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# M V M Mobility Vehicle Mechanics

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MOBILITY & VEHICLE MECHANICS

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# STRENGTH TESTING OF 3D PRINTED SPECIMENS

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RESEARCH ARTICLE

**ABSTRACT:** An important and interesting field of use of 3D printing is the production of parts exposed to physical stress. The strength of the component is influenced by many parameters. In addition to the material quality, fibre thickness, fibre direction, shape and size of the filling, possible composite fibre reinforcement, the conditions of use, e.g. UV light and air humidity also affect the component's load capacity. In our research, we examined 3D printed specimens. We examined the properties of four types of fibre fusion materials and five types of UV-hardening resins with tensile, bending, impact bending and twisting tests: PLA, PETG, ABS, ASA, Onyx, basic resin, water-washable resin, ECO resin, UV tough resin and ABS like resin test specimens made of materials were examined. The study also covered the effect of moisture content. We investigated the weight gain of the test specimens exposed to moisture as a function of time, and then the effect of the moisture content on the strength properties. After the tests, the surface of the specimens was examined with an electron microscope. The results can be well used to select the material and manufacturing technology of 3D printed parts exposed to physical stress and environmental effects.

**KEY WORDS**: *3D printing, strength test, composite 3D printing, moisture content*



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## ISPITIVANJE ČVRSTOĆE 3D ŠTAMPANIH UZORAKA

REZIME: Važna i zanimljiva oblast primene 3D štampe je proizvodnja delova izloženih fizičkom opterećenju. Na otpornost komponente utiče mnogo parametra. Pored kvaliteta materijala, debljine vlakana, pravca vlakana, oblika i veličine ispune, mogućeg ojačanja kompozitnim vlaknima, uslova upotrebe. Na primer, UV zračennje i vlažnost vazduha takođe utiču na nosivost komponente. U našem istraživanju ispitali smo 3D štampane uzorke. Ispitivali smo svojstva četiri vrste materijala za ojačannje vlakanima materijala i pet tipova smola otpornih na UV-zračenjea testovima na zatezanje, savijanje, udarno savijanje i uvijanje: PLA, PETG, ABS, ASA, Oniks, osnovna smola, vodoperiva smola, ECO smola, smole otporne na UV zračenje i ABS pomoću uzoraka napravljenih odo ovih materijala. Studija je takođe obuhvatila uticaj sadržaja vlage. Ispitivali smo povećanje težine ispitivanih uzoraka izloženih vlazi u funkciji vremena, a zatim i uticaj sadržaja vlage na svojstva čvrstoće. Nakon testova, površina uzoraka je ispitivana elektronskim mikroskopom. Rezultati se mogu dobro iskoristiti za odabir materijala i tehnologije proizvodnje 3D štampanih delova izloženih fizičkom opterećenju i uticajima životne sredine.

**KLJUČNE REČI**: *3D štampa, ispotivanje čvrstoće, 3D štampa kompozia, vlažnost*

# STRENGTH TESTING OF 3D PRINTED SPECIMENS

*Dániel Kecskés, László Tóth, István Péter Szabó*

## INTRODUCTION

There is not one way, 3D printing can be carried out. Currently, there are seven standard manufacturing processes recognized by the American Society for Testing and Materials (ASTM). All of these processes are additive in nature and differ only in the way layers are laid out. Efforts are on to innovate new processes other than the additive types, but currently only additive manufacturing processes are applicable to 3D printing.

## 1 PRESENTATION OF USED 3D PRINTING TECHNOLOGIES

### *1.1 Operating mode of FDM 3D printers*

Being an extrusion process, FDM (fused deposition modelling) involves a hot end and a cold end. The hot end is an extrusion head to which the fabrication material is supplied by unwinding plastic filament or metal wire off a coil. The wire or filament is feed to the head's nozzle in a worm-drive at a controlled rate. As the filament or wire enters the extrusion nozzle, it is heated past its glass transition temperature and gets melted.

When the molten filament or wire exits from the extrusion nozzle either exposed to air or an inert gas chamber, it solidifies immediately on a base or onto a preceding layer. The use of inert gas chambers is picking up high as it improves the adhesion of layers due to prevention from oxidation and improves the mechanical characteristics of the created object.

The extrusion nozzle is horizontally and/or vertically movable, while the base platform can move along the remaining third plane. The vertical and/or horizontal movement of the nozzle is controlled by a numerical mechanism, while its movement along the third plane is determined by a tool-path according to a computer aided manufacturing (CAM) software. The nozzle moves from bottom to up finishing deposition of each layer one after the other or remains stationary with respect to the moving platform. The motion of the nozzle is finally rectilinear in an XYZ plane guided by stepper motors. With recent innovations, deltabot has been successfully tried to move the nozzle end.

Usually in FDM, models are built using various types of thermoplastics and their support structures are generated simultaneously. The support structures are needed to keep the model in fixed orientation during the process. The materials used for creating support structures are respective soluble materials. There are two types of thermoplastics that are commonly used in FDM – Acrylonitrile Butadiene Styrene (ABS) and Polylactic acid (PLA). A number of other polymers like Polyamide (PA), lignin, Polycarbonate (PC), Polystyrene (PS), rubber etc. and some conductive materials are also used. [1]

### *1.2 Operating mode of SLA 3D printers*

The basic operation of SLA (stereolithographic apparatus) printers is based on resins (polymers) that bind to UV light. These types of printers are capable of very detailed printing, but they are more complicated to use compared to the previously presented FDMs.

This printing process is different from the production of components based on the principle of fibre fusion, as the liquid from which the test piece is built is located in a tub (VAT), the bottom of which is a thin, transparent film. Light can easily penetrate this FEP film, so its integrity and cleanliness are important. At the start of printing, the stage is immersed upside down in the tub full of resin, until only a very thin layer of resin remains between the stage and the film. Next, the thin layer is illuminated with directed UV light, and after the specific material has set, the stage is lifted and the set part is separated from the foil. After lifting, the table returns to the liquid, and leaving a thin medium between the already printed layer and the film, the UV exposure starts. This process is repeated until the given part is finished. [2]

There are three main categories of SLA processes, laser-based stereolithography (laser SLA), digital light processing stereolithography (DLP-SLA), and masked SLA (MSLA). For all these processes, a vat of photo-reactive liquid resin is selectively exposed to light in order to form very thin solid layers that stack up to create one solid object.

The laser SLA technology works by using a UV laser to draw each layer of the object and uses two mirrors driven by a motor, known as galvanometers or ‘galvos’ (one on the X axis and one on the Y axis), to rapidly aim the laser beam across the print area, solidifying resin as it moves along.

DLP-SLA uses a digital projector to flash a single image of each layer across the entire platform at once. Because the image of each layer is digitally displayed, it is composed of numerous square pixels, resulting in a layer formed from small rectangular bricks called voxels that stack up along the Z axis.

MSLA utilizes an LED array as its light source together with an LCD photomask in order to shape the light image from the LED array. Like DLP, the LCD photomask is digitally displayed and composed of square pixels. The pixel size varies based on how the LCD photomask is manufactured, and individual pixels are deactivated on the LCD to allow the LED light to pass through to form the resulting layer. Thus, the XY accuracy is fixed and does not depend on how well you can zoom/scale the lens as is the case with DLP [3].

## 2 FDM MATERIALS

### *2.1 Polylactic Acid (PLA)*

Nowadays, the demand for bioplastics is increasing more and more. It is not necessary to use petroleum for their production, and they also comply with environmental protection aspects. A 2004 study (by the Fraunhofer Institute and Utrecht University) predicted the use of more than 1.4 million tons of biodegradable plastic by 2020, up from 0.9 million in 2000. The food industry is mainly interested in these materials, because oil-based plastics may lose their price advantage due to high oil prices, and environmentally friendly packaging can improve the image of the company and its product. [4]

PLA (polylactic acid) is a plant-based plastic, mostly made from corn starch, and is a thermoplastic material. Scientists from James Madison University examined the material from a food safety point of view, and came to the conclusion that PLA is safe and ‘Generally Recognized As Safe’ for its intended uses as a polymer for fabricating articles that will hold and/or package food [5]. Nevertheless, the colouring materials used for PLA can be harmful, and the surface of the printed parts can have small holes and cracks in which bacteria can settle. Based on this, PLA can only be safe if it is made into single-use items or used for simpler things, such as storing water. [6]

Certain properties of PLA are worse compared to other materials, so it is used more for the production of prototypes or ornaments. It already warps above 40 °C, it can withstand the cold well. It has a tensile strength of about 61-66 MPa and a flexural strength of 48-110 MPa. It is resistant to fats, oils, alcohol and UV light. It is printed between 185-205 °C, but in some cases these values may change. The molten plastic does not emit harmful gases during the printing process.

### *2.2 Polyethylene terephthalate glycol (PETG)*

PETG is a variation of the highly popular Polyethylene Terephthalate (PET). PET is one of the most common plastics in the world today, and is being used for food containers, water bottles, and even clothing fibres. Its high mechanical strength, resistance to extreme temperatures, and ability to restrict moisture, has made it and its several variations useful for the food industry, as thermal insulation material, or as precursors for engineering resins.

Adding glycol during the polymerization process results in the formation of a “glycol-modified” PET, or PETG. The addition of glycol results in plastic that is more durable, less brittle, clearer, and easier to use. PETG has been widely used for outdoor signs due to its excellent printability and laminating characteristics. Other applications for PETG include medical and food containers, electronic devices, credit or gift cards, store fixtures, and prosthetic devices.

PETG has shown good chemical resistance, whether from acidic or alkali substances. It also retains the excellent moisture blocking characteristic of PET, making it a good choice for containers for water or other drinks. It also convenient for containers that are easier to grip due its softer and more pliable nature. [7]

Its tensile strength is 24-69 MPa, its hardness is 105-119 HRR, its bending strength is 39-89 MPa. In 3D printing, its main advantages are that it is less prone to warping and shrinkage, and it has very good layer adhesion. It combines the favourable properties of PLA and ABS. It is recommended for printing parts that are subject to permanent or sudden stress, such as protective and mechanical parts. It is printed between 220-245 °C, the table must be heated to approximately 70 °C, but 60 °C is sufficient for a glass table. It is recommended to store PET-G filament in an airtight container, even with the presence of silicate, which binds the moisture content of the air. If the filament is wet, it makes a hissing sound during printing, which is the sound of evaporating moisture. Exposure of the printed part to UV light can weaken it.

### *2.3 Acrylonitrile-Butadiene-Styrene (ABS)*

Acrylonitrile-Butadiene-Styrene copolymer got many properties which include light weight, easy formability, abrasion resistance, etc. This is useful for industrial application, making decorative, wheel covers, air conditioning parts, plastic metallization serves to make electronic housing which shows it will be a demanding material in near future. [8]

In addition to injection moulding, it is also used for CNC milling, turning and 3D printing. This plastic is an oil derivative, so it does not decompose in its natural environment. As a result of oil refining, it has the properties of being relatively light, wear-resistant and easy to shape.

Henshaw et al. analyses the failure of a particular brand of automobile seat belts. The failures described were part of what nearly became the most expensive and widespread automobile recall in U.S. history, affecting about 8.8 x 106 vehicles and with a potential total cost of U.S. $109 . The failures were caused by the degradation and fracture of the seat belts’ polymeric release buttons. [9]

The hardness of ABS is similar to PET-G (103-112 HRR). Its tensile strength is 42.55-44.8 MPa. It is printed at approximately 240 °C. During printing, the printer must be kept in a heated cabin so that the entire printing process takes place in a warm environment. Without a heated cabin, the layers can separate from each other. It withstands ambient temperatures of up to 90 °C. After printing, the ABS workpiece can be polished with acetone (acetone dissolves ABS).

### *2.4 Acrylonitrile Styrene Acrylate (ASA)*

ASA stands for Acrylonitrile Styrene Acrylate, a thermoplastic that can be used as a good alternative to ABS. Due to its excellent properties and strength, it is also present in automotive components. Its natural colour is off-white, but it can be coloured. ASA material is produced by introducing a grafted acrylic ester elastomer during the copolymerization reaction between styrene and acrylonitrile. The reason for such a change is that ASA is more resistant to weathering and has UV resistance. Some versions also comply with food safety regulations, which is why toothbrushes and coffee machines are also manufactured from it. It is also used for injection moulding, the final product has a high gloss, high impact resistance and good chemical and heat resistance.

ASA plastic is used instead of ABS for mechanical parts that require durability in 3d printing. The finished piece is as strong and resistant as its ABS counterpart, but more resistant to weather and sunlight. It has a tensile strength of about 47 MPa, a flexural strength of 75.5 MPa, and a hardness of 103 HRR. For printing, a temperature between 240-280 °C on a 90-110 °C table is recommended.

## 3 PRESENTATION OF USED 3D PRINTERS AND MATERIALS

### *3.1 FDM TECHNOLOGY*

The samples were produced with two Ender 3 printers. This type of structure has been one of the most popular FDM printers on the market for several years. Its popularity is due to its simple structure and good modifiability. Its operation is based on the right-angled X-Z principle already presented, the print head moves on an aluminium profile in the X direction, and a trapezoidal spindle ensures its movement in the Z direction. The stage moves in the Y direction on aluminium profiles. The printhead is manufactured with a PTFE tube, the disadvantage of which is that it melts above 230-240°C and emits harmful gases.

With this printing technology, we worked with four types of materials. All specimens were made with 100% filling.

### *3.2 PLA*

This material is perhaps one of the most common in 3D printing. It was printed with a 205°C head, a 60°C glass table and a speed of 50 mm/s, and does not require a heated space.

### *3.3 PET-G*

After PLA, it is perhaps the second most popular material due to its handling and durability. Its printing does not require significant modifications, it can also be used well with a basic level machine. During production, we worked with a 225°C head, a 75°C glass table and a speed of 50 mm/s.

### *3.4 ABS*

ABS is already a big step forward compared to previous materials. It can be said to be more difficult to use, in addition to a few major modifications, it also requires a heated space, because it can separate in layers during printing, one of the causes of which is its greater shrinkage during cooling. It was printed with a converted head at 245°C. The temperature of the stage was set to 100°C, but not with a glass plate but with masking tape, on which we also applied sticky tape to prevent the specimen from detaching. Printing speed reduced to 60%, which corresponds to 30 mm/s. Figure 2 clearly shows its printing conditions. The surface of the finished test piece creates a matte effect.

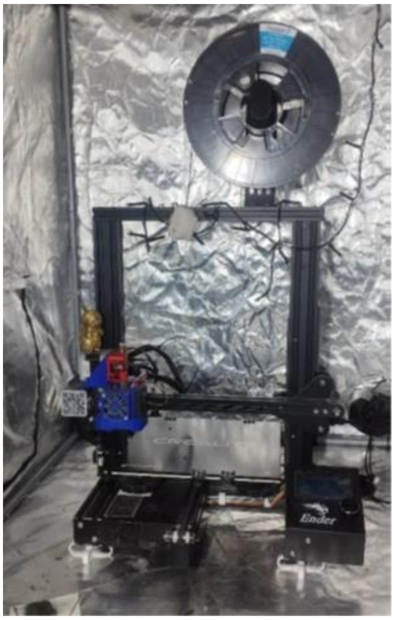


*Figure 1. Ender 3 type 3D printer.*


*Figure 2 Printing of ABS tensile test specimens ASA*

### *3.5 ASA*

This type of plastic can be used with similar settings as the aforementioned ABS. They were printed at the same parameters in terms of temperatures and speeds. The final result of one successful print is shown in Figure 3. It can be clearly observed, both in the figure of ABS and ASA that the masking tape was wrinkled after the workpieces cooled down, which is the reason for their greater shrinkage.

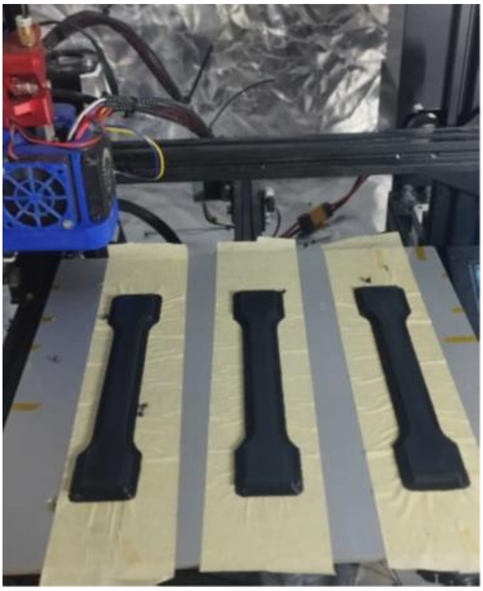

*Figure 3 Printing of ASA tensile test specimens*

## 4 SLA TECHNOLOGY

The Anycubic Photon S is an entry-level resin printer operating on the MSLA principle. It was still a popular structure a few years ago, but due to technological progress, printers that are much faster, have a larger stage, and are suitable for making more beautiful test pieces are now commercially available. The advantage of the printer we use is that there are two guide rails next to the trapezoidal spindle, which increases the stability of the table. In contrast, older models of the same age only used one.

*Figure 4 Anyicubic Photon S*

In the first step, we had to prepare the raw test pieces, for slicing them we used the factory program called anycubic photon workshop. The main printing parameters include a layer thickness of 0.05 mm, an exposure time of 70 s for the eight base layers, and 8 s for the other layers. The Photon S I used has a small stage and is one of the slower machines, so the production process required a lot of time.

### *4.1 Washing process*

The previously presented wash and cure 2.0 structure can already be used for this process, but due to the need for a large amount of liquid, the washing was carried out manually in a box. This operation must be carried out with increased attention and with appropriate protective equipment, as the medium used for washing isopropyl alcohol and the resins used can cause skin irritation and allergic reactions. After the removal of the supports and the washing process, wiping and drying follow.

### *4.2 Post-treatment process*

This process is shown in Figure 5. UV exposure lasted 2x2 minutes, interrupted by a 180° rotation. The average UV exposure time of the materials is 3 minutes, by increasing this time the structure of the material can be logarithmically strengthened, within certain limits.

*Figure 5 Post-treatment of specimens*

### *4.3 Moistening*

We wanted to investigate the effect of the moisture content of the test specimens on the strength properties. We performed several tests on the printed samples. After printing, we measured the mass of the test specimens and their dimensions. The workpieces were divided into three groups, one group was soaked in water, the other was dried, and the third was placed in a room with average humidity (temperature between 18-24°C, 35-45% humidity). Further investigations summarize these experiments with test specimens with three types of properties. The diagrams show the measurement results of the water-soaked, dried and smooth test specimens left in the air.

TENSILE TEST RESULTS

PLA

This material did not tear immediately after the maximum load, minimal flow is observed. Its maximum elongation is 8% on average.

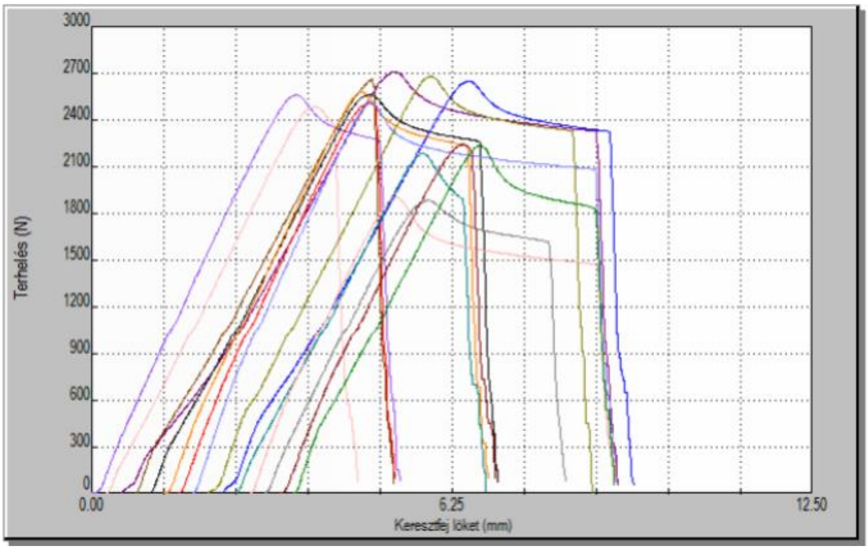


*Figure 6 PLA tensile test results*

Table 1 PLA test results (blue – moistened, green – dried)

| Specimen | | Thickness (a) (mm) | Width (b) (mm) | Ft (N) | Fm (N) | Rm ($N/mm^2$) |
|---|---|---|---|---|---|---|
| *1* | | 4,00 | 10,00 | 54,0 | 2231,5 | 55,79 |
| *2* | | 4,00 | 10,00 | 97,0 | 2238,5 | 55,96 |
| *3* | | 4,00 | 10,00 | 85,5 | 1879,5 | 46,99 |
| *4* | | 4,00 | 10,00 | 82,0 | 1901,0 | 47,53 |
| *5* | | 4,00 | 10,00 | 9,0 | 2181,5 | 54,54 |
| *6* | | 4,00 | 10,00 | 51,5 | 2646,0 | 66,15 |
| *7* | | 4,00 | 10,00 | -32,0 | 2675,5 | 66,89 |
| *8* | | 4,00 | 10,00 | 75,5 | 2505,5 | 62,64 |
| *9* | | 4,00 | 10,00 | 96,0 | 2504,0 | 62,60 |
| *10* | | 4,00 | 10,00 | 99,5 | 2575,0 | 64,38 |
| *11* | | 4,00 | 10,00 | 71,5 | 2559,0 | 63,97 |
| *12* | | 4,00 | 10,00 | 63,0 | 2609,5 | 65,24 |
| *13* | | 4,00 | 10,00 | 59,0 | 2706,0 | 67,65 |
| *14* | | 4,00 | 10,00 | 70,5 | 2482,0 | 62,05 |
| *15* | | 4,00 | 10,00 | 79,5 | 2556,0 | 63,90 |

### *4.4 PET G*

The same results were obtained for PET-G as for PLA. The average values of the basic samples (1890.8 N and 47.3 N/mm2) and the dried ones (1912.7 N and 47.8 N/mm2) do not differ much. The results measured during the process can be found in Table 2.

The workpieces soaked in water, on the other hand, broke due to already changed properties. The average values are 1696.2 N and 42.4 N/mm2, which means a 10.3% deterioration.

After the maximum force, the workpieces did not break, but the material flowed and stretched for a while after breaking (Figure 7).

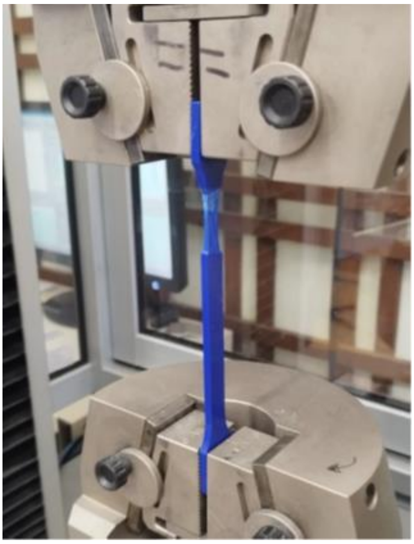

*Figure 7 Deterioration of a PETG specimen*

This deterioration can also be clearly observed in Figure 8, where the rupture curves of the moistened test pieces can be clearly distinguished. An average of 7%, and about 10% elongation after soaking, before breaking. It is typical for non-soaked specimens that the material broke after reaching the maximum load.

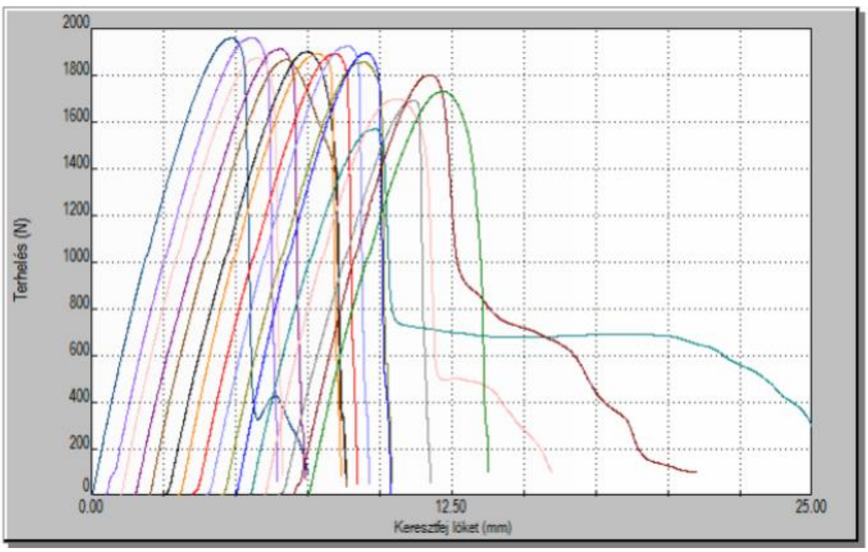


*Figure 8 PET G tensile test results*

Table 2 PET G test results (blue – moistened, green – dried)

| Specimen | | Thickness (a) (mm) | Width (b) (mm) | Ft (N) | Fm (N) | Rm (N/mm²) |
|---|---|---|---|---|---|---|
| *1* | | 4,00 | 10,00 | 97,5 | 1728,5 | 43,21 |
| *2* | | 4,00 | 10,00 | 99,5 | 1799,5 | 44,99 |
| *3* | | 4,00 | 10,00 | 57,0 | 1689,0 | 42,22 |
| *4* | | 4,00 | 10,00 | 98,5 | 1696,5 | 42,41 |
| *5* | | 4,00 | 10,00 | 94,5 | 1567,5 | 39,19 |
| *6* | | 4,00 | 10,00 | -38,5 | 1892,5 | 47,31 |
| *7* | | 4,00 | 10,00 | 52,5 | 1853,0 | 46,33 |
| *8* | | 4,00 | 10,00 | 49,0 | 1923,0 | 48,08 |
| *9* | | 4,00 | 10,00 | 47,0 | 1890,5 | 47,26 |
| *10* | | 4,00 | 10,00 | 82,0 | 1887,5 | 47,19 |
| *11* | | 4,00 | 10,00 | 72,0 | 1898,5 | 47,46 |
| *12* | | 4,00 | 10,00 | 35,0 | 1864,5 | 46,61 |
| *13* | | 4,00 | 10,00 | 69,0 | 1911,0 | 47,78 |
| *14* | | 4,00 | 10,00 | 86,0 | 1871,5 | 46,79 |
| *15* | | 4,00 | 10,00 | 62,0 | 1959,5 | 48,99 |
| *16* | | 4,00 | 10,00 | 97,0 | 1957,0 | 48,92 |

### *4.5 ABS*

The average value of the yield strength is 30.6 N/mm2, and the maximum tensile strength is 1223.9 N. The values of the test piece soaked in water are the same, and the dried one shows a 3% deterioration. In Figure 9, it can be observed that after the rapid run-up and the maximum tensile force, the specimens show yielding. During flow, an average load of 250-300 N less than the maximum is required (which is 20-25% of the original) to make the process sustainable. After some elongation (about 10-20%), the test pieces broke.

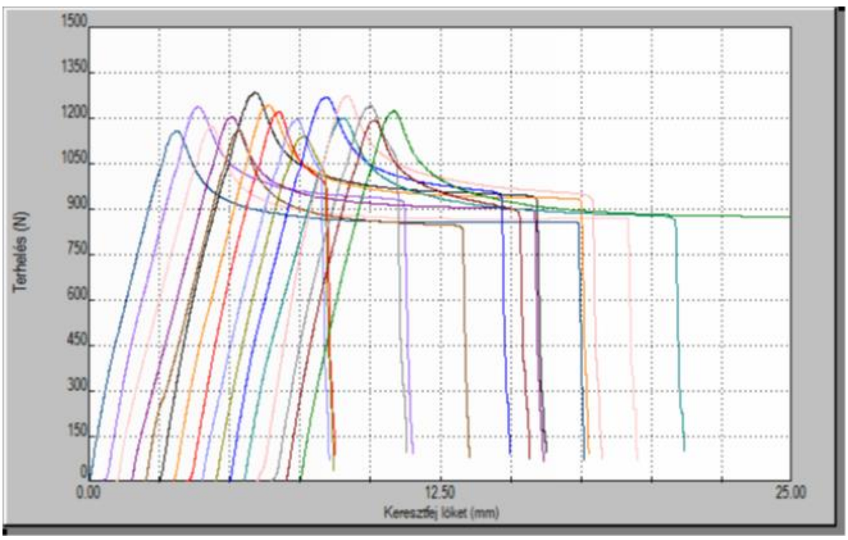


*Figure 9 ABS tensile test results*

Table 3 ABS test results (blue – moistened, green – dried)

| Specimen | | Thickness (a) (mm) | Width (b) (mm) | Ft (N) | Fm (N) | Rm (N/mm²) |
|---|---|---|---|---|---|---|
| 1 | | 4,00 | 10,00 | 88,0 | 1221,5 | 30,54 |
| 2 | | 4,00 | 10,00 | 74,5 | 1190,5 | 29,76 |
| 3 | | 4,00 | 10,00 | 96,0 | 1239,0 | 30,98 |
| 4 | | 4,00 | 10,00 | 75,5 | 1272,0 | 31,80 |
| 5 | | 4,00 | 10,00 | 99,0 | 1198,5 | 29,96 |
| 6 | | 4,00 | 10,00 | 90,5 | 1268,5 | 31,71 |
| 7 | | 4,00 | 10,00 | 36,5 | 1139,5 | 28,49 |
| 8 | | 4,00 | 10,00 | 72,0 | 1194,0 | 29,85 |
| 9 | | 4,00 | 10,00 | 88,5 | 1218,5 | 30,46 |
| 10 | | 4,00 | 10,00 | 92,5 | 1241,0 | 31,02 |
| 11 | | 4,00 | 10,00 | 98,0 | 1282,0 | 32,05 |
| 12 | | 4,00 | 10,00 | 79,0 | 1156,0 | 28,90 |
| 13 | | 4,00 | 10,00 | 68,5 | 1202,5 | 30,06 |
| 14 | | 4,00 | 10,00 | 72,5 | 1170,5 | 29,26 |
| 15 | | 4,00 | 10,00 | 94,0 | 1235,0 | 30,88 |
| 16 | | 4,00 | 10,00 | 72,5 | 1156,0 | 28,90 |

### *4.6 ASA*

Based on the data in Table 4, no significant difference can be established in the results of the test specimens made of ASA material. Average values are 1427.1 N maximum load and 35.7 N/mm2 tensile strength. A 1% increase can be achieved as a result of soaking, and a 2% deterioration can be experienced as a result of drying.

As a result of soaking, the material lost its elasticity, and no flow was observed after the maximum load, but the specimen immediately broke after a short run, which can be seen in Figure 10. With ASA, no large elongation can be observed, as with ABS, the specimen broke after 5-8% elongation.

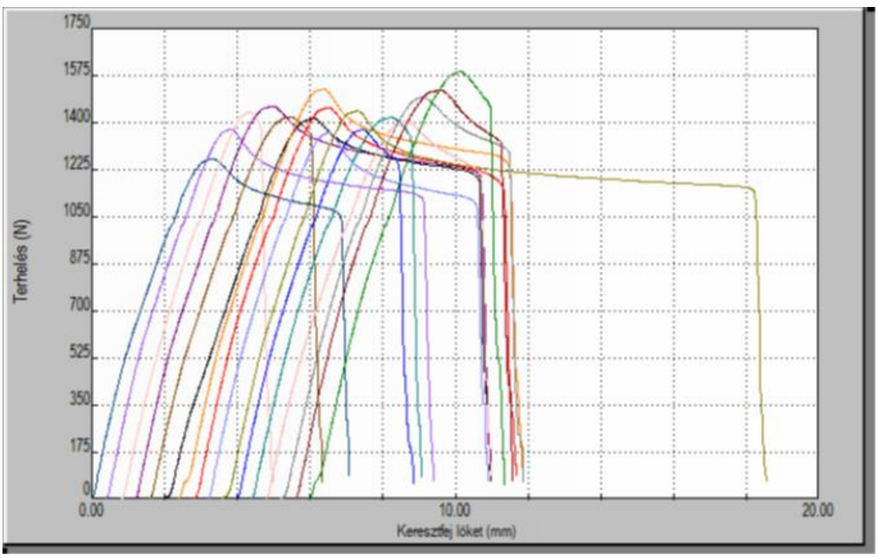


*Figure 10 ASA tensile test results*

Table 4 ASA test results (blue – moistened, green – dried)

| Specimen | | Thickness (a) (mm) | Width (b) (mm) | Ft (N) | Fm (N) | Rm (N/mm²) |
|---|---|---|---|---|---|---|
| 1 | | 4,00 | 10,00 | 54,0 | 1586,5 | 39,66 |
| 2 | | 4,00 | 10,00 | 65,5 | 1519,0 | 37,97 |
| 3 | | 4,00 | 10,00 | 64,0 | 1492,0 | 37,30 |
| 4 | | 4,00 | 10,00 | 90,0 | 1401,0 | 35,03 |
| 5 | | 4,00 | 10,00 | 85,0 | 1417,0 | 35,42 |
| 6 | | 4,00 | 10,00 | 59,0 | 1372,0 | 34,30 |
| 7 | | 4,00 | 10,00 | 65,5 | 1441,5 | 36,04 |
| 8 | | 4,00 | 10,00 | 68,0 | 1361,0 | 34,03 |
| 9 | | 4,00 | 10,00 | 88,5 | 1453,0 | 36,33 |
| 10 | | 4,00 | 10,00 | 80,5 | 1523,0 | 38,08 |
| 11 | | 4,00 | 10,00 | 66,0 | 1412,0 | 35,30 |
| 12 | | 4,00 | 10,00 | 62,0 | 1419,0 | 35,47 |
| 13 | | 4,00 | 10,00 | 98,0 | 1458,5 | 36,46 |
| 14 | | 4,00 | 10,00 | 61,0 | 1436,0 | 35,90 |
| 15 | | 4,00 | 10,00 | 69,0 | 1373,5 | 34,34 |
| 16 | | 4,00 | 10,00 | 89,0 | 1264,0 | 31,60 |

### *4.7 Onyx glass fiber reinforced carbon plastic*

This material is different from the FDM materials previously examined and was produced using the Onyx Pro printer located at the university. The printer handles two materials at the same time and adds glass fibre to the base carbon fibre nylon for reinforcement. The following data were obtained during the tearing of the test specimens, which can be found in Table 5. It can be observed that the material's maximum load and tensile stress are far ahead of those of the previously presented materials. (Among the other materials, PLA had the highest values, half that of onyx nylon.) For the printing of the onyx specimens we used a Markforged Onys Pro 3D printer (Figure 11).

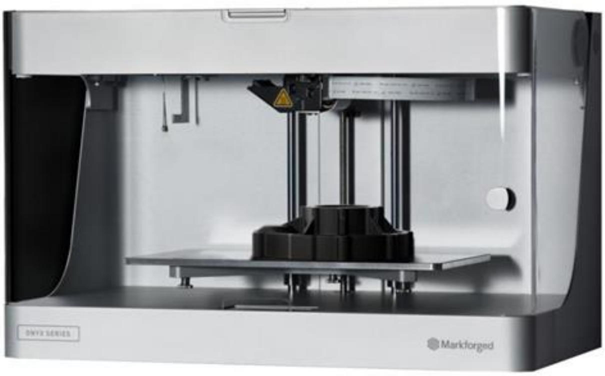

*Figure 11 Markforged Onyx Pro 3D printer*

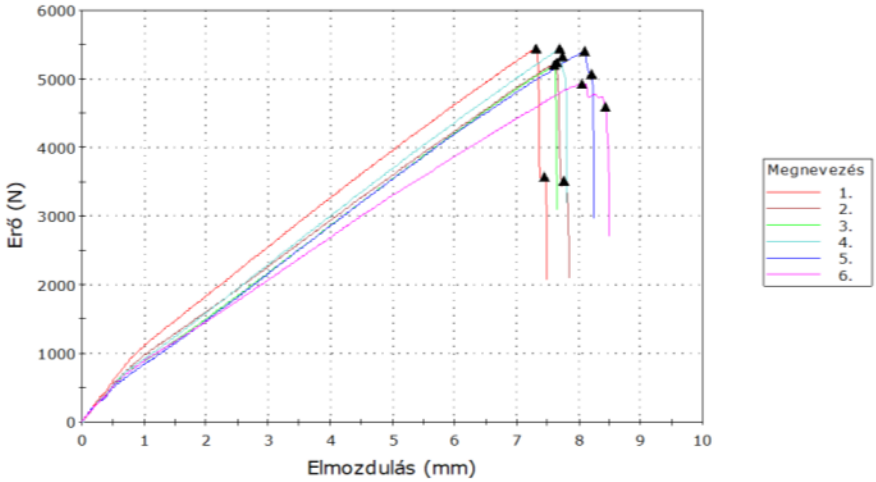


*Figure 12 Onyx tensile test results*

Table 5 Onyx test results

| Specimen | Modulus (MPa) | Elongation associated with maximum force (%) | Maximum tensile stress (MPa) | Maximum load (N) | Elongation at break (%) | Tensile stress at the moment of rupture (MPa) |
|---|---|---|---|---|---|---|
| 1 | 3455 | 6,36 | 136,14 | 5446 | 6,47 | 89,17 |
| 2 | 3164 | 6,65 | 130,93 | 5237 | 6,75 | 87,76 |
| 3 | 2971 | 6,62 | 129,87 | 5195 | 6,62 | 129,87 |
| 4 | 3092 | 6,69 | 136,02 | 5441 | 6,72 | 133,12 |
| 5 | 2787 | 7,04 | 135,18 | 5407 | 7,14 | 127,05 |
| 6 | 2949 | 7 | 123,35 | 4934 | 7,33 | 114,65 |
| Average | 3069,67 | 6,73 | 131,92 | 5276,67 | 6,84 | 113,60 |

## 5 BASIC RESIN

Compared to the basic values (maximum load of 1615.2 N and tensile strength of 40.4 N/mm2), a 12% improvement can be achieved by drying. As a result of soaking in water, the deterioration is 53%, the properties of the material change, its elasticity increases, instead of the average 3-4 mm long elongation, the material can deform 5-6 mm before tearing. Figure 13 clearly shows that the graphs of the three materials with different moisture content can be separated more easily, the difference between their properties has increased. After reaching the maximum load, the workpieces are broken, no flow is observed. Elongation of approximately 9% is observed when drying, 10% at room temperature, and approximately 15% when soaking. After the maximum load, the test pieces broke immediately.

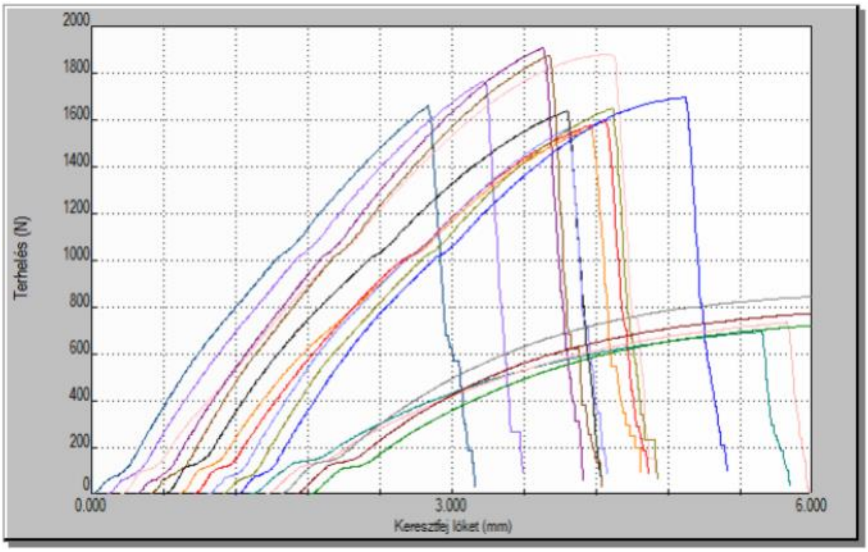


*Figure 13 Basic resin tensile test results*

Table 6 Basic resin test results (blue – moistened, green – dried)

| Specimen | | Thickness (a) (mm) | Width (b) (mm) | Ft (N) | Fm (N) | Rm (N/mm²) |
|---|---|---|---|---|---|---|
| *1* | | 4,00 | 10,00 | -28,0 | 751,5 | 18,79 |
| *2* | | 4,00 | 10,00 | -13,5 | 820,5 | 20,51 |
| *3* | | 4,00 | 10,00 | 23,0 | 867,5 | 21,69 |
| *4* | | 4,00 | 10,00 | -18,5 | 730,5 | 18,26 |
| *5* | | 4,00 | 10,00 | 35,0 | 691,5 | 17,29 |
| *6* | | 4,00 | 10,00 | 97,5 | 1693,0 | 42,33 |
| *7* | | 4,00 | 10,00 | 67,0 | 1648,5 | 41,21 |
| *8* | | 4,00 | 10,00 | 88,5 | 1560,5 | 39,01 |
| *9* | | 4,00 | 10,00 | 86,0 | 1591,5 | 39,79 |
| *10* | | 4,00 | 10,00 | 95,5 | 1563,0 | 39,08 |
| *11* | | 4,00 | 10,00 | 75,0 | 1634,5 | 40,86 |
| *12* | | 4,00 | 10,00 | 33,0 | 1872,5 | 46,81 |
| *13* | | 4,00 | 10,00 | 61,5 | 1906,5 | 47,66 |
| *14* | | 4,00 | 10,00 | 90,5 | 1879,0 | 46,97 |
| *15* | | 4,00 | 10,00 | 92,0 | 1743,0 | 43,58 |
| *16* | | 4,00 | 10,00 | 30,0 | 1656,5 | 41,41 |

## 6 CONCLUSIONS

When carrying out the tensile test for PLA, a 20% deterioration due to soaking is observed at the maximum load. With PET-G, there are no differences at maximum load, but differences can be found in elongation. The water samples did not break, but flowed. ABS and ASA materials are minimally affected by the moisture content ratio. In the case of resins, it can be said that the workpieces suffer a greater load and less deformation as a result of drying, but a greater elongation and a lower maximum load as a result of soaking.

Overall, it can be stated that the results of the experiments can help the application of these materials. In the future, more detailed and informative experiments must be carried out, but these experiences can serve as guidelines for the design of 3D printed parts exposed to physical stress.

**ACKNOWLEDGMENTS**

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# TECHNICAL SOLUTIONS FOR CATASTROPHIC EXTENT OF THE HUMAN FACTOR IN DRIVERS TRAINING AND STRUCTURAL SAFETY OF BUSES AND HEAVY VEHICLES

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RESEARCH ARTICLE

**ABSTRACT:** The concept of "human factor" is actively used in determining the guilt of pilots in plane crashes and drivers in railway accidents, as well as from a historical perspective, in economics and management of organizations, but surprisingly rarely when it comes to road transport. In addition, the human factor usually means the driver's fault, which is the main misconception. Other causes of road accidents include weather conditions, the state of the road infrastructure, and technical malfunctions, hiding the true cause, which in the vast majority of cases is also a consequence of human factors of various levels. An analysis of incidents with buses and trucks that regularly occur in Russia shows that it is possible to distinguish such levels of human factor as driver, managerial, political, legal, technological, production, system, and commercial. A bus or heavy truck accident is always fraught with particularly serious consequences and public outcry. However, public outcry does not yet mean that the authorities will take the necessary steps in this direction in terms of organizing transportation processes and monitoring motor transport enterprises. Therefore, it is necessary to invent technical solutions, including an integral brake valve, a driver monitoring system and a post-accident braking system.

**KEY WORDS**: *road safety, preventive motion control method, secondary braking system, driver monitoring system, secondary collision brake system*



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## TEHNIČKA REŠENJA ZA KATASTROFALNU OBIM LJUDSKOG FAKTORA U OBUCI VOZAČA I KONSTRUKCIJSKA BEZBEDNOST AUTOBUSA I TEŠKIH VOZILA

REZIME: Koncept „ljudskog faktora“ se aktivno koristi u utvrđivanju krivice pilota u avionskim nesrećama i vozača u železničkim nesrećama, kao i iz istorijske perspektive, u ekonomiji i upravljanju organizacijama, ali iznenađujuće retko kada je u pitanju drumski saobraćaj. Pored toga, ljudski faktor obično znači grešku vozača, što je glavna zabluda. Drugi uzroci saobraćajnih nezgoda su vremenske prilike, stanje putne infrastrukture i tehnički kvarovi, koji prikrivaju pravi uzrok, koji je u velikoj većini slučajeva i posledica ljudskih faktora različitih nivoa. Analiza incidenata sa autobusima i kamionima koji se redovno dešavaju u Rusiji pokazuje da je moguće razlikovati nivoe ljudskog faktora kao što su vozački, menadžerski, politički, pravni, tehnološki, proizvodni, sistemski i komercijalni. Nesreća autobusa ili teškog kamiona uvek je prepuna posebno ozbiljnih posledica i negodovanja javnosti. Međutim, negodovanje javnosti još ne znači da će vlasti preduzeti neophodne korake u tom pravcu u smislu organizovanja transportnih procesa i praćenja autotransportnih preduzeća. Zbog toga je neophodno izmisliti tehnička rešenja, uključujući integralni kočni ventil, sistem za nadzor vozača i sistem kočenja nakon udesa.

**KLJUČNE REČI**: *bezbednost na putu, preventivni metod kontrole kretanja, sistem sekundarnog kočenja, sistem za nadzor vozača, sistem kočnice pri sekundarnom sudaru*

# TECHNICAL SOLUTIONS FOR CATASTROPHIC EXTENT OF THE HUMAN FACTOR IN DRIVERS TRAINING AND STRUCTURAL SAFETY OF BUSES AND HEAVY VEHICLES

*Mikhail P. Malinovsky, Miroslav Demić, Evgeny S. Smolko*

## INTRODUCTION

The term “human factor” recently celebrated its centenary – it was first mentioned in a book by the British economist Benjamin Seebohm Rowntree in relation to entrepreneurship [1]. By the middle of the 20th century, it was increasingly used in technical fields [2–3]. Gradually, the concept of the “human factor” began to be associated with a set of human abilities and qualities in a wide variety of areas of human activity, for example, in economics [4–7], management [8–9], medicine [10–16], industry [17–22], pedagogy [23–25], sociology [26–27], ecology [28–30], resource use [31–32], agriculture [33–34], astronautics [35], logistics [36–37], safety management [38–39], mining [40] and oil and gas [41–42] industries, operator training [43–44], as well as in such modern areas as artificial intelligence [45] and cybersecurity [46–50]. But in technology, the concept of the “human factor” is most often associated with negligence, inattention, erroneous decisions made by a person and actions taken or, conversely, not taken by him in a critical situation [51-54], which entail significant damage and loss of life, including both natural [55-57] and man-made [58-63] disasters, especially at thermal and nuclear power plants [64-69] and, of course, in transport [70-74]. The term "human factor" is widely used in rail [75-83], sea [84-90] and especially air [91-100] transport, but much less often when it comes to road transport [101-104], although its influence in the area of road safety is difficult to overestimate. The phrase "catastrophic scale" in this case is not a metaphor or hyperbole, since the consequences of the human factor in road transport, as a rule, are the loss of life.

## 1 RESONANT ACCIDENTS

An accident involving a bus or a heavy truck is always fraught with particularly serious consequences and public resonance.

On June 20, 2012, at 21:43 (19:43 Moscow time), on the 1644th kilometer of the M5 Ural highway near the city of Yuryuzan (Chelyabinsk region), the brakes of a Volvo road train failed on a small descent. The road in this section is two-lane and has steep slopes on both sides. The driver, a Dagestani, a resident of Stavropol Krai born in 1981, tried to squeeze through along the center line, drove into the oncoming traffic lane and at high speed rammed a Kia Jess and VAZ-2106 passenger cars, a Gazelle minibus, a Scania road train, and then crashed into an oncoming KamAZ, the driver of which heard a warning on the radio and slowed down to the side of the road to let the out-of-control road train pass (Figure 1). The impact sent the KamAZ trailer flying into a ditch, and the tractor turned over on its side across the road. Several cars caught fire. The 61-year-old driver of the Kia Jess and the 58-year-old passenger of the Gazelle died in the accident. Nine more people received various injuries, three of whom had to be hospitalized. The Volvo driver fled the scene immediately after the tragedy, but was detained by police officers in the woods near the highway in the early morning of June 21. He was charged under Article 264 of the Criminal Code of the Russian Federation (violation of traffic rules and operation of vehicles, resulting through negligence in the death of two or more persons).

*Figure 1 Yuryuzan accident, 20.06.2012*

Eight years later, on June 16, 2020, at 1:09 p.m., another car accident occurred in almost the same area of the M5 highway on the bridge over the Silga River. The driver of a Shacman dump truck loaded with 15 tons of crushed stone with faulty brakes failed to slow down before the narrowing due to repair work being carried out on the bridge and rammed into the following cars that had slowed down: Lada Granta, Audi Q7, Renault Sandero, VAZ-2114 and a Hino truck (Figure 2). The driver could have turned right into a free space, but panicked and did not do so. As a result of the collision, the driver and passenger of the Lada Granta died on the spot. Other participants in the accident received less serious injuries. Later, the driver said that the air in the service brake system ran out on a long descent. As part of the criminal investigation, the children of the deceased couple have filed claims for six million rubles. The property of Gorod LLC, where the truck driver works, has been seized. The Katav-Ivanovo City Prosecutor approved the indictment in the criminal case against the dump truck driver, accused of committing a crime under Part 5 of Article 264 of the Criminal Code of the Russian Federation ("Violation by a person driving a car or other mechanical vehicle of traffic rules and the operation of vehicles, resulting through negligence in the death of two persons").

*Figure 2 Silga river bridge accident, 16.06.2020*

The worst thing happens when a bus gets in the way of a truck with failed brakes. On July 13, 2013, at about 1 p.m. (the incident report was received by the Ministry of Emergency Situations at 12:54 p.m.) in the village of Oznobishino (New Moscow, Novotroitsky District) at the intersection of the Kaluga Highway and a secondary road leading from the village of Shchapovo, a KamAZ-65115 dump truck overloaded with crushed stone and with failed brakes, driven by 46-year-old Armenian citizen Grachya Harutyunyan, who has been driving for over 20 years, accelerated to 70 km/h on a steep descent, while attempting to make a left turn, overturned onto its right side and rammed the rear of a LiAZ bus traveling with 64 passengers on route #1033 from the city of Podolsk to the village of Zhokhovo. The impact tore off the rear of the bus, and the passengers were buried alive under tons of rubble that spilled out of the dump truck into the passenger compartment. Fourteen people died on the spot (including the 66-year-old conductor), and four more died later in hospitals. Most of them were crushed by a pile of stones and suffocated. Those who were dug out suffered severe combined and compression injuries, fractures, bruises, and concussions. More than 30 passengers (16 of whom were in serious condition) were taken to medical facilities (with the participation of four helicopters) - the Podolsk Central Regional Hospital and the Sklifosovsky Institute.

The dump truck driver jumped out of the destroyed cabin without serious injuries (Figure 3). He was sober at the time of the collision. Immediately after the accident, the driver was put into a drug-induced coma, but the next day he came to and was immediately questioned by an investigator, after which he was charged under Article 264 of the Criminal Code of the Russian Federation "Violation of traffic rules and operation of vehicles, resulting in the death of two or more persons through negligence." It became known that in the previous year alone, Grachya Harutyunyan was brought to administrative penalties nine times for violating traffic rules, including for driving into the oncoming traffic lane and crossing a railroad crossing at a red light.

As for traffic violations, the traffic police punish a specific driver for them, and his employer is not informed about it. But if a traffic police officer stops a truck and finds faults, then the owner - a company or an individual entrepreneur - is informed.

In case of a vehicle malfunction in an accident, there is Article 266 of the Criminal Code of the Russian Federation, “Poor-quality repair of vehicles and their release into operation with technical faults,” which provides for up to 10 years in prison – even more than for the accident itself. However, it is unlikely that any lawyer will remember the last time this article was applied in practice.

As it turned out, the dump truck was deregistered in April 2013 and was used with transit numbers. The truck belonged to OOO Stroyavtoservis, which has been engaged in general construction work since 2003 and registered in Moscow to Gamlet Gulakyan, who owned two more companies: OOO Avtoservis-09, created in 2009, is engaged in wholesale and retail trade in motorcycles, car parts, car repair and maintenance, and OOO MMS, founded in 2000 in the Tambov Region, produces soft drinks, vegetable and animal oils and fats, processes and preserves fruits and vegetables, along with architectural design development and construction. Grachya Arutyanyun was hired by the company Stroyavtoservis to transport goods several years earlier.

*Figure 3 Oznobishino accident, 13.07.2013*

As always, not before, but after the tragedy, the acting governor of the Moscow region Andrei Vorobyov, at an emergency meeting, which he held right in the building of the Podolsk hospital after going around the wards with the wounded, set the task for law enforcement agencies to provide additional inspections of all rolling stock of the Moscow region (about six thousand buses), conduct medical examination of drivers before going on a trip, pay attention to dangerous intersections of the Moscow region, take punitive measures against cars that are used with transit numbers and are not registered with the state, and also toughen the punishment for drivers after repeated violations of traffic rules, especially on high-tonnage vehicles. However, the public outcry does not mean that the authorities will take the necessary measures in the sphere of organizing transportation processes and monitoring motor transport enterprises.

The issue of registering drivers who systematically violate traffic rules has been raised many times: it has long been necessary to supplement the administrative code and forcibly deprive them of their driving licenses. But in this case, it would not have helped: the dump truck driver worked in Russia with an Armenian license!

On August 4, 2014, the Trotsky Court of Moscow found Grachya Arutyunyan guilty of causing an accident with 18 victims and sentenced him to 6 years and 9 months in prison. During the investigation, it was discovered that the truck had not been properly maintained, and as a result, its brakes were malfunctioning. Arutyunyan, according to the investigation, should have known about this. Seven years in prison is the maximum sentence in Russia for an accident with more than two fatalities, if the culprit was sober at the time of the accident.

On June 3, 2014, at 8:42 p.m. in St. Petersburg on Nevsky Prospekt near house No. 64, not far from the Anichkov Bridge, the driver of a city LiAZ bus felt unwell and lost consciousness. The out-of-control bus smoothly crossed the solid line separating the lane for public transport vehicles and, without braking, drove onto the corner of the sidewalk and, knocking down an advertising board, crashed into a lamppost (Figure 4). As a result of the accident, 26 people were injured, including passersby who were hit by the fallen advertising board. 8 people were hospitalized, two of them (including the bus driver) are in serious condition.

The passenger bus belonged to a large private transport company, Piteravto, which serviced dozens of routes in St. Petersburg and neighboring regions. In total, Piteravto's fleet consisted of about 2,700 buses and minibuses. The next day, representatives of the St. Petersburg administration's transport committee came to the company to check compliance with transportation rules, the correctness of the waybill and its availability, what shift the driver spent behind the wheel, and in what condition he left for the route.

The accident on Nevsky Prospekt showed that the main reason for the low efficiency of active safety systems is a fragmented approach to considering processes in a car. A single lane keeping system, if installed on a bus, would be deactivated when the turn signal was turned on. Therefore, buses should be equipped with an active safety system that includes a promising driver fatigue monitoring system [105–106], which would record the driver's loss of consciousness [107–109] and take measures to stop using a collision avoidance system, while the lane keeping system would help keep the vehicle within the occupied lane.

On December 25, 2017, at 14:46 in Moscow on Kutuzovsky Prospekt near the Slavyansky Bulvar metro station, a LiAZ-5292.60 bus equipped with an automatic transmission spontaneously started moving from a stop, drove onto the sidewalk, went into an underground pedestrian crossing and stopped only when it hit the ramp of the crossing (Figure 5). As a result of the accident, 4 people died, more than 10 received various injuries.

*Figure 4 Nevsky prospect accident, 03.06.2014*

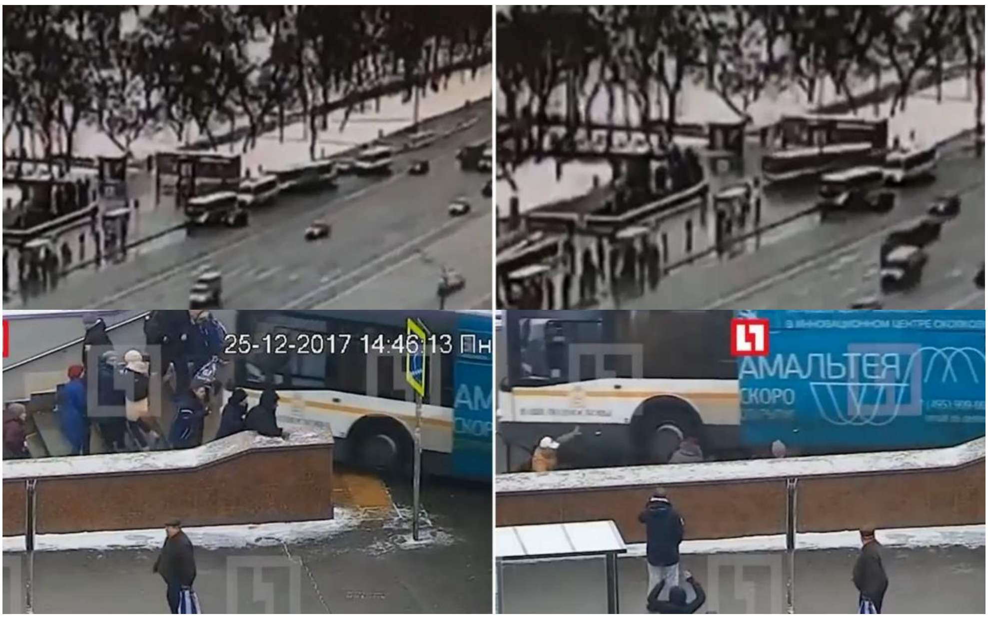


*Figure 5 Slavyansky boulevard accident, 25.12.2017*

Experienced driver Viktor Tikhonov could not give a clear explanation of what happened. The bus had a video recorder that was supposed to record all the driver's actions, and this recording could have become key evidence in a criminal case, providing an answer to the question about the driver's behavior. However, the video recorder was badly damaged, so only a few seconds could be restored. The recording captured the moment the car drove onto the sidewalk, and the driver's obscene language can be heard in the background.

According to the driver Viktor Tikhonov, he pulled up to the final stop, Slavyansky Bulvar. There were three people in the bus, and he had to wait another 15 minutes to board. Another bus pulled up behind him, and he decided to move over to give it his seat. When he released the handbrake, the bus suddenly started moving on its own. Despite all his attempts to stop the bus, the brakes did not work, and the bus continued moving. The bus has an automatic transmission, so he could not do anything else. Later, he said that before the tragedy, a plastic bottle of water rolled under his pedal and prevented him from reacting adequately to the situation. In addition, it became known that Tikhonov regularly works on another Mostransavto route, and that Monday he went out unplanned to replace a colleague, was driving a bus of this type for the first time, and was unable to make the right decision in a critical situation.

According to the manufacturer of the GAZ Group bus, the driver did not even try to brake. The bus was manufactured in 2016, transferred to the State Unitary Enterprise Mostransavto for work on regular routes in the Moscow Region and was registered on January 4, 2017, that is, it was practically new. Buses of this model are equipped with a certified Wabco or Knorr-Bremse pneumatic brake system with an anti-lock system, two working circuits and a parking circuit that functions as a spare brake system.

According to an unofficial version, the cause of the tragedy could be hidden in the system of blocking the movement with open doors. The spontaneous movement of LiAZ buses occurred regularly and often led to accidents. The last time was just 5 days before, on December 20, 2017, in Zelenograd on Kryukovskaya Square, where the bus almost rammed a flower stall. It was stopped by anti-ram bollards, which were installed in this place after buses of the same brand unexpectedly drove onto the sidewalk twice in 2016, and in both cases the driver was not in the cabin. Such incidents are far from uncommon. In Moscow, there were a number of episodes when new LiAZ buses drove away from drivers, leaving them outside. They left the car with an automatic transmission in the DRIVE position, and blocked the movement with open doors. The doors were closed, and the bus drove away. In 2012, in St. Petersburg, a LiAZ without a driver spontaneously started moving. The female conductor climbed into the cabin for some reason and accidentally switched the selector to DRIVE mode. Despite the fact that the parking brake was activated, the bus started moving and went towards the bus in front. The conductor tried to stop the multi-ton vehicle herself and ended up dying.

The State Duma deputies were in no hurry to draw conclusions and no statements were made on the topic of possible legislative initiatives. By December 30, about 800 concrete barrier blocks were urgently installed at the entrances to the busiest metro stations and in places of mass gatherings of people in Moscow. Incidentally, a similar practice appeared in Europe after the terrorist attack in Nice on July 14, 2016.

On May 10, 2024, at 1:03 p.m. in Saint Petersburg, the driver of the Volgabus 4298 city bus, route #262, 44-year-old native of Dagestan Rakhmatshok Kurbonov, despite the “Dangerous Turn” and “Maximum Speed Limit” signs of up to 20 km/h installed on Bolshaya Morskaya Street, entered the turn at a speed of 35 km/h and lost control. The bus drove onto the sidewalk, jumped over the anchors near the Naval Museum, knocked down the fence, drove into the oncoming lane, where it hit a Chery Tiggo, and, having overcome a high curb (the traction force, given the automatic transmission, was greater than the resistance force), fell from the Potseluyev Bridge into the Moika River (Figure 6). The most tragic thing is that 5 (!) seconds after falling into the water, the bus sank to the level of the roof. The first to come to the rescue were eyewitnesses driving across the bridge and two passing boats, one of which the bus almost fell into. Rescuers arrived seven minutes after the incident. Only two people, including the driver, managed to get out of the water-filled cabin. Three passengers died (drowned, not from injuries!) on the spot, another four were hospitalized in a state of clinical death, but they could not be saved.

At first, Rakhmatshoh Kurbonov reported faulty brakes. However, the video recorder installed inside the cabin showed that the driver had been driving in a panic for 15 seconds without ever attempting to press the brake pedal. A criminal case was opened against the driver under Part 5 of Article 264 of the Criminal Code of the Russian Federation, “Violation of traffic rules resulting in the death of more than two persons,” which provides for up to 7 years in prison. In addition, another case was opened against Kurbonov for fictitious registration of foreigners – according to the Investigative Committee, he registered 10 migrants in his apartment.

The driver was not the only person involved. A criminal case was also opened against the carrier under the article on providing services that do not meet safety requirements. Over the previous two years, the company was fined 23 times for gross violations of license conditions for a total of 3.6 million rubles. The head of the motorcade of the company OOO Taxi, where Kurbonov worked, 28-year-old Dzhakhangir Khalilov, violated the working conditions of the driver and set him an inconvenient schedule, which is why he came to work on the fateful day without getting enough sleep. Kurbonov's wife testified that her husband was forced to go on a trip the next morning after a 20-hour shift. Kurbonov arrived at about 2 a.m., having worked since 5 a.m., and at 7:30 he was woken up and told to go to work again. The operating director of the Taxi Company, Roman Yurenev, tried to refute this information. At the same time, the Investigative Committee studied the question of why for a year and a half the transport company was nominally headed by 49-year-old businessman Pavel Kuznetsov, who did not participate in the life of the enterprise in any way and received his salary for nothing. He was released on his own recognizance not to leave.

## 2 IN A NORMAL COUNTRY, AFTER ONE SUCH DISASTER, THE MINISTER OF TRANSPORT AND THE LEADERSHIP OF THE TRANSPORT HUMAN FACTOR LEVELS

The analysis of the above-mentioned accidents shows that the human factor should be considered not only from the perspective of driver errors, but in the broadest sense. The following levels of the human factor can be distinguished in driver training and operational safety:

- driver - driving errors, overestimation of one's own skills, low level of training;
- managerial or organizational - the motor transport enterprise does not conduct driver inspection or conducts it fictitiously, releases faulty vehicles on the road;
- political - the transport department does not monitor the situation or there is corruption in the inspection of motor transport enterprises, the minister is busy extorting money from drivers instead of safety, migrants with purchased licenses of the appropriate category without proper driving experience and training get behind the wheel of buses and heavy trucks;
- legal - the wrong person is judged, there is a constant search for a scapegoat and the concealment of responsible persons.

Committee would resign, but not in Russia.

*Figure 6 Mojka river accident, 10.05.2024*

Levels of the CF in design safety:

- technological – errors in the choice of technology, materials, suppliers (cheaper);
- production – defects in the work of plant employees;
- systemic – inertia of the standardization system when adopting new requirements and rules;
- commercial, or ideological – the established stereotype that the buyer allegedly does not want to pay for safety allows the management of automobile plants to save on the implementation of expensive active and passive safety systems.

Currently, there are no ways to fully solve the problem of the human factor, so it is necessary to offer technical solutions. The automotive community hopes for the introduction of unmanned technologies, but even with their introduction, as a number of fatal accidents have shown, the negative influence of the human factor is inevitable [110–112]. Autonomous vehicles will not help to overcome many of the listed levels, especially in Russia.

## 3 INTEGRAL BRAKING VALVE

A more detailed investigation into the circumstances of the Oznobishino accident showed that the dump truck driver did not even try to activate the backup brake system. The experience of specialists from the KamAZ driver training center shows that only 1 driver out of 10 remembers about the backup brake system in an emergency, and the reaction time increases to at least 3 seconds. An integral brake valve in two versions was proposed as a technical solution.

The technical task of the inventions consists in creating the possibility of emergency braking of a wheeled vehicle in the event of a pressure drop in the receivers of both working circuits of the brake system below the permissible limit without activating an additional control element. The solution to the technical task becomes possible due to the supply of the main two-section brake valve with a third section, which allows in the emergency braking mode in the event of failure of all circuits of the working brake system, i.e. in the event of a pressure drop in the receivers of the working brake system, to use the possibility of automatically activating the parking brake system when the driver presses the brake pedal due to the combination of the control element of the working brake system and the circuit of the parking brake system.

Figure 7 shows an integral brake valve with a parallel additional section [113]. In the initial position, when the brake pedal 7 is released, the receivers 3, 4, 5 are discharged, the upper follower piston 48 of the main two-section brake valve 6 under the action of the spring 49 and the lower follower piston 55 under the action of the spring 56 occupy the extreme upper position. The valve seats 50 and 57 are made as a single unit with the pistons 48 and 55, therefore the outlet ports of the valves 50 and 57 are open, and the brake chambers 8 and 9 of the tractor are connected to the atmosphere through the openings 64 and 65 and the hollow rod 53. Under the action of springs 52 and 59, valves 50 and 57 are pressed against fixed seats located in housing 38, and openings 60 and 61 are disconnected from openings 64 and 65, respectively. At the same time, control pistons 21 and 22 of the third section 12 of the integrated brake valve 13, under the action of springs 32 and 33, are in the extreme upper position, rubber seat 29 of atmospheric valve 28 is pressed against the movable seat in the lower control piston 21 by spring 31.

As receivers 3 and 4 are filled with compressed air from compressor 1 after the tractor engine is started, the pressure increases at inlet openings 60 and 61 of the main two-section brake valve 6, as well as at inlet openings 23 and 24 of the third section 12 of the integrated brake valve 13 and, accordingly, in cavities 17 and 18 above control pistons 21 and 22. When the force from the compressed air pressure exceeds the force of springs 32 and 33, control pistons 21 and 22 move to the extreme lower position, as a result of which the seat of the bypass valve 27 sits on the fixed seat in the housing 14, the cavity 19 connecting openings 25 and 26 is isolated from the auxiliary cavity 20 of the third section 12 of the integral brake valve 13, and the pusher 44 and the atmospheric valve 28 are lowered down. Thus, the lever 43 does not transmit force to the pusher 44 when turning, and the integral brake valve 13 does not affect the operation of the parking brake system of the tractor.

If the compressed air reserve in receivers 3 and 4 of the service brake system is sufficient, then during braking the force from pedal 7 through lever 41, pusher 42 and elastic rubber bushing 46 is transmitted to the upper follower piston 48 of the main two-section brake valve 6. The movable valve seat 50, moving together with piston 48, closes the outlet window of valve 50 and blocks communication through outlet 65 of brake chambers 9 with the atmosphere, and then tears valve 50 away from the fixed seat. Compressed air from receiver 4 through inlet 61, open valve 50 and outlet 65 enters the rear brake chambers 9, braking the tractor in the normal mode.

The pressure in the upper section 51 of the main two-section brake valve 6 increases until the force of pressure on the rubber bushing 46 is balanced by the force acting on the upper follower piston 48. Then the valve 50 sits on the fixed seat, and compressed air stops flowing into the brake chambers 9.

When the pressure in the cavity 69 of the upper section 51 increases, air enters the cavity 70 above the large piston 54 through the internal opening 68, which moves downwards together with the lower follower piston 55 and opens the valve 57. The compressed air enters the front brake chambers 8 through the inlet opening 60, the open valve 57 and then through the outlet opening 64. The pressure of the compressed air located in the space under the pistons

54 and 55 balances the force acting on the piston 54 from above. In the lower section 58 of the main two-section brake valve in the front brake chambers 8, a pressure is established corresponding to the force of pressing on the rubber bushing 46.

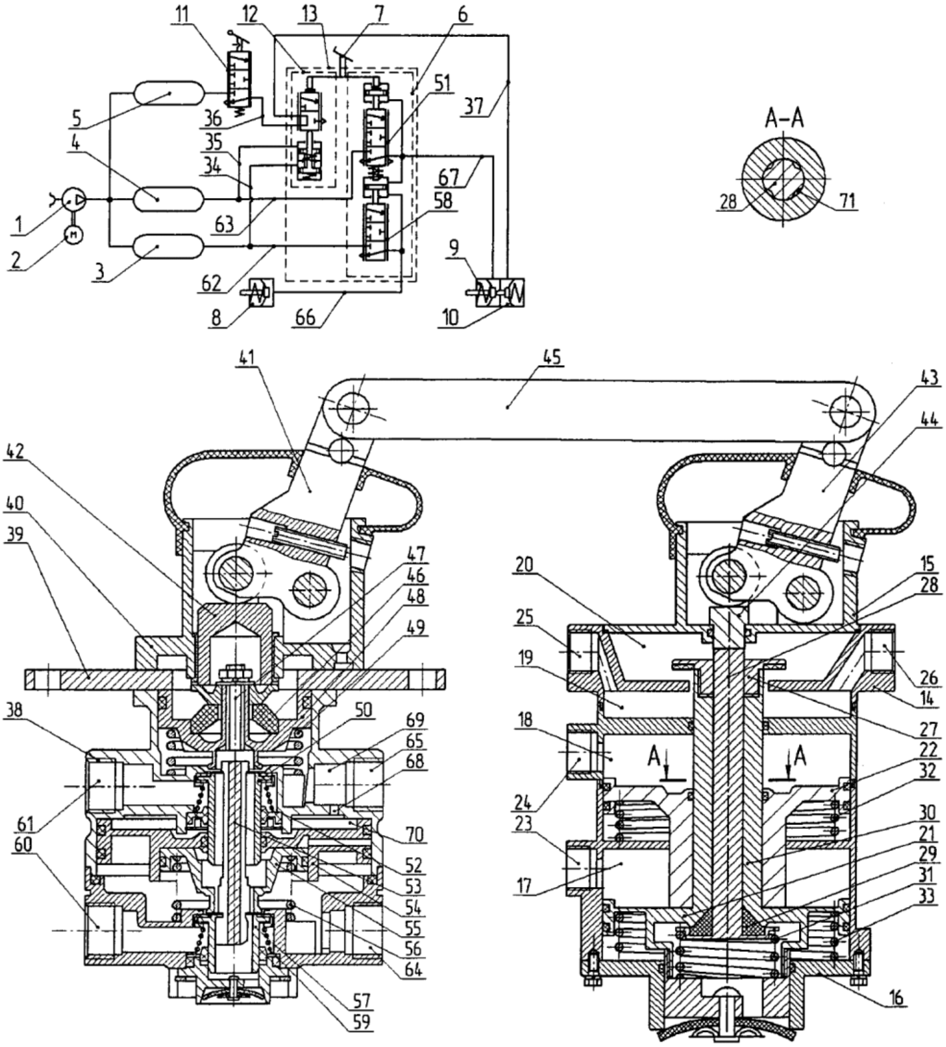


*Figure 7 Integral braking valve with parallel additional section:*
*1 - compressor; 2 - engine; 3, 4, 5 - receiver; 6 - two-section main brake valve; 7 - brake pedal; 8, 9 - brake chambers; 10 - spring energy accumulators; 11 - parking brake valve; 12 - third parallel section; 13 - integral brake valve; 14, 38 - housing; 15, 16, 39, 40 - cover; 17, 18, 19 - working cavity; 20 - auxiliary cavity; 21, 22 - control piston; 23, 24, 25, 26, 60, 61 - inlet; 27 - bypass valve; 28 - atmospheric valve; 29 - rubber seat; 30, 53 - hollow rod; 31, 32, 33, 49, 52, 56, 59 - spring; 34, 35, 36, 37, 62, 63, 66, 67 - pipeline; 41, 43 - lever; 42, 44 - pusher; 45 - earring; 46 - rubber bushing; 47 - thrust bolt; 48, 55 - follower piston; 50, 57 - valve; 51 - upper section; 54 - piston; 58 - lower section; 64, 65 - outlet holes; 68 - inner hole; 69, 70 - cavity; 71 - grooves*

When the force is removed from the lever 41, the piston 48 moves upward, the valve 50 is pressed against the fixed seat, and the outlet 65 communicates with the atmosphere through the outlet window of the valve and the hollow rod 53. The decrease in pressure in the upper section 51 causes the piston 54 to move upward, as a result of which the valve 57 also sits on the seat in the housing 38, and the outlet 64 communicates with the atmosphere, as a result of which the tractor is released.

During operation of the brake system, damage to the front and/or rear working circuit is possible, for example, in the event of a leak in the communication line, as well as in the event of a complete failure of compressor 1. In the event of a pressure drop in the upper section 51 of the main two-section brake valve 6 as a result of damage to the rear circuit, the force from the lever 41 through the stop bolt 47 is transmitted to the hollow rod 53, rigidly connected to the lower follower piston 55, and opens the valve 57. Thus, the lower section 58 will be controlled mechanically. In this case, its follower action will be preserved, since the force acting from above on the piston 55 will be balanced by the force on the piston, arising as a result of an increase in pressure in the lower section 58. When the pressure in the lower section 58 drops as a result of damage to the front circuit, the piston 54 sits on the lower stop in the body 38 of the valve 6, and the upper section 51 operates in the usual way.

The control pistons 21 and 22 of the third section 12 of the integrated brake valve 13 operate independently of each other. When the air pressure in the receiver 4 of the rear circuit of the service brake system drops (for example, as a result of a leak), the pressure also drops at the inlet opening 24 and in the cavity 18 above the upper control piston 22, which is displaced upward under the action of the spring 32. However, the bypass valve 27 is still closed, since the lower control piston 21 remains in the lower position.

When the pressure in the receiver 3 of the front circuit of the working brake system drops, the pressure also drops at the inlet 23 and in the cavity 17 above the lower control piston 21. However, the force from the compressed air pressure in the cavity 18 above the upper control piston 22 exceeds the total force of the springs 31 and 32, the control pistons 21 and 22 remain in the lower position, and the bypass valve 27 remains closed. If the compressed air pressure in receivers 3 and 4 simultaneously falls below the permissible limit, control pistons 21 and 22, under the action of springs 32 and 33, respectively, return to the extreme upper position, while the seat of the bypass valve 27 breaks away from the fixed seat in the housing 14. The atmospheric valve 28 moves upward, but its rubber seat 29 remains pressed against the movable seat in the lower control piston 21 by spring 31. Together with the atmospheric valve 28, the pusher 44 also rises upward until it stops against the roller of the lever 43.

Now, when there is a need to brake, when pressing pedal 7, the force from the lever 41 is transmitted through the earring 45 to the lever 43, which turns and moves the pusher 44 downward with the roller. The lower control piston 21 remains in the extreme upper position under the action of the spring 33, therefore the atmospheric valve 28, when acted upon by the pusher 44, moves downwards, overcoming the force of the spring 31, and the rubber seat 29 breaks away from the movable seat in the lower control piston 21. Compressed air from the spring energy accumulators 10 through the inlet opening 26, the open bypass valve 27, then through the grooves 71 in the atmospheric valve 28 goes out into the atmosphere. The tractor is braked by the spring energy accumulators 10, and the driver does not need to manually operate the parking valve 11.

As a result, equipping the tractor brake system with an integrated brake valve 13, having a third section 12, makes it possible to use the line of the spare parking brake system in the event of failure of both circuits of the vehicle's service brake system using only the brake pedal, which makes it possible to reduce the driver's reaction time and reduce the braking distance.

Figure 8 shows an integral brake valve with a sequential additional section [114]. The hollow rod 18 is designed to transmit mechanical force from the brake pedal 7 in emergency mode through the following movable elements of the main two-section brake valve 6: lever 27, stop bolt 30 and rod 36. A limit switch 58 is installed in flange 22 to transmit a signal to the driver's control panel about activation of the emergency mode.

In the initial position, when the brake pedal 7 is released, the receivers 3 and 4 are discharged, the upper follower piston 31 of the main two-section brake valve 6 under the action of the spring 32 and the lower follower piston 38 under the action of the spring 39 occupy the extreme upper position. The valve seats 33 and 40 are made as a single unit with the pistons 31 and 38, respectively, therefore the valves 33 and 40 are open, the brake chambers 8, 9 are connected to the atmosphere through the corresponding outlet openings 49, 50 and grooves in the rod 36 through the hollow rod 18 in the control piston 17. When the valves 33 and 40 are pressed under the action of the springs 35 and 42 to the fixed seats located in the housing 24, then the inlet openings 46 and 45 are disconnected from the outlet openings 49 and 50, respectively. At the same time, the control piston 17 in the additional, sequentially installed section 12, under the action of the spring 23, is in the extreme upper position and closes the outlet openings 56.

If the compressed air reserve in receivers 3 and 4 of the service brake system is sufficient, then during braking the force from pedal 7 is transmitted to lever 27, pusher 28 and elastic rubber bushing 29 on the upper follower piston 31 of the main two-section brake valve 6. The movable valve seat 33, moving together with piston 31, closes the outlet window of valve 33 and blocks the communication of the rear brake chambers 9 with the atmosphere, and then tears valve 33 away from the fixed seat. Compressed air from receiver 4 through inlet 46, open valve 33 and outlet 49 enters the rear brake chambers 9, performing braking in the normal mode.

The pressure in the upper section 34 of the main two-section brake valve 6 increases until the force of pressing on the rubber bushing 29 is balanced by the force acting on the upper follower piston 31. Then the valve 33 sits on the fixed seat, and the compressed air stops entering the brake chambers 9. When the pressure in the cavity of the upper section 34 increases, air enters the cavity above the large piston 37 through the internal opening 53, which, together with the lower follower piston 38, moves downwards and opens the valve 40. The compressed air enters the front brake chambers 8 through the inlet opening 45, the open valve 40 and then through the outlet opening 50. The pressure of the compressed air located in the space below the pistons 37 and 38 balances the force acting on the piston 37 from above. In the lower section 41 of the main two-section brake valve, in the front brake chambers 8, a pressure is established corresponding to the force of pressing on the rubber bushing 29.

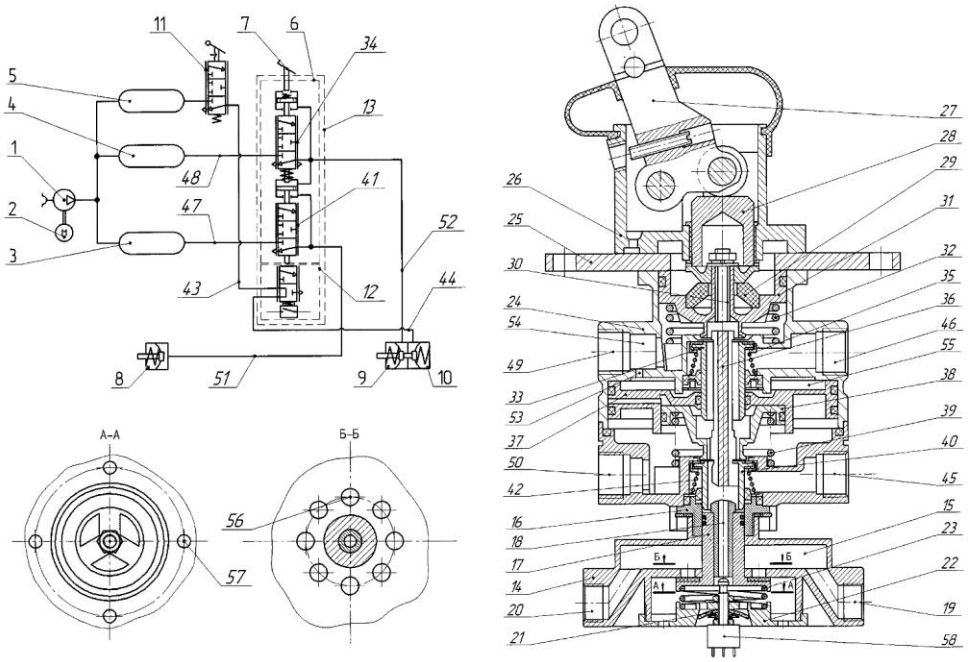


*Figure 8 Integral braking valve with a sequential additional section:*
*1 - compressor; 2 - engine; 3, 4, 5 - receiver; 6 - two-section main brake valve; 7 - brake pedal; 8, 9 - brake chambers; 10 - spring energy accumulators; 11 - parking brake valve; 12 - third sequential section; 13 - integral brake valve; 14, 24 - housing; 15 - working cavity; 16 - sleeve; 17 - control piston; 18 - hollow rod; 19, 20, 45, 46 - inlet; 21 - atmospheric valve; 22 - flange; 23, 32, 35, 39, 42 - spring; 25, 26 - cover; 27 - lever; 28 - pusher; 29 - rubber bushing; 30 - stop bolt; 31, 38 - follower piston; 33, 40 - valve; 34 - upper section; 36 - rod with longitudinal grooves; 37 - large piston; 41 - lower section; 43, 44, 47, 48, 51, 52 - pipeline; 49, 50 - outlet; 53, 56, 57 - inner hole; 54, 55 - cavity; 58 - limit switch*

When the force is removed from the lever 27, the piston 31 moves upward, the valve 33 is pressed against the fixed seat, and the inlet 49 communicates with the atmosphere through the open valve 33 and the grooves in the rod 36. The decrease in pressure in the upper section 34 causes the piston 37 to move upward, as a result of which the valve 40 also sits on the seat in the housing 24, and the outlet 50 communicates with the atmosphere, as a result of which the vehicle is released. During operation, there are cases of simultaneous failure of both working brake circuits, for example, when compressed air leaks occur along communication lines in the form of pipelines 47, 48, 51, 52, as well as when compressor 1 fails. In the event of a pressure drop in the upper section 34 of the main two-section brake valve 6 as a result of damage to the pipeline 52 of the rear working circuit, the force from the lever 27 through the stop bolt 30 is transmitted to the rod 36, rigidly connected to the lower follower piston 38, as a result of which the valve 40 opens. Thus, the lower section 41 will be controlled mechanically. In this case, its tracking action will be maintained, since the force acting from above on piston 38 will be balanced by the force arising as a result of the increase in pressure in the lower section 41. When the pressure in the lower section 41 drops as a result of damage to the pipeline 51 of the front working circuit, the large piston 37 sits on the lower stop in the housing 24, and the upper section 34 operates in the usual way.

If the compressed air pressure in receivers 3 and 4 simultaneously drops below the permissible limit, the force from lever 27 is transmitted through stop bolt 30 to rod 36, which transmits the force mechanically to hollow rod 18. Hollow rod 18, pressed against body 14 by means of spring 23 mounted on flange 22, lowers control piston 17, and compressed air from spring energy accumulators 10 exits into the atmosphere through openings 56 in body 14 and openings 57 on flange 22. Automatic braking of the vehicle is performed by the parking brake system, which performs a reserve function, while the driver does not need to additionally manually activate parking valve 11. Hollow rod 18 acts on limit switch 58, from which a signal is sent to the control panel about the emergency operation of the parking brake system of the vehicle.

Thus, equipping the main two-section brake valve with an additional, sequentially installed section makes it possible to reduce the stopping distance of a wheeled vehicle during emergency braking in the event of a decrease in pressure in the receivers of both working circuits of the brake system below the permissible limit by reducing the driver's reaction time by eliminating the need to activate an additional control element with informing the driver about the emergency mode of operation of the parking brake system.

## 4 SECONDARY COLLISION BRAKE ASSIST

Scientists estimate that about a quarter of all crashes involve multiple collisions. Secondary collisions can be especially dangerous because many safety systems, such as airbags and seat belt pretensioners, have already been deployed in the initial collision and cannot provide subsequent assistance. In addition, the vehicle’s structure is compromised by the initial impact and may be less able to absorb the energy of secondary collisions. Secondary collision brake assist (SCBA) reduces the likelihood and severity of secondary impacts (Figure 9).


*Figure 9 Secondary collision brake assist*

It is estimated that if all cars were equipped with SCBA, about 8 percent of fatalities and 4 percent of serious injuries could be prevented each year. The track tests included electronic simulations of airbag deployment and compliance checks in both high- and low-grip conditions. Testers covered almost a million kilometers to ensure there were no false alarms. SCBA has been independently tested by EuroNCAP and has been standard equipment on new Audi A3s since 2012.

If the airbag deploys in the initial collision, a signal is sent to the electronic stability control to automatically apply the brakes. If the vehicle is capable of safely and effectively braking, it automatically applies the brakes at a rate of 6 m/s2 to a speed of 10 km/h (6 mph) to prevent or at least mitigate a secondary impact with another vehicle or object on the road. During braking, the brake lights and hazard warning lights are turned on and remain on after stopping. In the event of a severe initial collision, there is a risk that the driver will be unable to steer, and SCBA will act automatically. If the driver detects that braking after the initial impact increases the risk, SCBA can be deactivated by pressing the accelerator pedal.

If the car is seriously damaged by the initial impact, SCBA will not act, as safe braking cannot be guaranteed. However, the electronic control unit is located in a well-protected area, so it is likely that SCBA will be able to help even if there is significant damage. On low-friction surfaces, the 6 m/s2 deceleration is not achieved, so the full benefit of SCBA cannot be realized.

The accident on the Moika River demonstrated the need to introduce a similar system on regular city buses.

## 5 CONCLUSIONS

The developments listed above have not yet been implemented in Russia, since the legislative system is very inert, especially in the area of standardization, and the commercial interests of the management of automobile plants diverge from the interests of society in the area of improving safety. Therefore, high-profile accidents with buses occur and will continue to occur. And the worst thing is that in any case, innocent victims are passengers who are not active participants in the traffic and are not able to influence the course of the disaster.

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# PERFORMANCES OF FAST CHARGERS FOR ELECTRIC BUSES IN BELGRADE ON THE EKO2 LINE

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RESEARCH ARTICLE

**ABSTRACT:** The performance of the electric bus charging system is an important aspect of electric bus operation. The correct choice of power and number of chargers on the line is essential to optimize the time required to charge or top up the battery/supercapacitor, to achieve the planned transport volume. The paper will present an analysis of the operation of fast chargers, power 400 kW, from the aspect of the time required to charge and transfer the amount of electricity to the E-bus, which is achieved under regular operating conditions, during regular waiting at the terminals, on the EKO2 line in Belgrade, which was put into operation on January 24, 2022, on which 8 E-buses are in traffic.

**KEY WORDS**: *Performance of Chargers, Electric bus, Time of charge, EKO2 line*



# PERFORMANSE BRZIH PUNJAČA ZA ELEKTRIČNE AUTOBUSE U BEOGRADU NA LINIJI EKO2

REZIME: Učinak sistema za punjenje električnog autobusa je važan aspekt rada električnog autobusa. Pravilan izbor snage i broja punjača na liniji je od suštinskog značaja za optimizaciju vremena potrebnog za punjenje ili dopunjavanje baterije/superkondenzatora, kako bi se postigao planirani obim transporta. U radu će biti prikazana analiza rada brzih punjača, snage 400 kV, sa aspekta vremena potrebnog za punjenje i prenos količine električne energije u E-bus, što se postiže u redovnim uslovima rada, pri redovnom čekanju na terminalima, na liniji EKO2 u Beogradu, koja je puštena u rad 24. januara 2022. godine, na kojoj saobraća 8 E-buseva.

**KLJUČNE REČI**: *Performanse punjača, električni autobus, vreme punjenja, EKO2 linija*

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# PERFORMANCES OF FAST CHARGERS FOR ELECTRIC BUSES IN BELGRADE ON THE EKO2 LINE

*Slobodan Mišanović*

## INTRODUCTION

Charging batteries or supercapacitors with electricity is an important aspect of the operation and organization of the bus with an electric drive. In practice, three basic strategies are used:

- Slow charging using a "plug-in" connector;
- Fast charging using a pantograph;
- Contactless charging.

The choice of electric bus charging system is determined by the type and size of the battery or supercapacitor, the requirements regarding the duration of charging, timetable and commercial speed, route lengths, kilometres operated per bus per day, the available energy capabilities of the electrical network, economics of AC versus DC charging, and the space provided for charging [1]. The most commonly applicable ways of charging electric buses are presented in Table 1 [2].

Table 1 E-bus charging method

| **Charging** | **Charging in garage** | **Charging at the terminus** | | **Charging on the line** | |
|---|---|---|---|---|---|
| | | **once** | **both** | **In the stations** | **Dynamically (Wi-Fi)** |
| Slow charging | yes | - | - | - | - |
| Fast charging | yes | yes | yes | yes | - |
| Combined, (Slow and Fast) | yes | yes | yes | | |
| Contactless | yes | yes | yes | yes | yes |

In practice, slow and fast charging strategies in garages or at terminals are currently the most prevalent, while contactless charging is less common in practice. Slow charging is used exclusively for E-buses with batteries. With this concept, bus charging is performed when the vehicle is not in operation, which is often during the night period, which is why it is usually called night charging. Electric buses with a standard length of 12 m, which are charged in this way, have batteries with a large capacity of 300÷500 kWh, which enables them to have a significant daily autonomy of movement, which can be over 250 km. The power of the slow charging charger installed in the garage is usually 60÷250 kW [3] (Figure 1), so the charging process lasts between 2.5 and 4 hours depending on the degree of battery discharge, capacity, and charging power. Table 2 presents the expected electrical losses that occur in the slow charging process of the E-buses from the charging source to the drive motor [4].

Table 2 Electrical losses in the charging process with "slow" charging

| System component | Efficiency coefficient ( $\eta$ ) |
|---|---|
| Charger | 0.95 |
| Battery charging (battery internal resistance) | 0.95 |
| Battery discharge (battery internal resistance and cable losses) | 0.93 |
| Inverter | 0.97 |
| Electric motor | 0.95 |
| Total for the whole system | 0.77 |

*Figure 1 Slow charging, charger "Winline" (2x125 kW) [3]*

One of the problems in the application of this charging concept is that if several buses are charged at the same time during the night or the day, they occupy a large working space in the depot and engage a large amount of power from the public distribution network at the same time. For the operation of a large number of electrically powered buses with this concept, significant investments are needed in the adaptation or construction of charging areas and chargers [3].

Fast charging of electrically powered buses can be done at stations along the route of the line or, more often, at the start/end stations (terminus) on the line where the E-bus is in operation, as well as at the depot where the vehicle parks and prepares for the next day. Electric buses with a standard length of 12m, with this charging concept, have lithium-titanium batteries (LTO) with a capacity of 60÷90 kWh [5] or a supercapacitor with a capacity of 20÷40 kWh [6]. Compared to electric buses with slow charging, this type of E-bus has limited autonomy, so they are used on predefined lines, where chargers are installed most often at the terminus so that the vehicle is recharged during the planned stay at the starting station.

Charging is done through a pantograph installed on the roof of the bus, which is activated at the place intended for charging. The average charging time is 3÷10 minutes and is performed after every completed half revolution (one direction), revolution (both directions), or more revolutions, depending on the capacity of batteries or supercapacitors, operating conditions, and power of the fast charging system. The power of the fast charging system installed at the terminus is usually 150÷600 kW [7,8,9]. Fast charging of electric buses is often called opportunity charging, given that depending on the battery capacity and operating conditions, the battery discharge can be of different intensity, so the optimal moment of battery charging is determined in this way, which is most often determined by SOC (State of charge) value between 30÷40%. Recharging this type of E-bus in the garage can be done via a pantograph (fast charging) or the vehicle is equipped with a plug-in connector for slow charging. In this way, there is a combined charging of the vehicle. Table 3 presents the expected electrical losses occurring in the fast charging process via the E-bus pantograph, which uses a supercapacitor as an electrical energy storage system, viewed from the charging source to the drive motor [10].

Table 3 Electrical losses in the charging process with "fast" charging

| System component | Efficiency coefficient ( $\eta$ ) |
|---|---|
| Charger+pantogarf | 0.95 |
| Internal resistance UC and cable losses | 0.97-0.98 |
| Inverter | 0.97 |
| Electric motor | 0.95 |
| Total for the whole system | 0.85 |

*Figure 2 Fast charging,Charger, "Gemamex" (400 kW)*

Compared to the slow charging system, in the case of fast charging using a pantograph, there is a smaller loss of electricity from the charging source to the drive electric motor. Charging of electric buses can also be done in a non-contact way, which is based on the principle of electric energy transfer using magnetic induction. The primary windings are embedded in the substrate, most often at the terminus. The secondary windings are installed on the E-bus (Figure 3) [11].

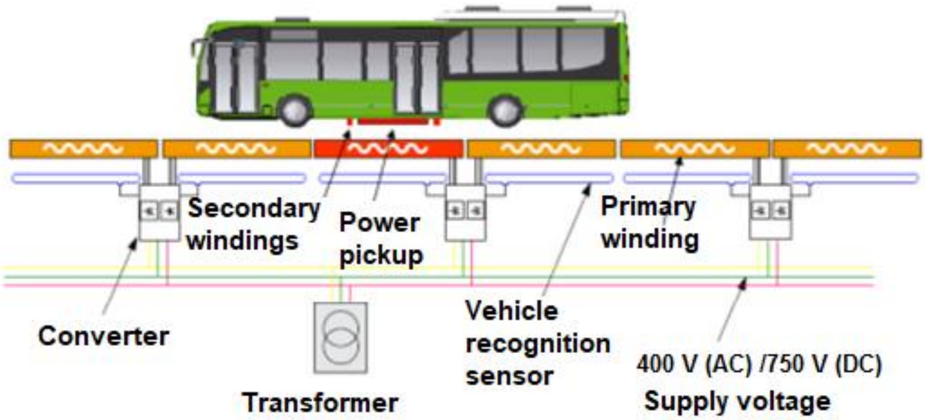


*Figure 3 Contactless charging E-bus*

Upon encountering the E-bus on the base where the primary is placed, the sensors recognize the E-bus, after which it is possible to turn on the system and contactless transmission of electricity, i.e. charging the battery on the vehicle. This process lasts 5÷8 minutes depending on the capacity of the battery and the power of the charger, which is 400÷600 kW. With this charging system, there is a greater loss of electrical energy from the charging source to the drive electric motor, given the greater number of components that make up the charging system. Further development of fast charging technology for electric-powered buses will lead to the development of technology for charging vehicles in motion, which will enable the E-bus to charge the battery or supercapacitor in the zone of certain stations via a wireless network (Connection). The world's leading manufacturers of electric bus charging systems are Siemens, ABB, Shunk, Jema Energy, Ekoenergetyka.

## 1 CITY LINE EKO 2

City line EKO2 (Sports Center M.G. Muskatirovic-Belgrade Waterfront) was put into operation on January 24, 2022. After the introduction of the EKO 1 line in 2016, it represents the continuation of the introduction of electric-powered buses into the Belgrade public transport system. The average length of the line is 7.1 km. There are 15 stations in direction "A" and 16 stations in direction "B". The average inter-station distance is 450 m. The line according to its spatial position is a diametrical line that connects parts of the city with a high degree of attraction: Kalemegdan, Trg Republike, Terazije, Trg Slavija, Nemanjina Street, Belgrade Waterfront (Figure 4). There are 10 electrically powered buses 12 m long, manufactured by Higer, KLQ6125GEV3 (Figure 5), which use a supercapacitor with a capacity of 40 kWh as an electrical energy storage system. Charging the E-bus is done using a mobile pantograph that is placed on the roof of the vehicle. The technical characteristics of E-bus Higer KLQ6125GEV3 are shown in Table 4 [10].

*Figure 4 Line EKO2 in Belgrade*

*Figure 5 Higer KLQ6125GEV3*

Table 4 Technical characteristics, Higer KLQ6125GEV3 [10].

| | Higer KLQ6125GEV3, Production 2021 |
|---|---|
| Length/width/height | 12000/2550/3680 mm |
| Curb weight | 12190 kg |
| Passengers | 90+1 |
| Doors | 3 |
| Max.speed | 70 km/h |
| Ultrarcapacitor | AOWEI 40 kWh |
| Charging time | Max 5 minutes |
| Traction motors | 1DB2016 6NBO6, permanent magnet |
| Power | 160 kW/230kW |
| Max. Torque | 2500 Nm |
| Inverter | DC/AC 600-720 V |
| Traction control | Siemens ELFA 3 |

## 2 FAST CHARGING INFRASTRUCTURE ON THE EKO 2 LINE

When defining the new EKO2 line in Belgrade, a necessary condition was the possibility of installing fast chargers at the terminus of the Sports Center- Milan G. "Muskatirovic" (Figure 6) and "Belgrade Waterfront" (Figure 7). At both terminals, there are two 400 kW AC/DC fast chargers, which are powered by 2 MW transformer stations, which are located near the chargers.

*Figure 6 Fast chargers, 2x400 kW, terminus Sports Center*

*Figure 7 Fast chargers, 2x400 kW, terminus Belgrade Waterfront*

*Table 5 Technical characteristics of chargers*

| | |
|---|---|
| Producer | Gemamex |
| Input Voltage AC | 3X380 V |
| Max. Power | 400 kW |
| Max. Output current, DC | 500 A |
| Max.Output Voltage, DC | 750 V |
| Charger efficiency | 97% |
| Pylon Height | 4.5-4.6 m |
| Trafo, AC | Dalcom, 2 MW |

Given that there are two fast chargers and charging points at each terminus, it is planned that these terminuses will be used in the future for new lines on which electric buses will operate, since one charger at each terminus is sufficient for the EKO2 line.

## 3 THE METHODOLOGY OF DATA ACQUISITION

Data acquisition to analyse the performance of fast chargers on the EKO2 line was carried out during the charging process at the terminal by collecting data via the S-CAN network of the E-bus using a LAPTOP computer or using the CARMON-ABRITES application for real-time data collection.

Figure 8 Data acquisition using a laptop computer


Figure 9 Current values of voltage and current on the supercapacitor in real-time on the EKO2 line

Downloaded data: current (A), voltage (V), and state of charging of supercapacitor SOC (%) are exported to an EXCEL file, with a base frequency of 0.25 s. It should be noted that electric buses on the EKO2 line are charged with electricity after each turn on the line (Direction "A"+direction "B"), where the vehicles run about 14.2 km. On several measurements, data acquisition was performed even after completing one-half turn, i.e. after running in one direction.

## 4 RESULTS OF THE DATA PROCESSING AND DISCUSION

Figure 8 presents a graphic representation of the downloaded data at the "Belgrade Waterfront" terminus, on February 10, 2023, in the period from 07:09:47 to 07:14:15 [12].

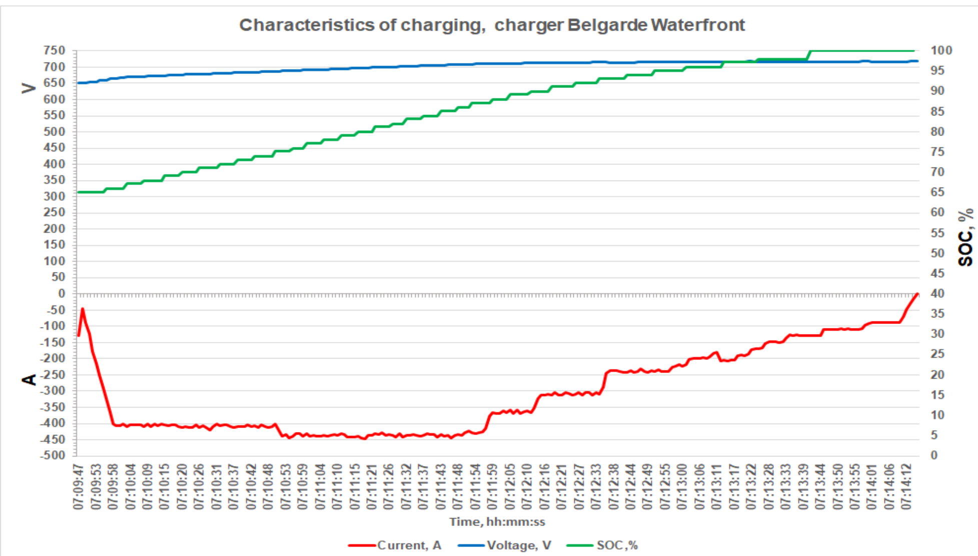


Figure 10 Current values of charging current (A), voltage (V) and SOC (%) on the E-bus supercapacitor

For the given example, in the period of charging, which was 04:28, 15.875 kWh of electrical energy was taken from the charger to the supercapacitor. The charging phase begins with the activation of the mobile pantograph located on the roof of the vehicle and its connection with the contact conductors of the charger located on the supporting pylon. After that, the interface connection is established and this phase lasts about 5÷10 seconds on average. After that, the filling phase begins. The current strength of the DC charging current (A) that charges the supercapacitor is regulated depending on the voltage reached on the supercapacitor. It can be seen from the Figure 10 that in the initial phase of charging, the instantaneous current reaches maximum values in the range of 400÷451 A, at voltage values of 650÷700 V. When the voltage on the supercapacitor reaches the value of 700 V, there is a rapid drop in the instantaneous charging current, so that for the value of the reached voltage of 720 V, the current value of charging is about 80 A, which reaches the charge of the supercapacitor of 100%, and the completion of the charging phase by the automatic disconnection of the charger and the pantograph of the vehicle. The maximum charging current was 451 A, the maximum charging power was 314.6 kW, the minimum power at the beginning of charging was 29.9 kW, and the average charging power during the entire phase was 212.3 kW. At the start of charging, the current charge level of the supercapacitor was 65.2% and the voltage value was 650 V. At the end of charging, a voltage of 720 V was reached, i.e. the charge level of the supercapacitor was 100%. To see as realistically as possible the performance of the fast chargers on the EKO2 line at the terminals "Belgrade Waterfront" (BW) and "Sports Center Milan G. Muskatirovic" (SC), data acquisition was performed during the filling process on a sample of 19 measurements. After processing the collected data, the performance of the charger is shown in Table 6 [12].

Table 6 Performance of chargers on the EKO2 line in Belgrade

| Charger, location | Date | Start of charging (hh:mm:ss) | End of charging (hh:mm:ss) | Duration of charging (mm:ss) | Duration of charging (ss) | Energy taken (kWh) | Average charge power (kW) | SOC start (%) | SOC end (%) |
|---|---|---|---|---|---|---|---|---|---|
| BW | 19.9.2022 | 08:28:22 | 08:31:39 | 03:17 | 197 | 11.690 | 212.55 | 73.2 | 100 |
| BW | 19.9.2022 | 05:48:40 | 05:52:05 | 03:25 | 205 | 11.153 | 194 | 74 | 100 |
| BW | 19.9.2022 | 07:11:28 | 07:15:05 | 03:37 | 217 | 12.506 | 206.52 | 72 | 100 |
| BW | 10.2.2023 | 05:49:08 | 05:54:02 | 04:54 | 294 | 19.897 | 242.68 | 56 | 100 |
| BW | 10.2.2023 | 07:09:47 | 07:14:15 | 04:28 | 268 | 15.875 | 212.30 | 65.2 | 100 |
| SC | 27.2.2023 | 06:30:35 | 06:35:08 | 04:33 | 273 | 13.650 | 199.01 | 67.2 | 100 |
| BW | 27.2.2023 | 05:54:34 | 05:59:32 | 04:58 | 298 | 17.461 | 210.9 | 59.2 | 98 |
| BW | 6.3.2023 | 23:18:06 | 23:23:34 | 05:28 | 328 | 21.237 | 228.3 | 54 | 100 |
| SC | 6.3.2023 | 11:49:36 | 11:51:53 | 02:17 | 137 | 6.722 | 174.77 | 85.2 | 100 |
| SC | 6.3.2023 | 06:29:20 | 06:33:16 | 03:56 | 236 | 12.268 | 185.77 | 73.2 | 100 |
| SC | 7.3.2023 | 18:34:09 | 18:38:27 | 04:18 | 258 | 18.927 | 263.01 | 57 | 100 |
| SC | 8.3.2023 | 06:30:44 | 06:33:05 | 02:21 | 141 | 10.020 | 253.74 | 74 | 97 |
| BW | 8.3.2023 | 07:08:28 | 07:11:40 | 03:12 | 192 | 10.568 | 204.38 | 74 | 98 |
| BW | 8.3.2023 | 16:34:01 | 16:37:20 | 03:19 | 199 | 15.301 | 273.35 | 62 | 96 |
| BW | 8.3.2023 | 09:47:46 | 09:51:34 | 03:48 | 228 | 10.533 | 236.29 | 65.2 | 98 |
| SC | 9.3.2023 | 17:24:11 | 17:28:06 | 03:55 | 235 | 18.244 | 278.54 | 57.2 | 100 |
| SC | 11.4.2023 | 17:14:17 | 17:15:58 | 01:41 | 101 | 7.229 | 254.59 | 81.2 | 97.2 |
| BW | 11.4.2023 | 16:34:13 | 16:35:20 | 01:07 | 67 | 4.107 | 217.28 | 86 | 95.4 |
| BW | 20.4.2023 | 11:14:12 | 11:16:49 | 02:37 | 157 | 11.582 | 264.5 | 69.2 | 95.2 |
| **Average value** | | | | **03:35** | **215** | **13.10** | **226.97** | | |

After processing the downloaded data, it follows that the mean time of charging the E-bus at the terminus is 03:35 (3 minutes and 35 seconds), while the mean value of the electricity with which the supercapacitor is charged is 13.10 kWh. The average charging power is

226.97 kW. The amount of electricity with which the supercapacitor will be charged (recharged) during the charging phase depends on its discharge, which is directly related to the total electricity consumption of the E-bus during operation on the line and the charging time.

The most significant influencing factor on the total electricity consumption of the E-bus is the use of the passenger and driver space heating system during the winter period of operation and the use of the passenger and driver space cooling system during the summer period of operation. From Table 6, it can be seen that the highest value of supercapacitor charging energy via the fast charger at the Belgrade Waterfront terminus was 21.237 kWh (March 6, 2022) and 19,897 kWh (February 10, 2022) during the winter period of operation.

If the electrical energy of charging is analysed as a function of the achieved charging time, a significant correlation dependence of these two quantities is reached, as shown in Figure 9 [12].

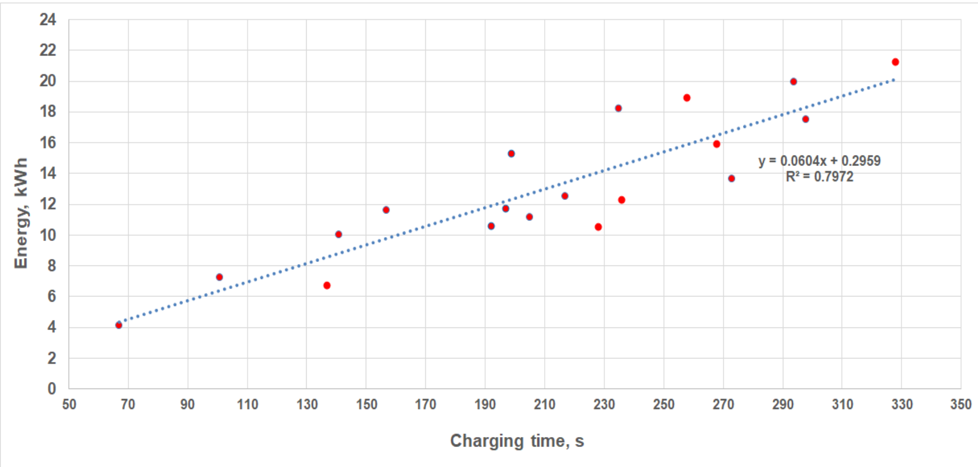


***Figure 11*** Dependence of charging energy and charging time on chargers, line EKO 2

The correlation dependence between charging energy and charging time has a significant linear dependence where the coefficient of dependence is $R^2$=0.797. Knowledge of the aforementioned charger performance, above all the dependence on the charging energy and the required charging time, is significant from the point of view of the organization of the operation of electric buses on the EKO2 line to optimize the waiting and charging time at the terminus. Considering that the prescribed time for the bus to stay at the terminus when changing the direction of movement is 5 minutes, it follows that it is optimal that the time of refuelling the vehicle via the charger should be within the stipulated time of staying at the terminus, i.e. under 5 minutes.

From the examples in Table 6, it is proven that the specified criterion is fulfilled, which practically means that from the point of view of the organization of the work of vehicles on the EKO2 line, it is recommended that the E-bus be topped up after each turn at one of the terminuses. Recharging the E-bus after driving in one direction (half a turn) is not recommended, considering that the capacity of the supercapacitor is 40 kWh and that its discharge, in that case, is relatively small and also decreases without the necessary activation of the movable pantograph mechanism located on the roof of the vehicle. In the case of E-bus operation, if 2 turns were made, the charging time would be between 7 and 8 minutes, which is more than the prescribed 5 minutes of staying at the terminus and would have an impact on the realization of the planned timetable.

## 5 CONCLUSION

The performance of fast chargers for electric buses represents an important segment of the planning, organization, and exploitation of the operation of vehicles on the line. The correct choice of the number and power of fast chargers results from the available possibility of connecting to a transformer station the expected consumption of electric energy of the E-bus on the selected line and the number of vehicles in operation. The best case is that the required charging time is less than 5 minutes, based on which the strategy of charging vehicles at the terminus can be defined, i.e. whether charging will be performed after each realized direction of movement, one or two half-turns. Based on the charging time, the amount of electricity that will be stored in the supercapacitor via the fast charger can be predicted.

The analysis of the performance of fast chargers on the EKO2 line in Belgrade proves that they meet the set criteria in terms of the time required for charging and the transfer of the amount of electricity that is achieved during the charging phase between the distribution network, the charger and the supercapacitor of the vehicle. The chosen strategy of charging the E-bus after each completed turn is justified, given that the charging time is under 5 minutes, which guarantees the realization of the planned bus schedule on the line.

## 6 CONCLUSIONS

During the 1600-hour UV aging process, we conducted mechanical tests on samples taken at various time intervals. Our goal was to assess how resistant each compound is to UV radiation and to what extent they change. Samples I and III were the most sensitive to UV radiation, while Samples II and IV were less affected. We recommend further development of the formulation used in Samples II and IV for the windshield sealing material.

Overall, this study demonstrates the varying levels of UV resistance among the tested rubber compounds. By identifying the compounds that show greater resilience, manufacturers can focus on optimizing these formulations for enhanced durability in real-world applications. The findings also highlight the importance of continuous testing and material development to ensure the longevity of rubber materials exposed to UV radiation in transportation settings.

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# TRAFFIC HAZARD DUE TO HIGH CENTRE OF GRAVITY

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RESEARCH ARTICLE

**ABSTRACT:** The combination of a trailer and load presents significant hazards on motorways, particularly due to high speeds and sharp curves. Proper loading is crucial to prevent load displacement during heavy braking or sudden directional changes. A load shift, especially when the centre of gravity is high, can initiate critical situations, increasing the risk of tipping and rolling.

This paper analysis the critical situations, emphasizing drivers responsibility in ensuring safe loading practices to avoid causing dangerous road conditions, such as vehicle overturning. Such incidents are unfortunately common. The paper will explore characteristic vehicles, safety systems, cornering dynamics, and both theoretical and practical demonstrations of load behaviour under various forces. Side-slip and rollover phenomena will also be examined.

**KEY WORDS**: *traffic, road danger, vehicle composition, high centre of gravity, driver responsibility*



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## ISPITIVANJE ČVRSTOĆE 3D ŠTAMPANIH UZORAKA

REZIME: Kombinacija prikolice i tereta predstavlja značajne opasnosti na autoputevima, posebno zbog velikih brzina i oštrih krivina. Pravilno opterećenje je ključno za sprečavanje pomeranja tereta tokom jakog kočenja ili naglih promena smera. Promena opterećenja, posebno kada je centar gravitacije visok, može da izazove kritične situacije, povećavajući rizik od prevrtanja i kotrljanja.

Ovaj rad analizira kritične situacije, naglašavajući odgovornost vozača u obezbeđivanju bezbednih praksi utovara kako bi se izbeglo izazivanje opasnih uslova na putu, kao što je prevrtanje vozila. Takvi incidenti su, nažalost, česti. U radu će se istražiti karakteristična vozila, bezbednosni sistemi, dinamika skretanja, te teorijske i praktične demonstracije ponašanja opterećenja pod različitim silama. Takođe će se ispitati fenomeni bočnog klizanja i prevrtanja.

**KLJUČNE REČI**: *saobraćaj, opasnost na putu, sastav vozila, visoko težište, odgovornost vozača*

# TRAFFIC HAZARD DUE TO HIGH CENTRE OF GRAVITY

*Franci Pušavec, Janez Kopač*

## INTRODUCTION

The safe operation of vehicles on motorways requires careful consideration of numerous factors, with the height of the centre of gravity being one of the most critical. The centre of gravity (C.G.) plays a pivotal role in determining a vehicle's stability, particularly when negotiating sharp curves or during sudden manoeuvres. Vehicles with a high centre of gravity are inherently more prone to tipping and rolling, especially when subjected to the dynamic forces encountered at high speeds [1-3].

The modern transportation industry increasingly relies on high-capacity trailers and semi-trailers to move large loads efficiently. However, this efficiency can come at a significant cost if proper precautions are not taken. The challenge of safely transporting goods becomes even more significant when dealing with loads that are bulky, tall, or unevenly distributed. The risk is exacerbated when such loads are not properly secured, as any sudden shift can drastically alter the vehicle's balance, leading to a loss of control. Example is shown in figure 1 [1].

Over the years, there have been numerous documented cases of accidents caused by improper load securing and the resulting shift in the centre of gravity. These incidents often lead to severe consequences, including vehicle rollover, multi-vehicle collisions, and, in the worst cases, fatalities. Despite advancements in vehicle safety technologies, the human factor—particularly the responsibility of the driver and those involved in the loading process—remains crucial in preventing such accidents [3, 4].

This paper seeks to shed light on the dangers associated with a high centre of gravity in vehicle compositions and to provide guidance on best practices for loading and securing cargo. By analysing the dynamics of cornering, the impact of speed, and the role of safety systems, we aim to equip drivers and transport professionals with the knowledge necessary to minimize the risk of accidents. The paper will also include case studies and practical demonstrations of how forces act on a load during different driving scenarios.

*Figure 1 Consequence of serious influence of load on vehicle balance.*

## 1 GENERAL PROBLEMS ASSOCIATED WITH HIGH C.G. LOADINGS

The composition: the towing vehicle, the semi-trailer and the load on it can be perfectly safe as long as the centre of gravity is low. However, if this is altered, the following scenarios can become reality:

### *1.1 Increased Risk of Vehicle Rollover*

One of the primary concerns when a truck is loaded with a high centre of gravity is the increased risk of rollover. When the centre of gravity is raised, the vehicle becomes more top-heavy, making it more susceptible to tipping over, particularly when making sharp turns, sudden stops, or during evasive manoeuvres. This risk is especially pronounced in vehicles such as flatbed trucks, which often carry large, bulky items like machinery or construction materials that are difficult to load evenly.

<u>Case study</u>

A flatbed truck carrying a stack of steel beams that are not properly secured and are loaded too high is a common example of a scenario where the vehicle's centre of gravity is dangerously elevated. In this case, even a moderate turn at standard road speeds could cause the beams to shift, leading to a rollover. Another example is shown on Figure 2.

*Figure 2 Dangerously elevated centre of gravity due to inappropriate truck loading.*

### *1.2 Load Shift During Transit*

When a load is not adequately secured, it can shift during transit, significantly altering the vehicle's centre of gravity. This sudden change can lead to loss of control, particularly if the driver is forced to brake suddenly or swerve to avoid an obstacle. The load shift not only affects the balance of the vehicle but can also lead to severe structural stress on the trailer, potentially causing it to fail.

<u>Case study</u>

Consider a situation where a truck is transporting large barrels of liquid that are not securely fastened. As the truck takes a sharp turn, the barrels roll to one side, dramatically shifting the centre of gravity and causing the truck to tip over. This is especially dangerous in conditions where the road surface is wet or uneven, as the reduced friction can exacerbate the risk of rollover.

### *1.3 Decreased Vehicle Manoeuvrability*

A higher centre of gravity adversely affects a vehicle’s manoeuvrability. The higher the centre of gravity, the more difficult it becomes to control the vehicle, especially when making sudden directional changes or when driving on uneven terrain. This reduced manoeuvrability can lead to accidents, particularly in situations where the driver needs to respond quickly to avoid a collision.

<u>Case study</u>

A delivery truck loaded with high C.G. elements (as show on Figure 3), will experience significant change in dynamics and behaviour of it during lateral acceleration. This situation can make it difficult for the driver to maintain control, especially in emergency situations where quick steering adjustments are required.


*Figure 3 Heavy high C.G. load on truck.*

### *1.4 Increased Stopping Distance*

A high centre of gravity, combined with an uneven load, can also increase a vehicle's stopping distance. This is due to the fact that the load may shift forward during braking, transferring more weight to the front axle and reducing the effectiveness of the brakes. This is even more dominant in non-braking trailer. In extreme cases, this can lead to brake failure or jack-knifing in articulated vehicles.

<u>Case study</u>

A truck carrying a tall, unsecured load of construction materials that suddenly brakes to avoid a collision could find that the load shifts forward, increasing the vehicle’s stopping distance and leading to a rear-end collision.

### *1.5 Strain on Vehicle Components*

A poorly loaded truck with a high centre of gravity can place undue strain on various vehicle components, including the suspension, tires, and axles. This not only increases the risk of mechanical failure but also contributes to higher maintenance costs and shorter vehicle lifespan.

Case study 1

A heavy load concentrated high above the truck bed can cause the suspension to compress unevenly, leading to premature wear and tear. Over time, this can result in component failure, such as a broken axle, which could lead to a serious accident on the road.

Case study 2

In 2019, a truck transporting large wind turbine blades overturned on a motorway due to the improper loading of the blades, which raised the centre of gravity. The driver attempted to take a curve at a speed slightly above the recommended limit, which caused the vehicle to tip over. The accident resulted in a complete road closure and significant delays, highlighting the dangers of transporting loads that elevate the centre of gravity.

## 2 CALCULATING VEHICLE SLIP AND ROLLOVER IN A BEND

This section will delve into the mathematical and physical principles governing vehicle slip and rollover in bends, emphasizing the importance of load securing and speed control. The analysis will cover the key factors that influence these phenomena, including the radius of the curve, the speed of the vehicle, and the height of the centre of gravity.

The rollover threshold, a critical concept in understanding vehicle stability, thus are analysed in detail. This threshold is influenced by the lateral acceleration experienced by the vehicle, which increases with the speed of the vehicle and the sharpness of the turn. The height of the centre of gravity is directly proportional to the likelihood of rollover, as a higher C.G. reduces the amount of lateral force needed to tip the vehicle.

### *2.1 Centrifugal Force on Vehicle Components*

When a truck with trailer is travelling into a bend (figure 4), the maximum speed can be determined according to the radius of the bend, the gradient of the road surface and the road-to-tire friction coefficient.

The coefficient of friction for dry asphalt is estimated to be $\mu$=0.6. The lateral coefficient of friction is 67% of the maximum friction coefficient. In the concrete case this means $\mu$ =0.4. The centre of gravity *h* can be determined from the individual centres of gravity and masses:

$$h = \frac{6000 \cdot 0.6 + 21641 \cdot 2.6}{27941} = 2.15\ m, \quad (1)$$

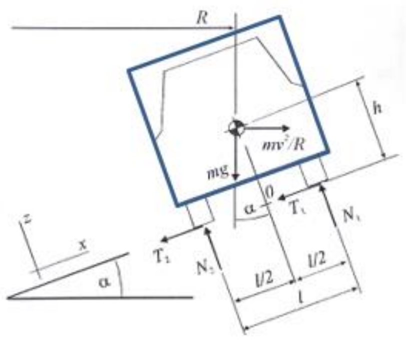


*Figure 5 Analysis of slip and rollover threshold in turn.*

$$v_{mejna-zdrs} = \sqrt{Rg\frac{\mu cos\alpha + sin\alpha}{cos\alpha - \mu sin\alpha}} = \sqrt{80 \cdot 9.81\frac{0.4cos4 + sin4}{cos4 - 0.4sin4}} = \mathbf{70\ km/h}$$

$$v_{mejna-prevrnitev} = \sqrt{Rg\frac{\frac{l}{2}cos\alpha + hsin\alpha}{-\frac{l}{2}sin\alpha + hcos\alpha}} = \sqrt{80 \cdot 9.81\frac{1.05\,cos4 + 2.15sin4}{-1.05sin4 + 2.15cos4}} = \mathbf{76\ km/h} \quad (2)$$


*Figure 4 Road situation for rollover case in a bend/turn.*

As a result of too high speed, the truck has rolled over as is shown in figure 6.


*Figure 6 Crossing the rollover tresholdof truck.*

## 3 CONCLUSIONS

The transportation of goods, particularly in vehicles with a high centre of gravity, presents significant challenges and risks that cannot be ignored. This paper has highlighted the critical role that proper loading and securing practices play in maintaining vehicle stability and preventing accidents. The examples and analyses provided demonstrate that a high centre of gravity increases the likelihood of vehicle rollovers, reduces manoeuvrability, and places additional strain on vehicle components.

Drivers, as well as those responsible for loading, must be acutely aware of these risks and take proactive measures to mitigate them. This includes ensuring that loads are evenly distributed, properly secured, and kept as low as possible within the vehicle. Moreover, adherence to safe driving practices, such as maintaining appropriate speeds and avoiding sudden manoeuvres, is essential to preventing accidents.

The consequences of neglecting these safety measures can be severe, leading not only to vehicle damage but also to potential loss of life. It is imperative that the transportation industry continues to prioritize safety by investing in training, adopting best practices, and utilizing advanced safety technologies designed to prevent rollover incidents.

In conclusion, while advancements in vehicle safety systems have reduced some risks, the human factor remains the most critical element in ensuring safe transportation. By fostering a culture of responsibility and awareness among drivers and transport professionals, the dangers associated with a high centre of gravity can be significantly minimized, leading to safer roads for everyone.

## 4 ACKNOWLEDGMENTS

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# METHODS FOR CATEGORIZING ROAD TUNNELS ACCORDING TO DANGEROUS GOODS REGULATIONS

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RESEARCH ARTICLE

**ABSTRACT:** According to the ADR Agreement, road tunnels should be assigned a specific tunnel category regarding the passage of dangerous goods. The categorization shall be based on examining the dangers of explosion, release of toxic gas or volatile toxic liquid and fires, which may cause numerous victims or serious damage to the tunnel structure. EU Tunnel Directive 2004/54/EC aims to ensure a minimum level of safety for users in road tunnels in the Trans-European Road Network. EU member states are required to develop, at national level, their own detailed methodology for tunnel risk assessment. Different risk models exist in the literature, however in many European countries the QRAM (Quantitative Risk Assessment Model) is the one most widely used and can satisfy the regulatory framework for tunnel categorization. In this paper, a methodological approach has been presented using the QRAM for determining optimum tunnel categorization according to ADR Agreement requirements.

**KEY WORDS**: *road tunnels, dangerous goods - ADR, tunnel category, risk assessment*



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# METODE KATEGORIZACIJE DRUMSKIH TUNELA PREMA PROPISIMA O PREVOZU OPASNIH MATERIJA

REZIME: Prema ADR sporazumu, drumskim tunelima treba dodeliti posebnu kategoriju tunela u pogledu prolaska opasnih materija. Kategorizacija će se zasnivati na ispitivanju opasnosti od eksplozije, ispuštanja toksičnog gasa ili isparljive otrovne tečnosti i požara, koji mogu izazvati brojne žrtve ili ozbiljna oštećenja konstrukcije tunela. Direktiva EU o tunelima 2004/54/EC ima za cilj da obezbedi minimalni nivo bezbednosti za korisnike u putnim tunelima u transevropskoj putnoj mreži. Od država članica EU se zahteva da razviju, na nacionalnom nivou, sopstvenu detaljnu metodologiju za procenu rizika od tunela. U literaturi postoje različiti modeli rizika, međutim u mnogim evropskim zemljama KRAM (model kvantitativne procene rizika) je onaj koji se najviše koristi i može da zadovolji regulatorni okvir za kategorizaciju tunela. U ovom radu je predstavljen metodološki pristup korišćenjem KRAM za određivanje optimalne kategorizacije tunela prema zahtevima ADR sporazuma.

**KLJUČNE REČI**: *drumski tuneli, opasni teret - ADR, kategorija tunela, procena rizika*

# METHODS FOR CATEGORIZING ROAD TUNNELS ACCORDING TO DANGEROUS GOODS REGULATIONS

*Željko Đurić, Snežana Petković, Valentina Golubović Bugarski, Nataša Kostić*

## INTRODUCTION

Tunnels have played an essential role in modern transportation systems since the mid-20th century. They reduce distances, represent stable connections free from the influence of seasonal and weather conditions and relieve urban areas from noise, exhaust fumes and dust. While most engineering techniques concerning tunnel construction and safety requirements have been continually improving, the problem of dangerous goods transport through tunnels has not been satisfactorily solved yet, [10].

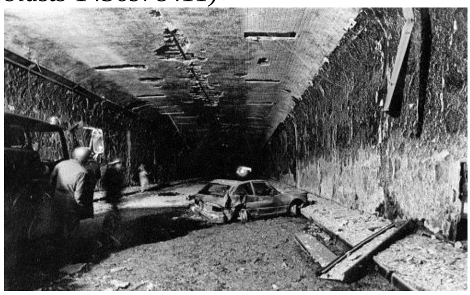
A serious incident involving dangerous goods in a tunnel can be very costly in terms of human lives, the environment, tunnel damage and transport disruption. On the other hand, needlessly banning dangerous goods from tunnels may create unjustified economic costs. There is significant risk of fire and explosion when transporting dangerous goods in a tunnel. Figure 1 shows some severe tunnel fire accidents, [15]:

- On 24 March 1999. a dramatic fire occurred in the Mont Blanc tunnel between France and Italy. It was initiated by a heavy goods vehicle which stopped near the middle of the tunnel and immediately burst into flames. The fire spread over 34 vehicles and was finally extinguished after 53 hours, 38 road users and a fireman lost their lives in the drama and the tunnel was seriously damaged and closed the tunnel for three years, Figure 1a, [15].
- In March 2014, a rear-end collision accident involving two methanol tankers occurred in the Yanhou tunnel in China, causing 40 deaths, 12 injured and 42 vehicles destroyed, [5,14].
- In July 2015 an incident occurred in a steep road tunnel in Norway (Skatestraum tunnel) with an tanker and a trailer carrying 16,500 l petrol which was incidentally released halfway up a 1 km long sloped tunnel (10%) and hit a tunnel wall. The initial fire size was estimated to be 212 MW and the maximum heat release rate including the tank fire was estimated to be 440 MW, Figure 1b. [5,14,15],
- In the Tauern Tunnel in Austria in 1999, one person died and 36 were injured when the temperature inside the tunnel peaked at around 1,000°C, Figure 1c, [5,14,15].
- In Caldecott Tunnel (USA) fire, in April 7, 1982, car struck the wall, blocking the roadway about halfway through the tunnel. A tanker truck hauling gasoline crashed into car and then was struck from behind by a bus, which somehow ended up outside the tunnel. The gasoline tanker inside ignited, creating an inferno that killed seven people, Figure 1d, [5,14,15].

*Mont Blanc tunnel, in 1999. (https://www.onlinesafetytrainer.com/the-mont-blanc-tunnel-fire-of-1999/)*

*Skatestraum tunnel, Norway, in 2015., (https://www.wsj.com/articles/norwegian-authorities-fear-tunnel-collapse-after-blasts-1436978411)*

*Tauern tunnel, Austria, in 1999, (https://www.researchgate.net/publication/284676361_Fire_proof_geopolymer_cements )*



*Caldecott Tunnel, USA, in 1982, (https://www.pressdemocrat.com/article/news/a-fiery-tomb-remembering-one-of-the-bay-areas-most-terrifying-disasters/ )*

*Figure 1 Tunnels after fire accidents, [15]*

All these events indicated the vulnerability of tunnels as infrastructural facilities and the great risk to people's lives, the economy and the environment. Tunnel fire accidents have shown that the toxic effects of the trapped smoke from the fire inside the tunnel in combination with the elevated temperature of the smoke itself can result in a high number of fatalities amongst the tunnel users, [2]. Furthermore, in the vicinity of the fire the tunnel structure is heavily damaged and the renovation period can last for a long period of time resulting in tunnel closure and traffic disruption of the route including the particular tunnel. The economic consequences may be very large. Therefore, necessary measures should be envisaged and implemented in order to increase the safety and availability to acceptable levels.

## 1 REVIEW CURRENT NATIONAL AND INTERNATIONAL REGULATIONS REGARDING THE TRANSPORT OF DANGEROUS GOODS THROUGH ROAD TUNNELS

In Europe, Transport of dangerous goods by road is regulated by the UN Agreement concerning the International Carriage of Dangerous Goods by Road (ADR codes). Most states in the United States and provinces in Canada follow codes in compliance with the United Nations Model Regulations. Australia and Japan have their own codes for defining dangerous goods, although Australia is currently aligning with the United Nations system.

In contrast, the rules and regulations for the transport of dangerous goods in tunnels vary considerably among countries and even within countries. Rules and regulations applying to specific tunnels have been devised in a number of countries. The definition, decision making, responsibility and enforcement are left to local or provincial authorities and politicians, the tunnel owners.

European Parliament and Council adopted the European Directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network (TERN), in which it is clearly required, when a tunnel is opened for example to the transport of dangerous goods, that a risk analysis should be carried out to establish whether additional safety measures and/or supplementary equipment are necessary to ensure a high level of tunnel safety, [4]. Risk analysis is an important tool that can be helpful for improving and/or optimizing the safety level of road tunnels.

Managing the risks involved with transporting dangerous goods through road tunnels and finding solutions to these complex problems required varied scientific experience and strong financial support. For these reasons, the OECD (Organization for Economic Co-operation and Development) and PIARC (World Road Association) launched a joint research project, which resulted in the Report covering both regulatory and technical aspects of dangerous goods passage through road tunnels, [7,11].

Since EU does not impose a methodology, member states are required to develop, at national level, their own detailed methodology for their country. Many European countries adopted the requirement for all their tunnels with the goal to have a comparable and uniform safety standard for all tunnels within the TERN. Different risk models have been developed by the scientific community and are discussed in the literature, however in many European countries (e.g. Austria, Switzerland, France, and Greece) the QRAM (Quantitative Risk Assessment Model), which was proposed jointly by PIARC and OECD with associated software developed by INERIS, is the one most widely used. A quantitative risk assessment (QRAM) compares level of the risks of transporting dangerous goods through a tunnel versus using an alternative route. A decision support model (DSM) was also developed as part of the research which allows decision makers to combine the results from the QRAM with other relevant data. J. Lundin, L. Antonsson presented a three step method to categorize Swedish road tunnels: the first is a logical decision model , the second is a simplified risk analysis method , finally, expert assessment for risk-based categorization is introduced as a third step, [9]. D. Lees, dealt with tunnel hazards due to fires and explosions from a number of sources including transportation of dangerous goods, traffic accidents, combustion of mechanical or electrical installations, sabotage or terrorism, [8]. A quantitative risk analysis regarding hourly traffic volume and percentage of heavy goods vehicles in order to assess their impact on the risk level of a directional road tunnel were analyzed in [3].

In the Republic of Srpska, the Ministry of Transport and Communications adopted the Rulebook on Minimum Security Requirements for Tunnels, which came into force in 2021, [12]. Regarding the transport of dangerous goods through tunnels, the Rulebook stipulates that the regulations governing the transportation of dangerous goods (ADR) should be applied. The following measures should also be taken conducting a risk analysis, placing appropriate traffic signs, and determining special operational measures aimed at reducing risks during the transportation of dangerous goods through tunnels.

This paper proposes risk charts that are useful for quickly assisting in making decisions on the most appropriate traffic control strategies

## 2 CATEGORIZATION OF TUNNELS ACCORDING TO ADR

The categorizing of tunnels are based on three main risks which can cause fatalities or severe damage to the tunnel construction. These risks, or rather accident scenarios, consist of explosion, release of toxic substance and fire.The main consequences of these hazards and the efficiency of possible mitigating measures, are following [1,11]:

“Large explosions”, where two levels could be distinguished:

“Very large” explosion is the explosion of a full loading of LPG in bulk heated by a fire (Boiling Liquid Expanding Vapour Explosion – BLEVE – followed by a fireball, referred to as “hot BLEVE”). A “very large” explosion would kill all the people present in the whole tunnel or in an appreciable length of tunnel and cause serious damage to the tunnel equipment and possibly its structure.

“Large” explosion is the explosion of a full loading of a non-flammable compressed gas in bulk heated by a fire (BLEVE with no fireball, referred to as “cold BLEVE”). The consequences of a “large” explosion would be more limited, especially regarding damage to the tunnel structure.

“Large toxic gas releases” can be caused by leakage from a tank containing a toxic gas (compressed, liquefied, dissolved) or a volatile toxic liquid. It would kill all the people near the release zone and in the area where the ventilation (natural or mechanical) would push the gas. A part of the tunnel may be protected but it is not possible to protect the whole tunnel, especially in the first minutes after the accident.

“Large fires” could have more or less important consequences (a certain number of victims and limited to serious damage to the tunnel) depending on the tunnel geometry, traffic and equipment.

From the above assumptions, a system with five groupings can be derived:

The order of these hazards: explosion /toxic release/ fire, corresponds to the decreasing consequences of an accident and the increasing effectiveness of the possible mitigating measures. From the above assumptions, a system with five groupings is derived, ranked A to E in order of increasing restrictions concerning goods permitted in tunnels, Table 1. Grouping A is the largest category. It contains all loadings which are authorized for road transport, including the most dangerous ones. Grouping E is the most restrictive one, containing only those loadings which do not require a special marking on the vehicle, i.e. the least dangerous ones.

Decisive factors for restrictions on the transportation of dangerous goods include the properties of the goods, the type of containment, and the amount being transported. The ADR regulations do not explicitly define terms such as “very large explosion”, “large explosion”' or “large toxic emissions", etc.

Table 1 Grouping goods in Tunnel category, [11]

| | |
|---|---|
| Grouping A | All dangerous goods loadings authorised on open roads. |
| Grouping B | All loadings in grouping A except those which may lead to a very large |

| | |
|---|---|
| | explosion (“hot BLEVE” or equivalent). |
| Grouping C | All loadings in grouping B except those which may lead to a large explosion (“cold BLEVE” or equivalent) or a large toxic release (toxic gas or volatile toxic liquid). |
| Grouping D | All loadings in grouping C except those which may lead to a large fire. |
| Grouping E | No dangerous goods (except those which require no special marking on the vehicle). |

## 3 A RISK ASSESMENT

Damage that can occur during the transportation of dangerous goods through the tunnel can be expressed by the loss of human life, environmental pollution, tunnel damage and economic loss. The types of harm are the same for vehicles transporting dangerous goods as for other vehicles, the difference is only expressed in the level of damage [6].

Harm to people (including injuries as well as fatalities) is the most important hazard type relating to the assessment of the transport of dangerous goods through tunnels. The most commonly used indicator for the quantitative assessment is statistical fatalities. The impact on the environment may also be relevant to the transport of dangerous goods. In the event of an accident in the tunnel, although the release of hazardous material may be confined to a narrow area within the tunnel, the consequences can still affect the surrounding environment, such as through soil pollution, groundwater contamination, and habitat destruction. Two types of economic loss may be distinguished: the (direct) capital losses due to the damage caused by the event, and (indirect) economic losses due to the tunnel closure. The risks linked to these types of harm can be analyzed either quantitatively (focusing primarily on the interaction and interdependence of events) or qualitatively (which allows for the calculation of characteristic risk values), or both (in cases where data is insufficient, a combination of qualitative and quantitative components might be used).

To managing the risks involved with transporting dangerous goods through road tunnels, it is necessary to perform a risk assessment. The risk assessment is a tool to identify the hazards and analyze the probability and magnitude of damage in order to obtain a quantifiable risk indicator. Figure 2 illustrates the typical procedure for a risk assessment [6,13]. The risk assessment procedure (presented by PIARC 2008, UNECE 2008) includes the stages:

- risk analysis,
- risk evaluation,
- and risk reduction.

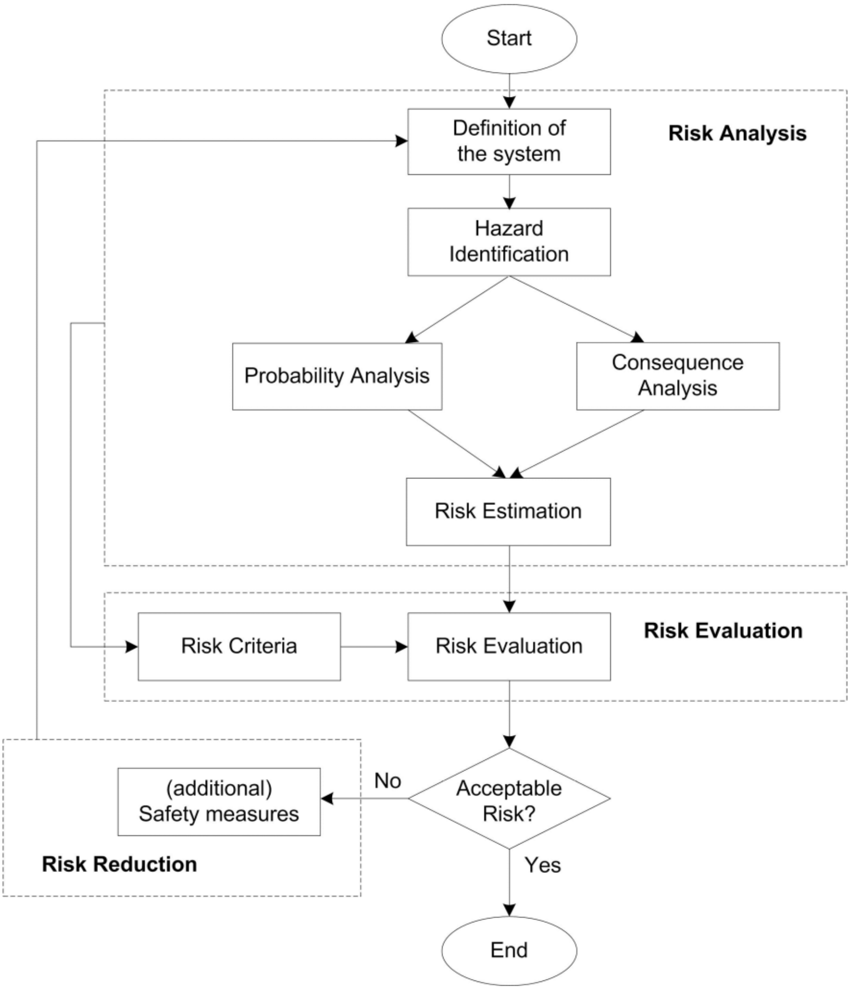



*Figure 2 Risk assessment flowchart [6,13]*

The first step in the risk analysis stage is the description of the tunnel itself, including its geometrical and traffic characteristics, as well as operating procedures and emergency planning. In the hazard identification step, all potential hazards that may result in particular risks are identified and categorized. For each potential risk, a frequency and consequence analysis is performed resulting in risk estimation. Following the risk estimation step, a risk evaluation is performed by comparing the estimated risks with the established risk criteria. In case the risk criteria are satisfied, the risk level is acceptable. On the other hand, if the risk exceeds the acceptable level, additional measures are proposed, and the risk assessment procedure is repeated until the risk level meets the acceptable criteria, [13].

### *3.1 The Quantitative Risk Assessment Model (QRAM)*

The QRAM aims to quantify the risks associated with the transport of dangerous goods on given road system routes, as well as to compare one route including a tunnel with an alternative route in open space. The components relevant to the development of the QRA model are as follows:

- indicators,
- accident scenarios,
- assessment of the probability of an accident,
- determination of physiological consequences, structural and environmental damage,
- determination of physiological consequences, structural and environmental damage,
- assessment of consequences for people,
- uncertainty/sensitivity analysis,
- validation.

### *3.2 Indicators*

The consequences of an accident are fatalities, injuries, destruction of buildings and structures and damage to the environment. The QRAM produces indicators which characterise the following risk aspects:

Societal risk: To describe social risk, F/N curves are calculated that illustrate the relationship between accident frequency and accident severity.

Individual risk indicators refers to the risk of fatalities or injuries to the local population due to an incident occurring. Individual risk is expressed as a frequency per year.

Structural damage (rough estimation).

Environmental damage (rough estimation).

### *3.3 Accident scenarios*

A complete risk assessment related to the transport of dangerous goods could require consideration of many variables: variety of hazardous materials, variety of weather conditions, variety of types of accidents, sizes of breaches, vehicles fully or partially loaded, etc. Since all circumstances are impossible to consider, simplifications have to be made.The model is based on consideration of 13 accident scenarios, which have been selected so as to satisfy the requirements of examining the three major dangers which may cause numerous victims or serious damage to the tunnel structure including explosions, release of toxic gas or volatile toxic liquid and fire. It also considers the accidents frequencies (based on historical data), the physical consequences of the accidents, and the effects of heat and smoke, Table 2. The use of QRAM software for conducting tunnel categorization according to ADR agreement can be made by assigning the proper scenarios to each tunnel category.

Table 2 Scenarios representative of each grouping in the QRA model, [13]

| | **Scenario** | **Danger** | **Tunnel Categories** | | | | |
|---|---|---|---|---|---|---|---|
| | | | A | B | C | D | E |
| 1 | HGV fire 20 MW | Medium Fire | √ | √ | √ | √ | |
| 2 | HGV fire 100 MW | Large fire | √ | √ | √ | | |
| 3 | BLEVE of LPG in cylinder | Small Explosion | √ | √ | √ | √ | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 4 | Motor spirit pool fire | Large Fire | √ | √ | √ | | |
| 5 | VCE of motor spirit | Medium Size Explosion(1) | √ | √ | √ | | |
| 6 | Chlorine release | Large Toxic Release | √ | √ | | | |
| 7 | BLEVE of LPG in bulk | Very Large Explosion | √ | | | | |
| 8 | VCE of LPG in bulk | Very Large Explosion | √ | | | | |
| 9 | Torch fire of LPG in bulk | Very Large Fire(2) | √ | | | | |
| 10 | Ammonia release | Large Toxic Release | √ | √ | | | |
| 11 | Acrolein in bulk release | Large Toxic Release | √ | √ | | | |
| 12 | Acrolein in cylinder release | Medium Size Toxic Release | √ | √ | √ | √ | |
| 13 | BLEVE of carbon dioxide in bulk (not including toxic effects) | Large Explosion | √ | √ | | | |

(1) VCE of motor spirit including the realization of a flash fire is considered to be equivalent to a large fire.

(2) Torch fire of LPG in bulk resulting in a very large fire is considered to be equivalent to a very large explosion since the fire size will cover almost the full tunnel length.

As we can see from the Table 2, only a limited number of scenarios are taken into account. The first two scenarios relate to fires of medium and important intensity involving heavy goods vehicles without dangerous goods. These scenarios represent a serious risk in tunnels. The other scenarios involve dangerous goods.

### *3.4 Assessment of the probability of an accident*

The purpose is to determine frequencies of occurrence of the chosen scenarios depending on the section of the route considered. For this purpose, the route must be subdivided into homogenous sections in terms of road elements, traffic, dangerous goods transported, environment and weather conditions. This must be done by the user of the model, who also has to provide and prepare the necessary input data.

### *3.5 Determination of physiological consequences, structural and environmental damage.*

The translation of the physical consequences into physiological ones is generally performed by means of probit functions. Probit functions indicate the relationship between the concentration of a substance in the air, the exposure time and the effect on (in this case) humans.

Structural damage represents: collapse or structural integrity problems, damage of tunnel roadway, strength loss of common structural material, failures of tunnel auxiliary equipment caused by high temperatures etc.

The main environmental impact of accidents with hazardous materials in the tunnel is the contamination of the atmosphere, water and soil.

### *3.6 Assessment of consequences for people (open and tunnel sections).*

Extensive calculations provide individual risk data and F/N curves for selected scenarios and for different types of transport.

### *3.7 Uncertainty/sensitivity analysis.*

Deterministic analysis involves uncertainties. Different parameters should be tested to assess their effects (variation in travel speed, variation in warning systems, variation in individual occupant response time, etc).

### *3.8 Validation*

This step in the development of the QRAM is necessary to test the developed model by persons not involved in the model-building process, but familiar with system behaviour, risk assessment and computer models.

## 4 TUNNEL CATEGORIZATION PROCEDURE

The proposed methodological approach for tunnel categorization, according to ADR agreement using QRAM software, is presented in Figure 3.

In the first step of "System Definition", an extensive and detailed description of the necessary inputs for QRAM software should be made regarding the tunnel itself along with the route including the tunnel and the alternative routes. Special attention should be given in the traffic characteristics ( the percentage of traffic distribution during the annual average day and the percentage of heavy good vehicles, traffic distribution of vehicles carrying dangerous goods during the annual average day).

In the next step, the number and range of time periods (TP) when traffic is allowed through the tunnel and alternative routes should be set. Also, in this step, the percentage of ADR vehicles that will use an alternative route in case of a ban on passing through the tunnel during their agreed travel time schedule should be assumed, while the other mentioned vehicles will move the agreed travel time schedule to the closest time period in which they are allowed to pass through the tunnel.

Following the time periods definition, the assignment of tunnel categories (TC) to each time period (TC/TP) is being initiated in a loop procedure. The five (A, B, C, D and E) possible tunnel categories are assigned to the three time periods in 65 proposed combinations.

The next step includes the risk analysis calculations by using the QRAM software. In each of the aforementioned QRAM software calculations, the Risk in terms of Expected Value is calculated for each of the 13 scenarios for the tunnel, for the route including the tunnel and for the alternative route. The Expected Value represents the annual expected fatalities from the consequences of accidents due to the involvement of the carried dangerous goods.

If the risk through tunnel $R_T$ is acceptable, it is stored in the database. If not, then the risk through an alternative route $R_{AR}$ is examined.

Once all possible TC/TP configurations have been examined, the necessary data of the accepted configurations have been saved in order to be used in the “Cost Benefit” Analysis step, where the final tunnel categories assigned to the different time periods will be finalized and the tunnel categorization will be completed.

In the final step “Cost Benefit Analysis” the various contributors saved in the step “Database” are measured in monetary values.The expected life cycle cost derived by tunnel categorization is calculated as the sum of the costs of safety measures and the cost of residual risk. At the end, the TC/TP configuration with the minimum life cycle cost is selected and the tunnel categorization process is complete.

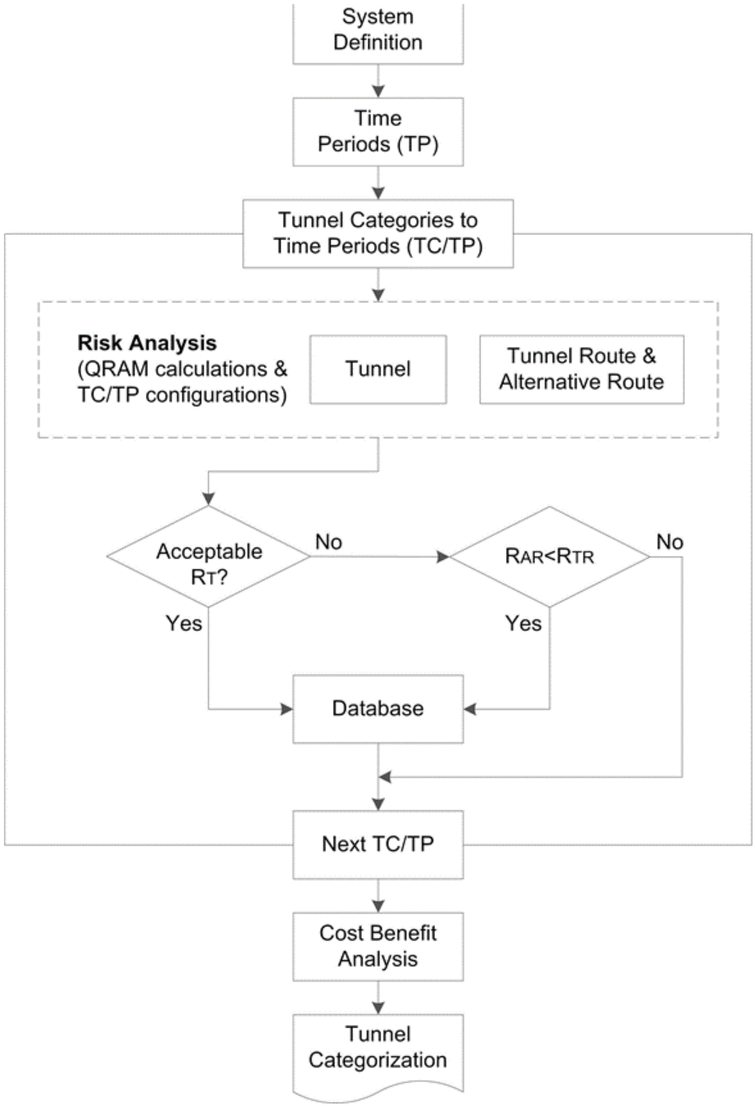



***Figure 3*** Tunnel categorization procedure [13]

## 5 THE DECISION SUPPORT MODEL (DSM)

Decision Support Model (DSM), which incorporates political aspects, is clearly separated from the QRAM, which is purely technical. The DSM uses the output from the QRAM and other information supplied by the decision maker as shown in Figure 4.

In the decision-making process regarding which groupings are permitted in tunnels, it must be considered that goods not allowed in the tunnel should be transported via an alternative route One of the primary aims for the decision on which grouping to permit in a tunnel is to minimize the risk to human life, but there are other factors that need to be taken into account. The features that are evaluated and weighted by a decision support model (DSM) are following [11]:

- Injury and fatality risks to road users and the local population using the indicators from the QRAM.
- Material damage due to possible accidents on tunnel or alternative route.
- Environmental impact due to an accident on tunnel or alternative route.
- Direct expenses (investment and operational cost of tunnel risk reduction measures as well as possible additional costs in the transport of dangerous goods).
- Inconvenience to road users due to a possible accident (time lost during repair works after an incident in the tunnel).
- Annoyance to local population (environmental impact of dangerous goods traffic, with the exclusion of possible accident consequences, but possibly including psychological impact).

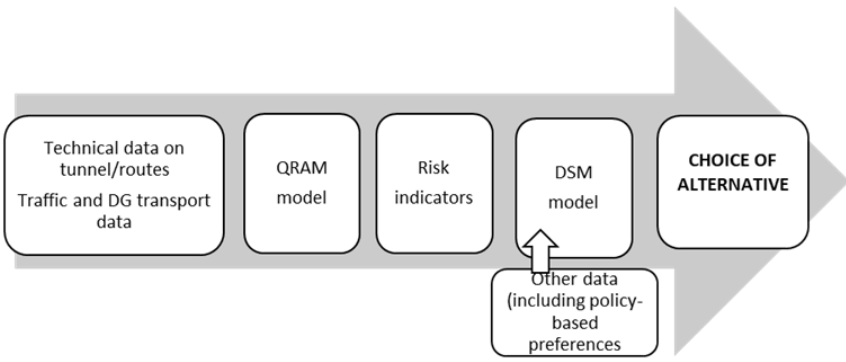



*Figure 4 Structure of the decision process*

In the decision-making process, must determine which characteristics are relevant and how they should be weighted against each other. A computer program was developed that allows the mentioned characteristics to be taken into account in a rational way.

## CONCLUSIONS

Safety measures to be applied in road tunnels are based on a systematic consideration of all aspects including: tunnel infrastructure, works in tunnels, users and vehicles. If there are additional characteristics which must be taken in account, such as the transport of dangerous goods through tunnel, a detailed risk analysis must be carried out to determine if there is a need for additional safety measures and/or additional equipment to ensure a high level of tunnel safety. Based on the risk analysis of the transport of various dangerous goods through tunnels, their categorization is carried out. Categorization is a complex process where it is necessary to address the risks in the tunnel, the risks along the alternative route for transports considered to be restricted from the tunnel and what risk reducing measures that are practically applicable. A Quantitative Risk Assessment model (QRAM) was developed by international consultants in order to provide risk indicators which can be used in a decision support model (DSM) to compare a route including one or several tunnels with alternative open routes, and possibly with risk acceptance criteria. The DSM model determines which features are relevant and how they should be weighted relative to each other. A computer program has been developed that allows the mentioned characteristics to be taken into account in a rational way. Based on the risk analysis for the transport of dangerous goods through tunnels, the categorization of tunnel is done (A - E), regulating the types of dangerous goods to be allowed to go through the tunnel, in order to avoid any hazards with major consequences.

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