destructed, (c) reduction of the bodywork area.

At high angles and collision speeds, the two situations above are combined, because the vehicle has enough energy to create a ramp and partially run over the barrier, which reduces the load on the bodywork (Figure 8). The barrier is crossed when the allowed impact energy on the barrier is exceeded (Figure 8c).

Figure 8. Damage at large impact angles: (a) partial run over the barrier over the ramp, (b) partial crossing of the barrier, (c) complete crossing of the barrier.

The most dangerous collision cases are impacts when the contact area is in the area between the side members of the car, close to one of them (Figure 9a), as well as in the cases of roll cages with low stiffness. The consequences of such impacts are similar to the crash test of cars with a 25% displacement (Figure 9), which is considered one of the most difficult operational conditions for the bodywork because of a high asymmetry of the impact.

Figure 9. Vehicle after impact: (a) cable barriers, impact not to the side members, (b) cable barriers, impact to the side members, (c) crash test with 25% overlap.
4. Conclusions

In most cases, cable barriers are effective for their purpose: they prevent frontal collisions of vehicles and reduce the severity of road accidents. The analysis of cable barriers with closed posts shows that the collision process follows different scenarios depending on the initial conditions of the impact. The initial conditions at the vehicle-barrier collision are largely random and circumstantial. During certification tests, only 1 passenger car collision is carried out and the latter - under rather limited conditions, which does not allow to fully understand whether other collision development scenarios are safe for drivers. Therefore, if one certification test with a passenger car is maintained, an understandable principle of the barrier action shall be achieved, which would be strictly followed during the entire collision process; otherwise, the safety of the barrier for the roads cannot be guaranteed.

References
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