Application of digital modeling to determine design criteria for mobile frontal barriers

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Abstract. The work is devoted to the issues of finite element modeling of mobile frontal barriers (MFB, truck mounted attenuators, mobile crash cushions), based on computer simulation of digital modeling of the behavior of elements in the MFB system, which includes a cover truck and a test vehicle designed to ensure the safety of road workers, when they are hit by cars in places of works on public roads that require temporary changes in the organization of traffic. It discusses various designs of trailer MFBs, the basic principles of damping devices, and defines the criteria for developing structures, based on digital mathematic modeling by the finite element method (FEM).

1. Introduction
Collision of vehicles (V), mainly cars, with a cover truck in the places of road works is one of the most dangerous types of road traffic accidents (RTA). A radical way to increase safety in such collisions is the installation of mobile frontal barriers (MFB) either directly on cover trucks or as a non-self-propelled trailer [1, 10] (figure 1). The use of this kind of security systems can reduce the number of victims from 44% to 35%, and the death rate from 19% to 4% [8]. Currently, active work is underway to create domestic MFB designs, but engineers are faced with a large number of difficulties due to the lack of knowledge of their mechanics. Digitalization is one of the main trends in the Russian economy, so digital models were the basis for the work. In this article, on the basis of digital modeling, the mechanics of the operation of the trailer MFB, one of the MFB types, is considered, typical problems of the structure's operation are highlighted and requirements for the safety of the structure and testing are formulated.

The vehicle and a structure collision process is fast (not more than 0.5 s), with complex boundary conditions in the form of contacts and restrictions on displacements, accompanied by large displacements and deformations in the system; therefore, to solve the problem, the finite element method was used in an explicit formulation. All calculations have been performed using the LS-DYNA software package [4].
Figure 1. Collision with a shadow vehicle, covering road works: a — without an impact attenuation system, b - with an impact attenuation system

2. MFB operating principle
The main task of impact attenuation systems like MFB is to absorb the kinetic energy of an oncoming vehicle, then stop or redirect it along a safe path.

Figure 2 shows some designs of foreign manufacturers [12, 13]. The oncoming vehicle impact attenuation in such structures is carried out by the work of deformation, friction forces or destruction of specially designed MFB structural elements [6, 7, 12, 13] (figure 3).

Figure 2 Trailler MFB designs: (a) - Vorteq, (b) - Scorpion II

Figure 3. An example of energy attenuation at the impact to a MFB due to: (a) deformation, (b) friction, (c) destruction

The behavior of the vehicle and the risk of injury upon impact can be described by the following parameters: roll and pitch angles (rotation around the longitudinal and transverse axes of the vehicle), speed and the driver and passengers head overload, the center of gravity (CG) overload. These characteristics can be obtained by a number of tests [3, 5]: direct impact over the MFB axis, direct impact with displacement, and impact at a 10° angle to the MFB axis with displacement. However, in the real conditions it is impossible to predict the initial impact parameters, therefore, the general operation principle of the impact attenuation system should be maintained regardless of the vehicle collision conditions.

When designing, it is possible provide for an additional absorbing capacity, but there are restrictions on the mass-dimensional characteristics [11]: width, height and mass, so the design process becomes a non-trivial task.
3. Finite element model of MFB construction and virtual model of crash test

The investigated MFB (figure 4) is a structure of steel bent sections and sheets with a thickness of 2.8 - 5 mm, fastened to each other by bolted and welded joints, mounted on a uniaxial suspension. Energy absorption occurs due to deformation and the formation of plastic hinges.

The FE model was built using shell elements with the application of an elastoplastic material model MAT_024_PIECEWISE_LINEAR_PLASTICITY with setting the true deformation curve and strain rate sensitivity constants according to the Cowper-Symonds model [4].

![Figure 4. The main components of the MFB structure are: 1 - draw-bar, 2 - fairing frame, 3 - frame, 4 - wheels with axles, 5 - rear bumper reinforcement](image)

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Figure 5 shows the complete FE model of a virtual test (crush-test), consisting of a cover truck with a MFB attached to it, and an oncoming car weighing 1500 kg at a speed of 70 km/h.

![Figure 5. FE model of a virtual test with a collision along the axis of the MFB device](image)

Figure 5. FE model of a virtual test with a collision along the axis of the MFB device

The after-collision view of the MFB obtained during the virtual test is shown in figure 6. The local area of impact is located below the center of gravity of the MFB, therefore, the resulting bending moment led in this case to the loss of stability of the draw-bar due to its insufficient rigidity. As a result, the longitudinal axis of the main impact attenuation part of the structure (frame) deflected from the initial position and turned out to be in a vertical position. Figure 7, a and b shows the process of deformation of the draw-bar, and figure 7, c - a general view of the energy-absorbing frame after impact.

![Figure 6. The MFB after the impact](image)

Figure 6. The MFB after the impact
Figure 7. MFB structural elements deformation: (a), (b) draw-bar, (c) frame

For such damping systems as MFB, the sequential inclusion of structural elements in operation, starting from the point of impact, is the preferred case, while, in our example, the elements are deformed in a chaotic way (figure 8).

Figure 9 presents a chart of the change in the speed of the CG of an oncoming vehicle during an impact, showing an area without a decrease in speed, which indicates the ineffectiveness of the considered structure.

Figure 8. The time dependence chart of the energy absorbed by the MFB parts and the vehicle

Figure 9. The chart of the vehicle speed change over time

Also, this MFB was tested with a displaced angle impact from a car (figure 10) with similar speed and mass, 70 km/h and 1500 kg, respectively. With such test parameters, the impact area is displaced relative to the CG of the MFB downward and sideways, and the force vector is at an angle, which leads to eccentric tension-compression and torsion of the structure.
This resulted in a negative test result: the vehicle lifted the guardrail and drove under it (figure 11). The speed of the approaching vehicle after contact with the MFB was 40 km/h, after which there was a collision with the rear of the cover truck. This result, as in the first case of impact, was due to the draw-bar low bending rigidity.

![image]

**Figure 10.** Testing the MFB at a 10° angle to the axis with an off-set

![image]

**Figure 11.** MFB after impact at an angle with an off-set

### 4. Formulation of principles for designing MFB

When designing MFB, it is necessary to structurally ensure longitudinal compression: the impact load must be evenly redistributed over the entire cross section.

In case of a direct impact, the uniformly retarded motion of the vehicle is achieved by selecting the rigidity of the main energy-absorbing elements and the geometry of the MFB. The height is selected in such a way so as to exclude oncoming vehicle driving under or onto the MFB during the impact, which can lead to serious consequences, and the CG of MFB should be at the impact level.

When the impact is produced with an off-set or at an angle, the MFB structure is subject to eccentric extension-compression, therefore, the bending rigidity must also be correctly selected. However, this will only partially solve the problem, since the rotational degree of freedom remains in the hinge of the trailer. Therefore, draw-bars with a telescopic structure [7] (figure 12, a, b) or hydraulic dampers [9] (figure 12, c) are used in the structures of the MFB, which allow preventing the MFB from turning during the impact.
5. Analytical model for calculating the length of a trailer MFB

The design principles formulated above and the prerequisites for them made it possible to develop an analytical model for calculating the length of the MFB, developed for a certain impact energy. The resulting overloads upon impact should not exceed the permissible values, specified in regulatory documents [3, 5].

To determine the minimum distance $S$ that the CG of the vehicle must pass upon impact, the equation of uniformly accelerated motion is used:

$$ S = \frac{v^2 - v_0^2}{2 \cdot a} $$

(1)

where:
- $v$, $v_0$ – initial and final vehicle speeds, m/s,
- $a$ – acceleration of the CG of the vehicle, m/s$^2$.

In case of an ideal impact, when the CG of a vehicle performs uniformly retarded motion along the longitudinal axis of the impact, only longitudinal accelerations occur $N_x$. They can be expressed in terms of the formula (2), which is used to find the injury severity index $I$ [2]:

$$ I = \left[ \left( \frac{N_x}{12} \right)^2 + \left( \frac{N_y}{9} \right)^2 + \left( \frac{N_z}{10} \right)^2 \right]^{0.5} $$

(2)

where:
- $N_x, N_y, N_z$ – average values of a vehicle CG overloads in g fractions along X, Y, Z axes, m/s$^2$.

Next, the formula (2) is used and the overload along the longitudinal axis of the impact is expressed:

$$ N_x = I \cdot 12g $$

(3)

Substitute $N_x$ into formula (1):

$$ S = \frac{v^2}{2 \cdot N_x \cdot g} = \frac{v^2}{24 \cdot I \cdot g} $$

(4)

where:
- $v$ – vehicle speed before impact, m/s.

Thus, using formula (4), it is possible to determine the minimum distance that the CG of the vehicle must travel when driving over the MFB down to a standstill.

It is also necessary to take into account the margin for the deviation of the vehicle CG upon impact from the longitudinal axis, at which vertical and lateral accelerations occur, as well as the residual length of the deformed MFB elements. This distance is called the safety length $S_a$ and is found using the formula:

$$ S_a = S \cdot k,$$
where:
k – safety factor.

Figure 13 shows a diagram for determining the length of the MFB draw-bar, determined by the formula:

\[ l = l_1 + l_2 + l_3, \]

where:
\( l_1 \) - the distance from the trailer to the rear surface of the body of the cover truck,
\( l_2 \) - safety length when turning,
\( l_3 \) - the distance from the back surface of the cover truck body to the main energy-absorbing part of the MFB.

Distance from the back of the cover truck to the surface of the MFB - \( l_2 \) depends on the width of the cover truck. Also, it is necessary to take into consideration the trailer location \( l_1 \) and some margins \( l_2 \) required when turning. If the height of the MFB is lower than the height of the lower surface of the cover truck body, then the length of the draw-bar may be less, because, when turning, the MFB will pass under the truck body. It can also \( l \) be less if there is a limitation on the angle at which the MFB can turn when moving, or if the width of the MFB is reduced.

![Figure 13](image)

**Figure 13.** Calculation of the length of the MFB draw-bar: 1 - shadow vehicle, 2 - MFB

In total, the required full length of the MFB was obtained:

\[ L = S_3 + l = \frac{v^2}{24 \cdot l \cdot g} \times k + l_1 + l_2 + l_3 \]

6. **Conclusions**

On the basis of the conducted virtual analysis using digital simulation modeling of the collision of a trailer MFB and a vehicle, the mechanics of work, the ongoing processes and design features of the MFB were studied. The possibility is shown using the example of the proposed energy method to assess the effectiveness of the MFB and its capacity to cope with its task which is the safe stop of an oncoming vehicle. This made it possible to formulate recommendations for the designs of trailer MFB and develop an analytical model for calculating their length for a given value of the injury index \( I \) [3].

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