Design issues of energy-absorbing truck mounted attenuators

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Abstract. The work is devoted to the issues of finite element modeling of energy-absorbing truck mounted attenuators (TMA) used on the shadow vehicles in the zones of stationary and mobile road and construction works to protect workers from collisions with vehicles, as well as to reduce the severity of an accident for the driver who collided. Discusses various designs of TMAs, the main problems in design and defines the criteria for the development of structures based on mathematical modeling by the finite element method.

1. Introduction

The one of the most dangerous types of road accidents is a collision with a shadow vehicle. This type of road accidents is the fourth most common (6.88%) and is as traumatic as head-on collisions of vehicles. Truck mounted attenuators (TMAs) fixed on shadow vehicles are used to reduce the severity of accidents [1, 2] (figure 1). The use of such security systems can reduce the number of victims from 44% to 35%, and the death rate from 19% to 4% [3]. Currently, persistent efforts are underway to create local TMA designs, but engineers are faced with a large number of difficulties due to the lack of knowledge of these devices mechanics. Digitalization is one of the main trends in the Russian economy, therefore, the work was based on digital models, which make it possible to predict the behavior of a structure with high accuracy throughout the entire life cycle. This article, based on a digital model, examines the TMAs mechanics of one of the types, highlights the typical problems during operation and formulates requirements for design and testing safety. The work was carried out as part of the GOST R development "Public roads. Truck mounted attenuators. General requirements. Test methods" with the Federal Road Agency (FRA) support.

Figure 1. Collision with a shadow vehicle, covering road works: (a) without an impact attenuation system, (b) with an impact attenuation system.
2. The operation principle of the impact attenuation systems

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

Figure 2 shows some TMA designs by foreign manufacturers [4, 5]. The oncoming vehicle impact attenuation in these structures is carried out by the work of deformation, friction forces or destruction of specially designed TMAs structural elements [6, 7, 8] (figure 3).

![Figure 2. Truck mounted TMAs designs: (a) TTMA-100, (b) SST trailer.](image)

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 vehicle center of gravity (CG) overload. These characteristics can be obtained by a number of tests [9, 10]: direct impact over the TMA axis, direct impact with displacement, and impact at an 10° angle to the TMA 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 collision conditions.

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. Next, we will consider the impact attenuation system structure, and, based on it, will formulate the basic design principles of these systems.

3. Study of the impact attenuation system structure by the finite element method (FEM)

Figure 4 shows a TMA based on the deformation principle of energy absorption due to the formation of plastic hinges. The main energy-absorbing element is the steel frame to which the draw-bar, fairing frame and rear bumper reinforcement are attached. The structure is mounted on a single-axle suspension and is attached to the shadow vehicle hitch with a steel loop.

The structure consists of rectangular sections and sheet stamped and bent parts with a thickness of 2.8 - 5 mm, therefore, the developed finite element (FE) model was built with shell elements. The shell elements size is 5 mm. In the FE model, an elastoplastic model of the material
MAT_024_PIECEWISE_LINEAR_PLASTICITY was used with the specification of the full deformation curve and the constants of the effect of strain rates according to the Cooper-Symonds model [11].

The structure has connections that should be disconnected during the operation of the attenuators. They connect the draw-bar arch with the crossbar (figure 5 (a)), and parts of the coupling (figure 5 (b)). Based on this, these connections were modeled using FE models of bolts. In other bolted connections, were used CNRB elements, rigidly connecting the parts to each other.

Figure 5. Collapsing joints during the TMA operation are: (a) the arc and the draw-bar connection, (b) the coupling connecting parts.

Figure 6 shows the complete FE model of a virtual test, consisting of a shadow vehicle with an TMA attached to it, and a driving vehicle weighing 1500 kg at a speed of 70 km·h⁻¹.
4. Structural analysis based on the FEM calculation

Figure 7 shows the TMA after the impact. The longitudinal axis of the main impact attenuation part of the structure (frame) deflected from the initial position and turned out in a vertical position. This was due to the resulting bending moment and loss of the attenuators stability, since the point of impact was significantly lower than the central axis of the impact attenuation system structure, which the draw-bar could not withstand due to lack of rigidity. Figure 8, (a) and (b) shows the process of the draw-bar deformation, and figure 8 (c) — energy-absorbing frame after impact.

![Figure 7. The TMA after the impact.](image)

![Figure 8. TMA structural elements deformation: (a), (b) draw-bar, (c) frame.](image)

Consider in more detail the work of the structure on the internal energy of the main parts (figure 9). The impact kinetic energy was 283.56 kJ. The graph of the absorbed energy shows that the structure elements do not work sequentially and the energy absorption is interrupted (the graph is parallel to the time axis), in contrast to the most optimal case, in which energy is absorbed by the elements from the impact point to the draw-bar sequentially along the links.

The frame and the truck parts absorbed the same amount of energy during the impact: 58.9 kJ and 57.8 kJ, respectively. The draw-bar absorbed the greatest energy (67.9 kJ), which is not acceptable, since the metal consumption of the draw-bar is less than that of the frame, which is the main energy-absorbing element of the TMA structure. The TMA absorbed 180 kJ of energy in total.

Also, the work of the structure can be assessed by the speed graph of the vehicle's CG: the smoother the graph, the more efficiently energy is absorbed. However, figure 10 shows the period of time in which the vehicle does not decelerate, and the path of the vehicle in which deceleration could occur is not used.
Figure 9. The time dependence graph of the absorbed energy by the TMA parts and the truck.

Figure 10. The graph of the vehicle speed change over time.

The collision case considered above is similar to the case shown in figure 11. The beam is hinged on one side (tow hitch), in the middle the point cannot move downward (suspension). The force is applied longitudinally, below the geometric CG. The result is an eccentric compression of the attenuators.

Figure 11. Conditional scheme of the TMA test with direct impact.

In the case of an angular impact with a displacement (figure 12), the impact point is displaced relative to the TMA center of gravity not only downward, but also sideways, and also applied at an angle. As a result, there is a compression and a bending moment in two planes, which tends to deflect
the test structure up and to the side (figure 13). The TMA did not pass the virtual test: the vehicle passed under the attenuators and was not stopped. The speed of the approaching vehicle after contact with the TMA was 40 km·h⁻¹, after which there was a collision with the rear of the shadow vehicle. This result, as in the first case of impact, was due to the draw-bar low bending rigidity.

![Figure 12](image1)

**Figure 12.** Testing the TMA at an 10° angle of to the axis with displacement: (a) FE model, (b) schematic diagram.

![Figure 13](image2)

**Figure 13.** TMA after impact at an angle with displacement.

5. **Design principles**

When designing TMAs, it is necessary to strive to structurally ensure the impact redistribution of load evenly over the entire cross section, so that there is only longitudinal compression.

In the event of a direct impact, a safe uniformly slow motion of the vehicle is achieved by selecting the rigidity of the main energy-absorbing elements and the geometry of the TMA. The height is so selected that the oncoming vehicle does not run under or onto the TMA during the impact, which can lead to serious consequences, and the TMA CG should be at the impact level.

When impact with displacement or at an angle, the TMA structure is subjected to eccentric compression, therefore, the bending stiffness must also be correctly selected, but this will only partially solve the problem, since in the hinge of the hitch remains the rotational degree of freedom. Therefore, draw-bars with a telescopic structure (figure 14 (a), (b)) or hydraulic dampers [12] (figure 14 (c)) are used in the TMA designs, which make it possible to prevent the TMA from turning during the impact.
6. Conclusions

The study, based on virtual digital analysis, made it possible to study the mechanics of operation and the processes that occur as a result of a vehicle hitting a truck mounted TMA. Using the energy method as an example, it is shown how to evaluate the efficiency of the structure for the successful fulfillment of the assigned task — the safe stop of an oncoming vehicle. The constructed conditional schemes of the considered impact problem — eccentric compression with loss of stability and oblique impact, made it possible to formulate the basic principles of these safety structures designing. The performed research is the initial stage of work on the design of a domestic truck mounted TMA.

Acknowledgment

The authors are grateful to their scientific advisor, professor, doctor of technical sciences I.V. Demiyanushko for advice and attention to work.

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