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Design Verification and Testing of Road Tankers Transporting Dangerous Goods

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The design and production of vehicles transporting dangerous goods comprises of three stages: design, manufacturing, inspection and testing. The design follows specific rules, Norms and Regulations according to the European Agreement concerning the international carriage of dangerous goods by road (ADR). Manufacturing depends on the experience of the manufacturer and the design rules followed. Certified inspection bodies carry out the inspection procedures and tests for the design approval and the homologation of each separate road tanker produced. Inspection and testing are specified in the ADR Regulation in force during the design period, along with a set of requirements concerning the strength of the tank shell, equipment, vehicle components, measures for fire protection during the tank operation, load distribution, and roll-over protection. A systematic approach for the inspection and testing procedure concerning the application of the requirements for the construction, equipment and type approval of tank vehicles, and vehicles for the transportation of dangerous goods was developed and evaluated since 2001 by the authors in collaboration with the Mechanical Engineering and Aeronautics Department of the University of Patras. Important issues from this experience concerning a rigorous procedure for the design verification and testing of vehicles transporting dangerous goods, along with evaluation of damping properties for structural health monitoring is reported here.

Keywords: ADR, dangerous goods, road transportation, road-tankers, inspection and testing, design verification, Regulation for roll-over protection R-111

Introduction. Accidents involving hazardous materials transported by road may cause fire, explosion, adverse acute or chronic health effects, a threat to public health, and environmental damage. A sense of false security has always been with people at large that the man-created problems will somehow take care of themselves or disappear in time [1]. The quantitative assessment of risks arising from road transport of dangerous substances in a populated area is the result of interaction between the traveling risk source, the road network and the impact area. As a consequence, the calculation of risk measures, such as individual and societal risk, usually take into account the possibility that an accident may occur along the route. Various methodologies have been developed for the risk analysis of road transportation of hazardous chemicals, and the corresponding societal risks were evaluated and compared [2].

Serious accidents with vehicles transporting dangerous goods have been reported in Greece. On Friday, 30th April 2000, an LPG tanker traveling from Athens to the town of Lamia, 212 km away while stopped for a police control caught fire due to the collision of a small van at its back. A fire engine arrived 30 minutes after the incident and one hour later a boiling liquid expanding vapor explosion occurred to the LPG tank. Eye witnesses report a 100 meter radius fire ball which ascended 150 meters into the sky. Large drops of burning liquid LPG were dropping from the sky at a distance over 300–400 meters away from the explosion. The tank lorry and the fire engine totally disintegrated (*Figure 1*). All three firemen who were close to the centre of the explosion were killed instantly. The tanker driver, standing about 400 meters away, was killed by a piece of a flying vehicle axle and the small van driver was evaporated by the

a *b*

Figure 1. The semitrailer tractor (*a*) and a fire engine (*b*) disintegrated by the boiling liquid expanding vapor explosion

explosion and never found. Thirteen bystanders standing up to 300 meters away were injured and taken to hospital (some of the injured were later reported dead, totaling seven fatalities). Buildings and cars within a radius of 500 meters were damaged [2].

An accident involving a road tanker traveling from Salonica to Athens, carrying 38 m^3 of unleaded gasoline occurred on April 6 2005. The tractor's driver traveling at 85 km/h, after a frontal impact with a passenger car, erroneously applied the endurance braking system (retarder) in a slippery road causing jackknifing of the semi-trailer. If service braking was applied by the driver, then the anti-lock system would keep the vehicle on its route, and overturn would have been avoided. During the accident the tractor and trailer did not separated. The passenger car was destroyed by fire, but the tanker didn't caught fire. No fatalities were reported. The semi-trailer after an airborne travel came to rest by its right side forcing the tractor to the ditch (Figure 2). The tractor was completely destroyed, while the semitrailer returned to operation with minor repairs [2].

The tractor's chassis was completely destroyed by the semitrailer's impact on its fifth wheel and cabin (see figure 2). The road tanker suffered minor damages, and no leaks in its top filling covers or the vent recovery system occurred. Its shell sustained the high stresses from impact. The design and construction of the road tanker strictly followed the Agreement concerning the international carriage of dangerous goods by road (ADR) requirements and the vehicle was inspected and certified by the first author some months ago according to ADR 2005 and EN-13094. Shell material was aluminium 5186 H111. Tests for the design approval followed EN-12972 (2001). The shell material and the tanker equipment effectively sustained the high stress levels induced by this roll-over and no considerable damage occurred [2, 3].

An accident of a road tanker that collided at the back of a bus with four fatalities and 6 serious injuries in the island of Crete, Greece is investigated and reconstructed in [2] (Figure 3).

The road tanker was in operation in Greece since 1995. It was inspected for the first time from the testing body in 2001 according to the ADR

a *b*

Figure 2. The semitrailer loaded with 38 m^3 unleaded gasoline, after an airborne 180 degrees travel rests on its right side on the road guardrails. The road tanker before the accident was travelling downhill in the reverse direction from this laying in picture (*a*) The tractor's chassis was completely damaged during the accident (*b*)

Figure 3. The road tanker in flames and the bus stopped 122 m away from the point of crash

1995 Regulation. But, according to Section 8 of ADR 1995 (Transitional Measures) there were specific provisions for tanks built before 1 October 1978 and not conforming to the requirements of this Appendix may, if they were built in conformity with the requirements of ADR, be used until 30 September 1984.

On the expiry of this period the aforesaid units may be kept in service if the equipment of the shell meets the present requirements and pressure tests be conducted at a higher test pressure of 200 kPa (2 bar) (gauge pressure) for the cases of aluminium shells and aluminium-alloy shells. The tank construction, equipment, and testing was not fulfilling the aforementioned requirements and the road tanker was still in operation, and a potential hazard [2].

Although in most cases of road accidents involving vehicles transporting dangerous goods human error is implicated as a direct cause of the incident, inherent poor safety management systems, poor safety culture, inadequate assessment of thresholds on societal risks, potential threats from the operation of aged heavy vehicles, inappropriate emergency handling strategies along with poor inspection and testing procedures were detected [3].

The authors have been involved in all phases of road tankers design, production, type approval and testing from different positions. The first and second author served as ADR qualified inspectors, the third and fourth authors are experts in road tankers design and fifth and sixth authors are the design and production engineers of one of the largest firms producing road tankers for military and public use in Greece. The experience gained by the authors from road tankers design and construction, type approval, and ADR inspection and testing is presented here, along with remarks on the evolution of the application of the Regulation ADR in Greece [3–7].

A systematic approach for the design, inspection and testing procedure concerning the application of the requirements for the construction, equipment and type approval of tank vehicles, and vehicles for the transportation of dangerous goods was developed and evaluated since 2001 by the authors. Important issues from this experience concerning a rigorous procedure for design verification, inspection and testing of vehicles transporting dangerous goods in accordance with the ADR Regulation in force and are reported here [3–7].

The ADR regulation. The European ADR was done at Geneva on 30 September 1957 under the auspices of the United Nations Economic Commission for Europe, and it entered into force on 29 January 1968. The Agreement itself was amended by the Protocol amending article 14(3) done at New York on 21 August 1975, which entered into force on 19 April 1985. The Agreement was grouped under two Annexes A and B.

Annex A contains general provisions and provisions concerning dangerous articles and substances, and Annex B contains provisions concerning transport equipment and transport operations (UN-ECE Regulation No. 105). The Working Party on the Transport of Dangerous Goods (WP15) of the Economic Commission for Europe's Inland Transport Committee decided, at its fifty-first session (26–30 October 1992), to restructure Annexes A and B, on the basis of a proposal by the International Road Transport Union (TRANS/WP15/124) [2, 3, 8, 9].

According to Article 2 of the Agreement, dangerous goods barred from carriage by Annex A shall not be accepted for international transport, while international transport of other dangerous goods shall be authorized subject to compliance with: the conditions laid down in Annex A for the goods in question, in particular as regards their packaging and labelling and the conditions laid down in Annex B, in particular as regards the construction, equipment and operation of the vehicle carrying the goods in question.

The structure of the ADR Agreement has been split into nine parts, grouped under two Annexes to align with the wording of Article 2 of the Agreement itself as follows: Annex A: General provisions and provisions concerning dangerous articles and substances. Part 1 General provisions, Part 2 Classification, Part 3 Dangerous goods list, special provisions and exemptions related to dangerous goods packed in limited quantities, Part 4 Packing and tank provisions, Part 5 Consignment procedures, Part 6 Requirements for the construction and testing of packaging, intermediate bulk containers (IBCs), large packaging and tanks, Part 7 Provisions concerning the conditions of carriage, loading, unloading and handling. Annex B: Provisions concerning transport equipment and transport operations, Part 8 Requirements for vehicle crews, equipment, operation and documentation, Part 9 Requirements concerning the construction and approval of vehicles.

The restructured ADR adopted by WP15 is consistent with the United Nations Recommendations on the Transport of Dangerous Goods, Model Regulations, the International Maritime Dangerous Goods Code (IMDG Code), the International Civil Aviation Organization's Technical Instructions for the Safe Transport of Dangerous Goods by Air, and is fully harmonized with the Regulations concerning the International Carriage of Dangerous Goods by Rail (RID).

Similar Regulations apply in USA (DOT 406) and Australia (ADG). In China the Regulation of Automobile Transportation of Dangerous Goods, JT 617-2004 — Rules of Transportation, Loading and Unloading of Dangerous Goods by Automobile, JT 618-2004 are in force. A comprehensive test procedure is followed with the addition of technical details on the mileage of the vehicle inspected. A list of Rules in action worldwide for the transportation of dangerous goods is published by Verband Der Chemischen Industrie e.V. (VCI 2007).

The transportation of hazardous substances is highly regulated in Greece since 1987 when the provisions of the ADR were introduced as part of the national legislation. In 1999 the legislation was harmonized, with the Commission Directive 94/55/EC Agreement (ADR 1995), and the 96/86 EC Agreement (ADR 1997). On September 2001 the legislation was harmonized with the Commission Directive 2000/61/EU (ADR 1999), in 2004 with the 2001/7/EC (ADR 2001), in 2005 with 2004/111/EC (ADR 2005), in 2007 with ECE/TRANS/185/2006/89/EU (ADR 2007), in 2009 with 2008/68 (ADR 2009), in 2011 with 61/2010 (ADR 2011), in 2013 with 2012/45 (ADR 2013, in 2015 with 2014/103 (ADR 2015) governmental gazette KYA 20655/2897/2015), and 2016/2309 (ADR 2017) KYA 22039/2825/2017) [8].

A systematic approach for the inspection and testing procedures concerning the application of the requirements for the construction, equipment and type approval of tank vehicles, and vehicles for the transportation of dangerous goods was developed and evaluated by the Motor Vehicles Tests and Homologation Center of the Mechanical Engineering and Aeronautics Department of the University of Patras [8, 9].

Algorithms in MATLAB were prepared to support design evaluation and inspection and testing procedures [10]. The Lab was certified according to ISO/IEC 17020 (replaces the European standard EN 45004:1995) defining the basic requirements for all bodies performing technical inspections of all types [11]. Specific requirements for design approval, initial testing, periodic testing and testing after severe damages or maintenance operations were integrated to the testing procedures. EN 12972/2002 was adopted from the very beginning for the inspection and testing of vehicles transporting dangerous goods [9].

A sample of a test report with the proposed procedure is shown in Appendix I. This procedure is already integrated, as initially proposed by the authors, within the latest editions of ADR 2015, and ADR 2017 [8, 9].

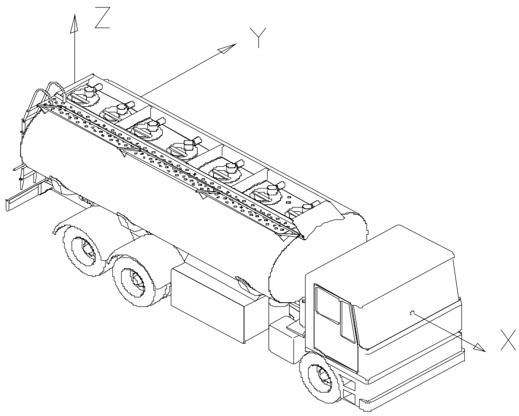
Road tanker design verification. Road tanker tank-chassis configuration. The design and production of vehicles transporting dangerous goods comprises of three stages: design, manufacture, inspection and testing. The design follows specific rules, Norms and Regulations, described below. Manufacturing depends on the manufacturer's experience, engineering, equipment, staff, and facilities available. The Certified Inspection Bodies undertake the inspection procedures and tests for the design approval and the homologation of each separate road tanker produced. The Inspection Body, Certified as a Testing Body from the Competent Authority assures that the design and manufacturing of the product adapts to internationally adopted practices regarding conformity with the ADR Agreement, Norms and Regulations in force [12–14].

The design of a road tanker follows specific steps: 1) chassis-cab selection; 2) tank cross-section determination, and loading capacity; 3) tank positioning on the chassis and axles load sharing; 4) loading forces and stresses acting on the chassis and superstructure during operation. Those design parameters affect vehicle handling, dynamic stability, braking dynamics, safety and power consumption [1–8]. Figure 4 depicts a 3-axle road tanker and the coordinate system.

For an initial estimation of the tank capacity appropriate for road tankers of categories N1, N2, and N3, Table 1 provides main dimensions and loading capacity for road tankers of categories N1, N2, and N3. Category N3 incorporates 3- and 4-axles road tankers chassis configurations. This data range is the result of a thorough survey on road tanker's design characteristics.

For a travelling vehicle road surface irregularities wheel forces fluctuate about the static levels. Those fluctuating loads, the dynamic wheel tire–ground interaction forces excite vibrations on the vehicle. The factors mostly affecting the vehicles' vertical dynamics are: the frame and superstructure flexibilities, the superstructures' CG positioning in the vertical plane, and the suspension and tires' parameters. Since chassis manufacturers and traffic regulations require that the front axle load sharing is at least 25–30 % of the road tanker's gross weight, an algorithm was used in order to ensure vehicle steerability [4–8].

Fatigue life and tank flaws detection. In addition to vertical dynamics forces, fatigue life prediction is of great importance for the design of the tank superstructure. The design evaluation, and inspection, and testing procedures followed herewith provide the means for a thorough investigation of fatigue life prediction of the superstructure. The



a

b

Figure 4. A 3-axle Road tanker design configuration in the coordinate system (*a*), and the finished product (*b*)

Table 1

Road tanker's design characteristics

Characteristic	Vehicle category		
	N1	N2	N3
Chassis weight, kg	1500–2000	3000–4500	6500–9500
Gross weight, kg	2000–3500	3500–12000	12000–33000
Wheelbase, mm	2500–3550	3000–3600	4300–5200
Tank weight, kg	400–500	800–1100	1700–2200
Tank capacity, l	1500–2500	5500–9500	10000–24000
Tank length, mm	2000–2500	3600–4200	6600–7800

method can be further extended yielding a methodology for cracks or flaw identification from damping properties of the structure. A wealth of analytical and experimental techniques in fatigue life prediction exist today [15–19].

Analytical and experimental investigations providing the determination of the dynamic characteristics of cracked structures yield the structural damping factor, a property of both the material and structure, the material damping factor and a good correlation of depth of crack with the damping factor. Although the damping factor is significantly affected by crack severity, crack identification procedures require accurate determination of damping modifications, depending on the crack position, the crack depth, structure geometry, and material properties. In addition for damped systems.

Energy dissipation within a structural element provides a measure of structural damping. In metallic materials, among the mechanisms of energy dissipation, the factors affecting damping mechanisms are: friction, on the atomic/molecular level, dry friction, viscous friction in fluids, nonlinearities-among them flaws or cracks, plastic deformation and internal Coulomb damping.

It is assumed that the damping force is proportional to the velocity of oscillation; and thus, the work done by one oscillation cycle depends on the frequency of oscillation. In the model of structural damping, the work done per cycle is independent of the oscillation frequency, and the dissipation of vibrational energy is proportional to the square of the amplitude.

The method of equivalent viscous damping is frequently used to obtain an average of these effects. The damping constant c is a property of the damper, while the damping ratio ζ and the logarithmic decrement δ are system properties. The logarithmic decrement for small damping ($\zeta << 1$) $\delta = 2\pi\zeta$. For hysteretic damping (related to fatigue strength) the equivalent damping constant has the form $c_v = \gamma/\omega$, where γ is a material constant (loss factor defined experimentally), the ratio of the energy dissipated over the energy stored to the vibrating member over a full cycle, and ω is the driving frequency.

Then, the energy dissipation per cycle is $U_h = \pi\gamma k X^2$. The energy stored in the spring is $V = 0.5kX^2$ and the total energy over the cycle $2V = kX^2$, and thus yields $\pi\gamma = U_h/2V$ which is the energy dissipated over the energy stored to the spring (the structural element) at full deflection over a full cycle.

The modal damping ratio ζ_i of the cracked structural member is related to the logarithmic decrement of vibrations δ_c adopted from experimental tests as

$$\zeta_i = \delta_c/(2\pi).$$

If the energy dissipated during a loading cycle is $\Delta U_c(\sigma_c)$, and $U(\sigma)$ is the maximum stored energy, then damping results are presented in the form

$$\psi(\sigma_\alpha) = \Delta U_c(\sigma_c)/U(\sigma).$$

Then, the relationship between the logarithmic decrement of the undamaged member $\delta(\sigma_\alpha)$ and the damping ratio $\psi(\sigma_\alpha)$ is

$$\delta(\sigma_\alpha) = 0.5\psi(\sigma_\alpha).$$

The method can be of help for structural health monitoring of the road tanker superstructure based on a sound criterion that of the damping properties that can be monitored even during the operation of the vehicle [15–19].

Tank cross section geometry. The European Standard EN 13094/2008 [20] specifies minimum requirements for the design and construction of metallic tanks for the transportation of liquid cargo. An important factor in road tanker design is the selection of the appropriate tank cross-section area, and the tank's overall length affecting the vehicle's wall to wall turning radius, and axles load share. Chassis length and cabin configuration yield constraints related to maximum tank length, height, and furthermore, tank cross-section area providing maximum volume for the substances to be transported. The shape of tank cross-section followed today by most tank manufacturers is elliptic, although circular shapes are gaining interest [6, 7].

Geometry of an elliptic cross-section in YZ coordinate system is shown in Figure 5, along with R_v, R_h, and W, the principal design variables providing different cross-section configurations [6–8].

Coordinates of point P, where change of curvature occurs, are given as

$$Y_P = \frac{(W - 2XR_h)}{2\left(1 - \frac{R_h}{R_v}\right)},$$

distance K_v of arc with radius R_v from axis Y is

$$K_v = \frac{Z_P(W - 2R_h)}{2Y_P - W + 2R_h},$$

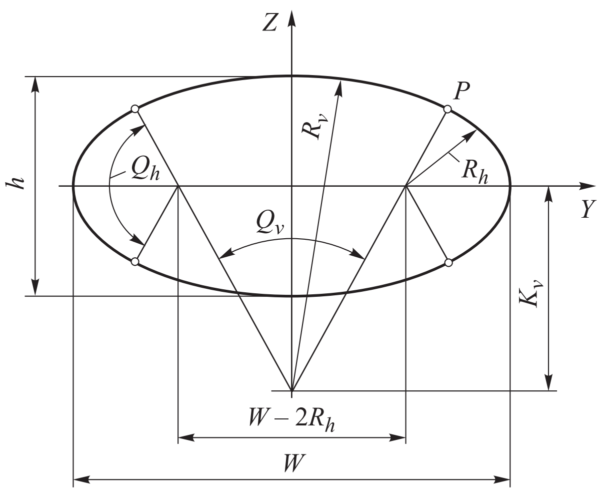


Figure 5. Tank cross-section coordinates

angles θ_v and θ_h are calculated as

$$\theta_v = 2\ \sin^{-1}\left(\frac{Y_P}{R_v}\right);\ \ \theta_h = 2\sin^{-1}\left(\frac{Z_P}{R_h}\right)$$

and the cross-section area yields

$$A = \theta_h\left(R_h - t\right)^2 + \theta_v\left(R_v - t\right)^2 - \left(W - 2R_h\right)K_v,$$

where t is shell thickness.

Then the Z coordinates of point Z_P and the center K_v of the arc with radius R_v, are calculated as

$$Z_P = \sqrt{R_h^2 - \left(Y_P - \frac{W}{2} + R_h\right)}.$$

Initial selection of an elliptic cross-section, with 2450 mm limit for the long horizontal principle axis provides a good start for tank design. An algorithm in MATLAB [10] provides a set of cross-sections configurations for specific constraints based on the road tanker under design. Dimensional constraints for the tank are mentioned as: cross-section maximum width and height 2550 mm and 2000 mm respectively, and tank length range 7000–8000 mm. In this way, verification of the tank design against the ADR provisions and the tank-chassis configuration is possible.

Tank loading. For metallic tanks for the transport of dangerous goods with a working pressure not exceeding 50 kPa gauge (0.5 bar) the requirements of the European Standard EN 13094/2008 and the ADR Regulation in force concerning design loads and 30 years fatigue life prediction shall apply [8, 20]. Loading of the tank and the supports comprising of inertial loads from the own weight of the tank and supports, inertial pressure loading from the goods transported, pressure loading uniformly distributed during loading and unloading the tank, and loading during braking and turning maneuvers, overturn or collision.

The corresponding loading cases imply accelerations: $\eta_x = 2g$ for braking, $\eta_y = 1g$ for lateral acceleration, $\eta_z = 2g$ vertical loading upwards, or $\eta_z = -1g$ vertical downward acceleration. Thus the acceleration vector for design becomes $\boldsymbol{\eta} = \{\eta_x, \eta_y, \eta_z\}$. Tank is considered to be filled with larger liquid cargo density UN-1202 $\rho = 845$ Kg/m^3, internal vapor pressure $p_w = 0.280$ bar, static pressure test $p_t = 0.530$ bar, external atmospheric pressure –0.030 bar [8, 9].

In addition to the loading cases required by the ADR Regulation and EN 13094/2008, combined loadings were incorporated in the design process, thus providing six compound loading cases: 1) 1G braking in the forward direction combined with 0.8G lateral turn; 2) 1G braking in the forward direction combined with 1G vertical acceleration; 3) 1G braking in the forward direction combined with –1G vertical acceleration; 4) 0.5G right turn combined with 1G vertical acceleration; 5) 0.5G right turn combined with –1G vertical acceleration;

Table 2

The mechanical properties of aluminium alloys used for road tankers superstructures

Property	St42.2	XTRAL	Al 6061 T6	Al 5186 H111
Modulus of elasticity E, GPa	207.000	70.500	68.410	69.500
Poisson ratio ν	0.292	0.334	0.330	0.334
Ultimate tensile stress S_u, MPa	410.000	309.000	262.000	275.000
Yield strength S_y, MPa	250.000	169.000	242.000	125.000
Elongation (20 %) A	23.000	27.000	7.000	24.000
Material density ρ, kg/m^3	7820.000	2680.000	2718.000	2720.000
Welding factor λ	0.800	0.800	0.800	0.800

6) Manhole assembly overturn protection, and rear bumper protection [8, 9].

For shells with a circular cross-section the design verification shall be implemented in accordance with EN 14025 [21], while for shells with non-circular cross-sections dynamic testing, or a finite element stress analysis, or a calculation method should be applied. The mechanical properties of aluminium alloys used for road tankers superstructures is shown in Table 2, compared with steel material St42.2 that is also used in road tankers industry.

For a 20.6 m^3 tank, with seven-compartments 2.6, 3.1, 4.2, 3.2, 2.3, 2.6, 2.6 m^3, material Al-5182 H111, detailed design and stress analysis is performed with a commercially available finite elements (FE) algorithm. Figure 6 shows the tank FE model with supports, partition plates (buffers) and the top equipment overturn protective structure. The tank has the oval shape, curvatures radii, R_h = = 700 mm (sides), R_v = 1920 mm (top and bottom), width W = 2480 mm, cross-section height h = = 1652 mm, and tank length 6610 mm. Material properties are: Young's modulus E = 69.50 GPa, Poisson ratio ν = 0.33, tensile strength 20 °C S_u = = 280 MPa, yield strength 20 °C S_y = 125 MPa, elongation (20 %) A = 24, material density ρ = = 2720 kg/m^3, welding factor λ = 0.80.

An algorithm in MATLAB [10] provides a set of cross-sections configurations for specific constraints based on the road tanker to build.

The force vector **P** for the inertial load and the tanker weight applied on each tank surface element (Figure 6) is calculated as [1]

$$\mathbf{P} = \rho g \boldsymbol{\eta} A t,$$

where is gravity acceleration; g = 9.81 m/s^2; A is the element area, m^2; t = 5 mm the element thickness.

Loading due to internal gas vapor pressure is calculated as

$$\mathbf{P} = pA,$$

where $p = p_x + p_y + p_z + p_0$, $p_x = \rho g \eta_x A \Delta x$, $p_y = \rho g \eta_y A \Delta y$, $p_z = \rho g \eta_z A \Delta z$, p_0 is the static pressure (Δx, Δy, Δz is the distance of the liquid transported free surface from the geometry center of the corresponding tank shell element).

The FEM algorithm provides solutions for stresses and strains on the tank surfaces and sup-

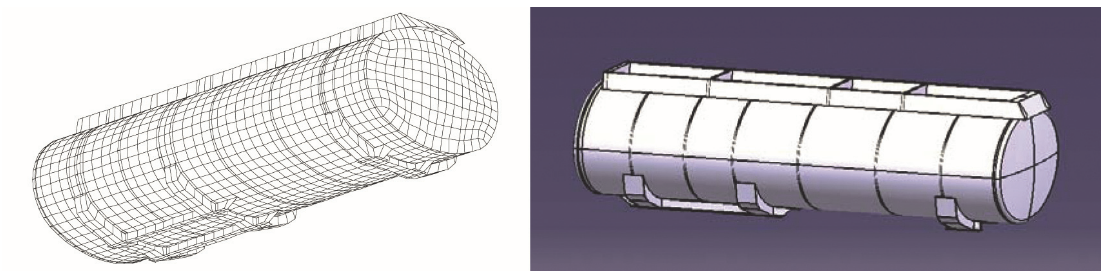


Figure 6. The tank FE model with supports, 7-partition plates (buffers) and top equipment protection

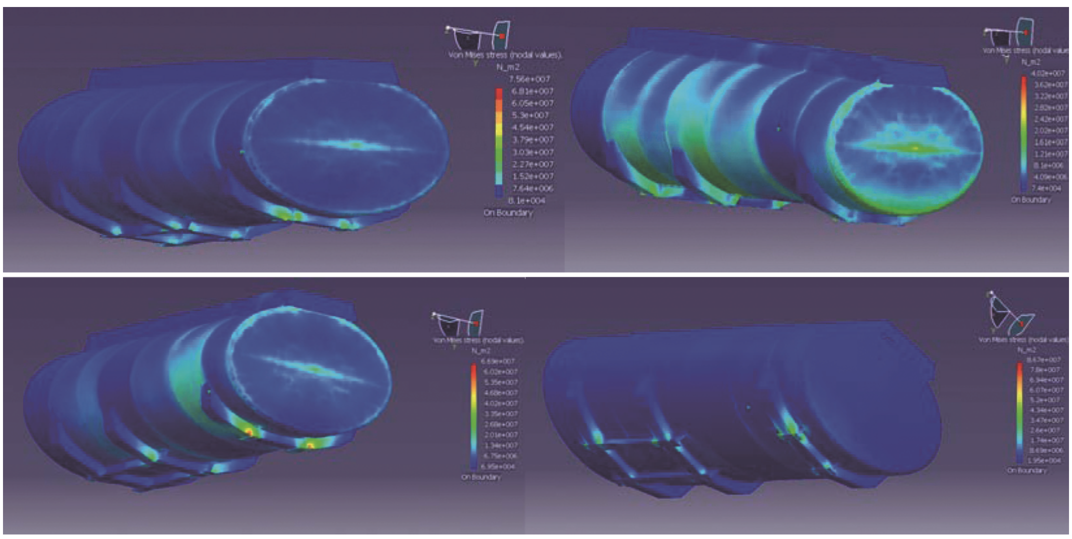


Figure 7. 20.6M^3 tank, seven-compartments 2.6, 3.1, 4.2, 3.2, 2.3, 2.6, 2.6 m^3, material Al-5182 H111 FE stress analysis

ports for the aforementioned six loading cases assuming the worst case of 100 % tank fill. The Von Mises shear energy theory is applied for the equivalent stress calculation according to the following equation

$$\sigma_{eq} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2},$$

where σ_1, σ_2, σ_3 are the principle stresses calculated [1].

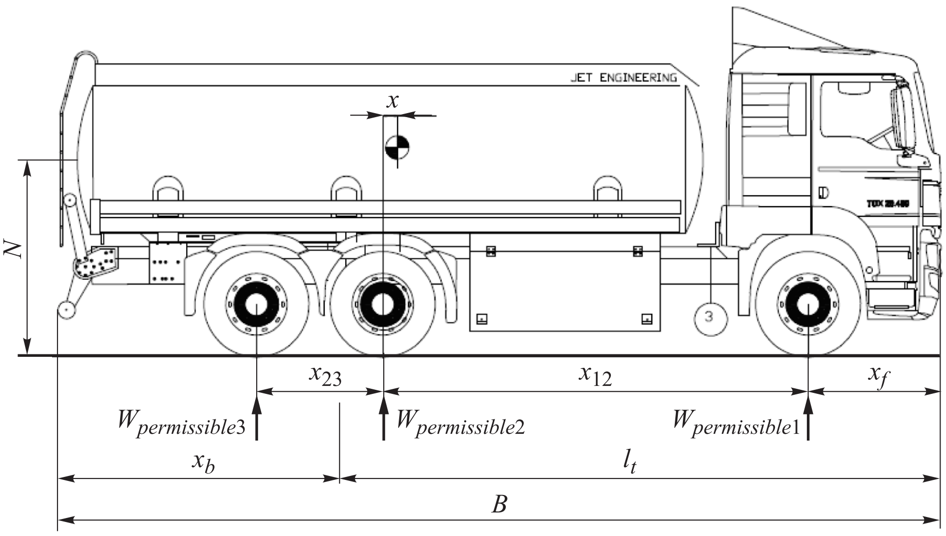
The margin of safety is calculated as [1]

$$\text{M.S} = n - 1,$$

where n is the safety factor, $n = R_e \sigma_{eq}$ (R_e is the yield strength of the material, R_e = 125 MPa).

Results for the loading case 1 are shown in Figure 7. Calculated maximum stresses for the tank shell were: 53.01 N/mm^2 for the tank shell, 76.27 N/mm^2 for the external bottoms and the internal buffers, and 97.167 N/mm^2 for the supports, thus yielding the corresponding safety factors between 1.2 and 2.2.

Axles load sharing and handling. From the results of the preceding analysis the three-axle road tanker configuration and the prototype with MAN TGX 26.480 truck chassis are shown in Figure 8. The 6610 mm long tank is assembled on a sub-frame attached to the chassis via flexible mounts. Total vehicle length 9500 mm. The road tanker's chassis will be considered rigid for a parametric analysis of the axles load share. For this chassis-tank configuration the axles' loading capacity follows as: front axle $W_{permissible1}$ =7500 kgr, drive axle $W_{permissible2}$ = = 12000 kgr, rear axle $W_{permissible3}$ = 7500kgr. Main dimensions: B = 9505 mm, front overhang x_f = = 1470 mm, x_{12} = 4500 mm, x_{23} = 1350 mm, rear overhang x_b = 3350 mm [6, 7].



a

b

Figure 8. Three-axle 26T gross-weight road tanker:
a — tank CG and distance from drive axle; *b* — MAN TGX 26.480 truck chassis with tank 6610 mm long assembled, total vehicle length 9500 mm

For the three-axle road tanker the front and rear axle loading factor variation vs. the tank CG distance from the drive axle and the tank's filling factor (%) and for the rated payload is calculated through an algorithm developed in [6].

The loading design constraints for the three-axle road tanker yield the following system of constraint equations:

$$\begin{aligned} W_F - \frac{x\Omega}{x_{12}} - AR_{FRONT} &= 0; \\ W_R - \frac{\Omega(x_{12}-x)}{x_{12}} - AR_{REAR} &= 0, \end{aligned} \tag{1}$$

where W_F and W_R are front and rear bogie capacity, kN; x is tank CG from drive axle, m; Ω is the road tanker's payload, kN; x_{12} is axles 1–2 distance, m; AR_{FRONT} and AR_{REAR} are chassis and cab curb weight corresponding axles load share.

Figure 9 shows the solution of equation (1) for a two-axle road tanker that best fits for a three-axle road tanker considering the rear bogie compound suspension properties. Figure 9, *a*: front axle — drive axle rear bogie load factor vs. tank CG-drive axle distance and tank filling factor. Figure 9, *b*: front axle — rear bogie load/gross weight. The solution of equation (1) yields tank's CG positioning 100 mm from the drive axle on the longitudinal plane (Figure 8).

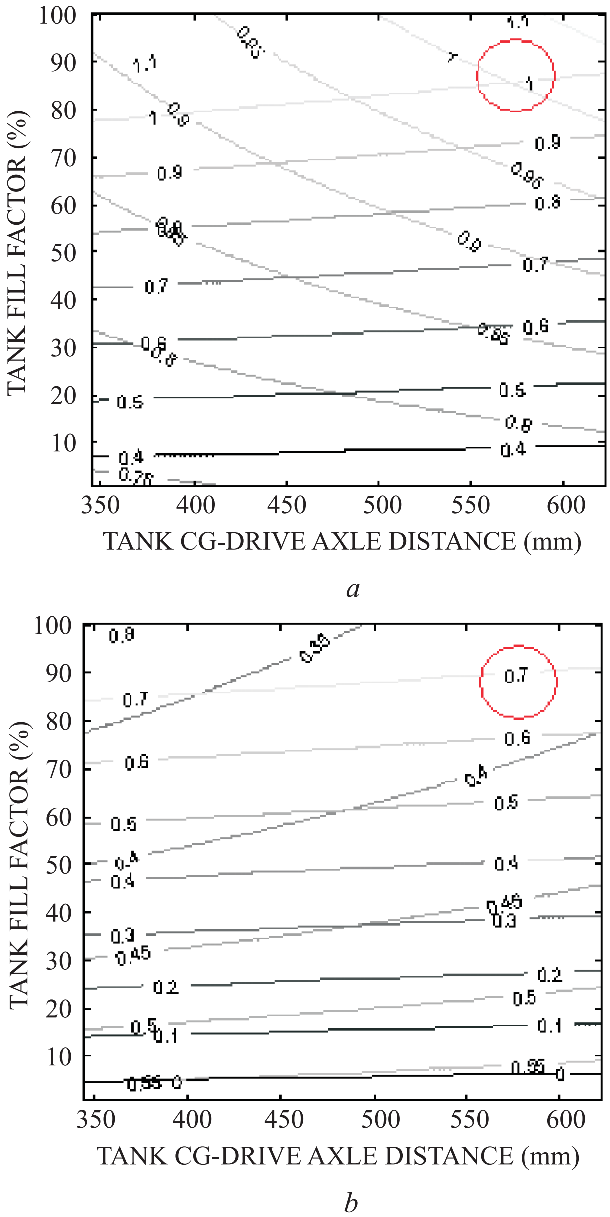


Figure 9. Three-axle 26T road tanker 20.6 M^3 tank:
a — front axle — drive axle load factor vs. tank CG-drive axle distance and tank filling factor;
b — front axle — rear bogie load/gross weight distribution

The dynamic model verification. A heavy vehicle in motion is a multi-input system responding to steering input, braking and acceleration, and road profile with pitch motion, vertical bounce and roll motion. The physical/mathematical model of the vehicle represents a superset of vehicle dynamics simulators, providing a high-fidelity model for use in dynamic simulations. The 3D vehicle geometry is used to visualize the vehicle model and to assign mechanical/structural properties to the vehicle exterior. The visual representation of the vehicle dynamic model is shown in Figure 10. Again, the two-axle dynamic model will be adopted for the three-axle road tanker with appropriate considerations for the rear bogie compound suspension parameters. The vehicle model contains extensive parameters defining the exterior geometry, sprung mass, unsprung masses, tires, brake system, steering system, safety systems and drivetrain. The sprung mass of the vehicle is defined by parameter groups including inertias, C.G. location, inter-vehicle connections, aerodynamic drag and body torsional stiffness. The unsprung masses of the vehicle are defined by parameter groups including parts physical location, wheels and hubs, brake assembly design, suspension and tires.

A simplified three-dimensional dynamic model of a 2-axle road tanker with 7 degrees of freedom and 21 state variables was considered in [7] as shown in Figure 10. Vertical displacement, roll, and pitch for the sprung mass, and vertical displacement and roll for the unsprung masses of the front and rear axles are considered. The model consists of three rigid body masses, the suspended chassis and body mass, and the masses of the front and rear wheel and axle assemblies. The truck body is mounted on the wheel and axle assemblies through four suspension systems consisting of a linear spring in parallel with a viscous damper. The model neglects the compliance of the tires and suspension [7].

For the rigid body road tanker model accelerating on a curve, the following set of linear differential equations of motion hold:

• for the sprung mass

$$\sum F_y = m_c \ddot{y}_c;\ \sum M_x = J_c \ddot{\theta}_c;\ \sum M_z = J_z \ddot{\varphi}_c,$$

where F_y is the vertical force due to tire-road interaction, m_c is the sprung mass, y_c is the sprung-mass vertical motion; M_x the moment about x-axis due to the centrifugal force; J_c is the sprung-mass moment of inertia; θ_c and φ_c are the rotational displacement of the sprung mass about its CG in pitch and roll respectively; M_z is the moment about z-axis due to acceleration or deceleration;

• for the front axle unsprung mass

$$\sum F_y = m_1 \ddot{y}_1;\ \sum M_{x_1} = J_1 \ddot{\theta}_1; \quad (2)$$

• for the drive axle and the wheels assembly

$$\sum F_y = m_2 \ddot{y}_2;\ \sum M_{x_2} = J_2 \ddot{\theta}_2, \quad (3)$$

where subscripts 1 and 2 correspond to the unsprung masses of the front axle and wheel assembly, and the rear bogie with drive-axle and wheel assembly respectively.

The vehicle equation of motion in generalized coordinates is written as [1, 7]

$$[M]\ddot{y}(t) + [C]\dot{y}(t) + [K]y(t) = [K_F]y_o, \quad (4)$$

where $[M]$ is the vehicle mass matrix; $\ddot{y}(t)$ the acceleration vector; $[C]$ is the vehicle damping matrix; $\dot{y}(t)$ is the velocity vector; $[K]$ is the vehicle stiffness matrix; $y(t)$ is the column vector of the generalized coordinates; $[K_F]$ is the excitation distribution matrix of the displacement excitation vector; y_o is the road vertical displacement excitation vector.

The vector of the generalized coordinates can be written in matrix form as

$$\{y\} = \{y_c, \theta_c, \varphi_c, y_1, y_2, \theta_1, \theta_2\},$$

where y_1 is the vertical displacement of front axle and wheel assembly, y_2 is the vertical displacement of rear axle and wheel assembly, θ_1 is the rotational displacement of the front axle and wheel assembly along the longitudinal axis of the vehicle, θ_2 is the rotational displacement of the rear axle and wheel assembly along the longitudinal axis of the vehicle.

The road profile is represented by a vector $\mathbf{y}_j$ — as a function of road travel — yielding the j^{th} axle tire (left or right) vertical displacement $\mathbf{y}_s$ from which the wheel's vertical velocity and acceleration are calculated, along with the required assumptions. The solution of the system of equations (2)–(4) provides the pitch-bounce-roll dynamic behaviour of the road tanker.

A simulation algorithm for the road tanker dynamic behaviour was developed with the aid of MATLAB 7.1 software [10]. A Monte Carlo simulation method is introduced for a sensitivity analysis of the road tanker's dynamic behaviour in relation with vehicle's design parameters. Design parameters are considered to vary from a nominal value according to a specific rule. A standard deviation of critical design characteristic along with road profile data were introduced. A large number

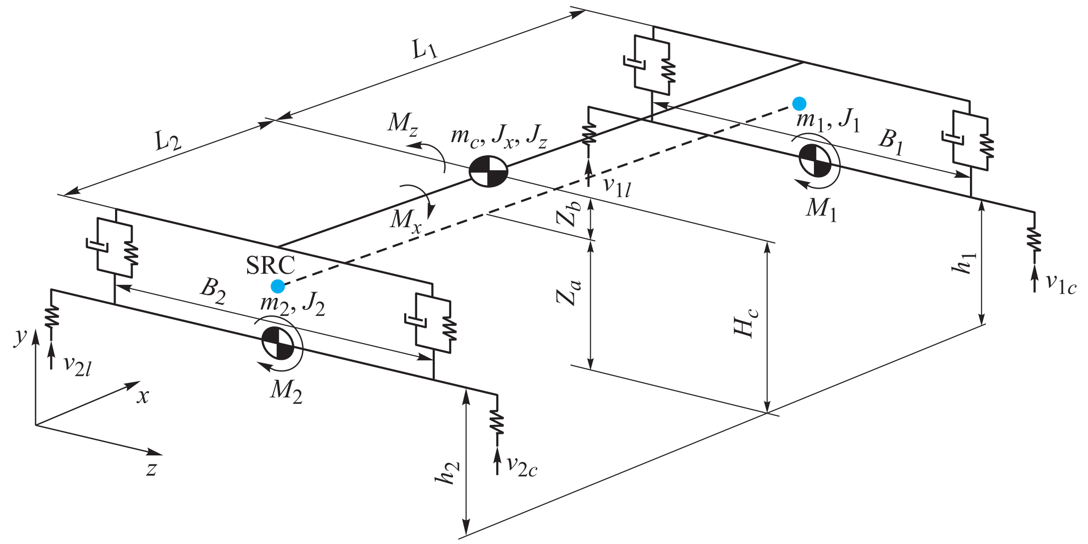


Figure 10. Model of a two axle fixed-tank vehicle with 7 degrees of freedom

of simulations were performed to investigate the road tanker's dynamic response for various road excitation types and standard manoeuvres.

Desirable vehicle handling under both moderate and severe cornering and braking conditions is an important consideration of vehicle design. The vehicle dynamic model is used to study single and double lane change manoeuvres, J-turns, or other manoeuvres involving simultaneous cornering and braking. A static model with inputs obtained from the Monte-Carlo simulation were further evaluated according to the ISO 14792 test for assessing the suspension and roll-over characteristics of the road tanker [22]. The obtained results from the aforementioned algorithm for the suspension characteristics were further evaluated with experimental results for lateral stability and stresses and distortions in tank and chassis.

a

b

Figure 11. The 26T road tanker with trailer, totaling a 42T road train tested for lateral stability, handling, and braking, on a highway (*a*), and on a rough terrain (*b*)

Road tanker inspection and testing. In 2010 there was reported a number of 50 small and medium factories spread around the country producing road tankers and vehicles transporting dangerous goods. It was noticed by the Competent Authority that there have been cases of type approvals and periodic inspection tests not complying with the Standards and Norms in force. It was further apparent the requirement for the standardization of the relevant procedures of inspections and test reports from the certified bodies, in the frame of a uniform application of ADR legislation and liability that may arise in the event of an accident, a procedure was proposed by the authors for a common approach for type approvals complying with EN 13094 for tank design and unified tests in accordance with EN 12972/April 2001, and EN 13094/2004 March 2004 [8, 9, 20–22].

A critical phase of the vehicle design process is physical testing of prototype designs at a proving ground. Vehicles are subjected to tests involving various road and weather conditions, road grades, steering and braking maneuvers and even high speeds to study handling behavior, ride comfort, and compliance with FMVSS, SAE and European standards.

Tests certify the specific requirements posed by the ADR Regulation for the vehicles transporting dangerous goods. Desirable vehicle handling under both moderate and severe cornering and braking conditions is an important consideration of vehicle design (Figure 11).

Forces and stresses acting on the prototype tank were measured with strain gauges and accelerometers. Then, the finite elements results were further evaluated. Figure 12 shows the positions of the strain gages and accelerometers on the tank shell, the on-board A/D converter and computer, and the tests results. The on-board A/D converter and PC used to record measurements have 16 channels for each set of measurements, 32 channels in total. The sampling rate per channel was set to 500 Hz [15].

For the evaluation of the FEA algorithm the Strains-Stresses measured in positions 1 and 2 calculated with the FEA algorithm are shown in Figure 13. Loading conditions correspond to 0.65g braking in the forward direction, 0.2g continuous left turn combined with 0.1g vertical acceleration.

From the measured stresses during road tests the equivalent stresses were compared with the stresses calculated with the FEA algorithm. Both methods provide similar results, maximum stresses obtained were 4.88, 3.77, 11.44, and 22.16 MPa for the loading cases 1, 2, 5, and 6 respectively. Variations of the arithmetic and experimental results lie in the range of 10 %, confirming that design requirements were met with the tank-chassis configuration. Test results within design specifications are invaluable for proving the proper interaction of individually developed systems to provide for safe operation of a vehicle. Unsatisfactory test results require redesign and testing of the system components until a suitable configuration provides the expected results. Both satisfactory and unsatisfactory results provide real world feedback to the design engineers.

The aforementioned requirements were integrated in the tests for type approval and initial

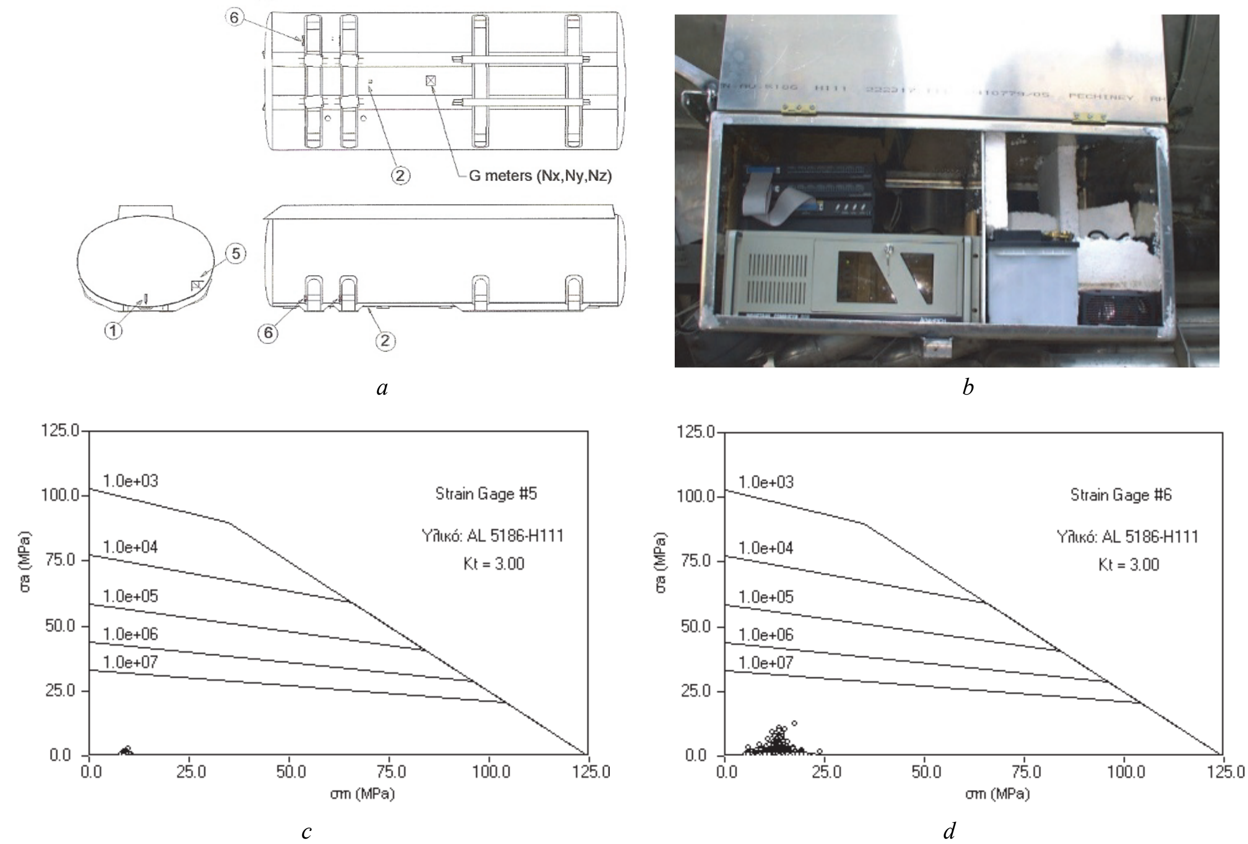


Figure 12. Positioning of the strain gages and accelerometers (*a*) and the onboard A/D converter (*b*). Stresses (MPa) measured in positions 1 (*c*) and 2 (*d*)

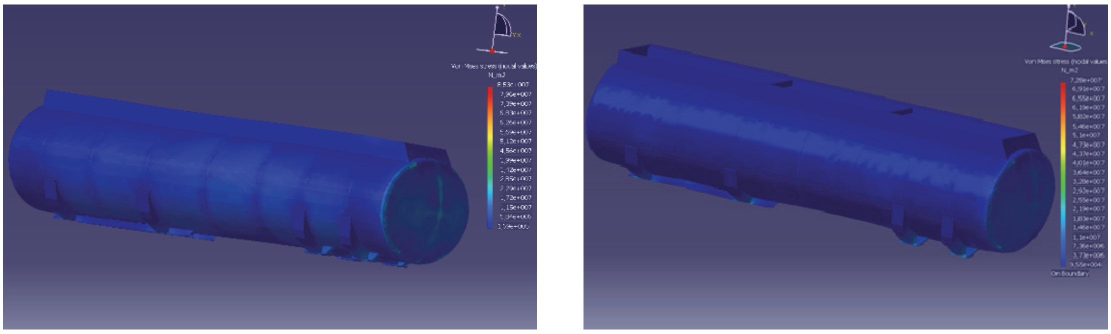
checks of road tankers and vehicles transporting dangerous goods submitted to the Competent Authority since 2004. A sample of the proposed methodology is presented herewith for a three axles 26 T road tanker with a RENAULT KERAX 6X4 KERAX 410 chassis. An examination of this 2009 proposal reveals that from the experience gained at this time, and the proposed methodology suggested, similar procedures are adopted almost identically by the ADR 2015 and ADR 2017 for the type approval and initial tests for vehicles transporting dangerous goods [8, 9].

ADR type approval and testing. The European ADR provides the general guidelines for the design, construction, type-approval and test procedures. The intention of the ADR Regulation is to adapt road tankers to technological progress concerning design, manufacturing, and equipment, and testing procedures. A rigorous procedure concerning inspection and testing were specified accordingly by the Vehicles Test and Homologation Laboratory of the University of Patras since 2002 in order to comply with the requirements of the ADR Agreement.

Inspection and testing and the issuing of the test certificates was organized in a systematic way. For the design approval of new tanks and their attachments tests are performed to prove their capability to withstand the maximum allowable working pressure, in combination with the inertia loads specified by the ADR Agreement. Tank shells and their equipment undergo periodic inspection at fixed intervals including: external and internal examination, hydraulic pressure test of the tank, equipment testing and dimensional measurements [23–27].

Following the ADR Agreement the construction requirements shall conform the provisions of Part 9. Requirements concerning the construction and approval of vehicles of categories N and O, as defined in Directive 98/91/EC intended for the carriage of dangerous goods. Directive 98/91/EC of the European Parliament and of the Council of 14 December 1998 relating to motor vehicles and their trailers intended for the transport of dangerous goods by road and amending Directive 70/156/EEC relating to the type approval of motor vehicles and their trailers.

The inspection certificate for the tank shell and its equipment includes: checking of conformity to



a *b*

Figure 13. Stresses (MPa) calculated by FEA in positions 1 (*a*) and 2 (*b*)

the approved type, check of the design characteristics, examination of internal and external conditions, hydraulic pressure test at the test pressure indicated on the manufacturer's plate, leakproofness test, and check of satisfactory operation of the equipment. Specific stages include: examination of documents; verification of the tank against the design (manufacturing methods and conditions, material grades and wall thickness, the condition of the tank, main dimensions, non-destructive testing of the welds); inspection of the tank interior; inspection of the tank exterior; hydraulic pressure test or vacuum test; leakproofness test; determination of water capacity; inspection of service equipment; inspection of frame or other structural equipment of portable tanks [23–28].

Electrical equipment is checked according to ADR, national and international standards. Braking equipment have to be in accordance with all relevant technical requirements of ECE Regulation No. 13 or Directive 71/320/EEC. Prevention of fire risks for the vehicle cab, the fuel tanks, the engine, the exhaust system, the speed limiting device the vehicle endurance braking system and the combustion heaters are checked according to the ADR standards. Coupling devices of trailers comply with the technical requirements of UN-ECE Regulation No. 55, or Directive 94/20/EC [29–31].

Concerning stability, tank-vehicles with fixed tanks with a capacity of more than 3 m^3 intended for the carriage of dangerous goods in the liquid or molten state tested with a pressure of less than 4 bar, are tested to comply with the technical requirements of ECE Regulation No. 111 for lateral stability [32]. Rear protection of vehicles is checked and a bumper sufficiently resistant to rear impact has to be fitted over the full width of the tank at the rear of the vehicle. VOC emissions resulting from the storage of petrol and its distribution from terminals to service stations (including transportation by the road tanker) are controlled by European Directive 94/63/EC. The design engineer performs a stability analysis based on ECE Regulation No. 111 for lateral stability. A separate test report is then issued from the Inspection Body concerning lateral stability for the inspected road tanker based on the suspension characteristics provided in the stability analysis reported, along with geometrical data concerning tank CG location on chassis, and a thorough check of tank geometry and dimensions in order to assure compliance with the engineering drawings and equipment [28, 32].

The proposed algorithm can be used as a design and evaluation tool from tank manufacturers for the optimum chassis selection for a tank type, and the estimation of the road tanker roll-over characteristics from an early design stage. Efficient load distribution of the gross vehicle weight on the road tanker axles is important ensures payload maximization, rational load distribution among the axles, increased profitability, reduced environmental impact, and enhanced road tanker safety. Also, the method provides a means to predict compliance or desired vehicle handling of a complete vehicle design prior to the actual physical testing of the prototype.

The proposed test and inspection report provides a useful tool for a complete and detailed registration of a road tanker, its equipment and testing procedures followed. It might be necessary that independent ADR certification bodies in collaboration with the Ministry of Transportation proceed with the inspection of all the existing fleet of ADR certified vehicles under the frame of a strict actions list concerning vehicles technical data (adequate chassis-superstructure configuration, ADR equipment, braking equipment: UN-ECE Regulation No. 13 and Directive 71/320/EEC, endurance braking; Coupling devices of trailers to comply with the technical requirements of UN-ECE Regulation

No. 55; speed limitation device with ECE Regulation No. 89 electrical equipment; fire risk prevention for the vehicle cab, the fuel tanks, the engine, the exhaust system, the vehicle endurance braking system and the combustion heaters; lateral stability according to the technical requirements of UN-ECE Regulation No. 111; and the application of the ADR transitional measures [28–34].

Conclusions. The aforementioned procedures for the design and testing of vehicles carrying dangerous goods that started by the authors since 2002 are integrated to the recent ADR Regulation 2017. The experience gained is embodied in inspection and tests reports including: vehicle mounting requirements for the superstructure, list of drawings, manufacturer's certificate of conformity, list of Norms and Regulations applied. The inspection and testing methods presented integrates modern methods of design, production and testing of vehicles of vehicles transporting dangerous goods. This methodology could be followed by inspection bodies offering advantages for a precise registration of inspected vehicles and equipment.

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