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On wind stability requirements for emergency car warning triangles

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Abstract. This work discusses the wind stability requirements specified by UN Reg. 27 on emergency car warning triangles, which are of mandatory use in many countries. Wind tunnel experiments have been carried out in order to determine aerodynamic coefficients of commercial warning triangles and the friction coefficients between the triangle legs and an asphalt base that fulfils the roughness requirements stated by Reg. 27 for wind stability certification. The wind stability specifications for warning triangles are reviewed, compared with pressure field measurements and discussed. Results of wind tunnel tests and comparison with field measurements reported in the literature show that the requirements could be excessively conservative.

Keywords: warning triangles; drag coefficient; wind stability; UN regulations

1. Introduction

An intensive discussion has arisen in the Argentinean Association of Automotive Engineers and Technicians (*AITA*) concerning the wind stability requirements for advance-warning triangles, stated in Addendum 26 to UN Regulation No. 27, "**Uniform Provisions for the Approval of Advance-Warning Triangles".** This regulation, adopted as the standard for the Argentinean code "*IRAM 10.031/84 - Balizas Triangulares Retrorreflectoras*", states the shape and dimensions of the advance-warning triangle and its base, and specifies a wind-stability test that the triangle must pass in order to fulfill the Regulation requirements.

The basic geometry of a warning triangle is very simple: when mounted for use, its shape is that of an equilateral triangle with an inner equilateral hole, usually supported on a square or rectangular base. The triangular base must have a minimum clearance from the ground for a 0.3 m wide × 0.3 m long × 0.05 m high rectangular prism. The reflection and material requirements stated by Reg. 27 are an outer rigid triangle of retro-reflecting surface, and an inner red fluorescent area that does not need to be rigid. In fact, many warning triangles with a thin and flexible plastic fluorescent surface are commercially available, as well as triangles with this surface made of rigid materials. Reg. 27 states literally, "The advance-warning triangle shall be open at the centre and shall comprise a red border

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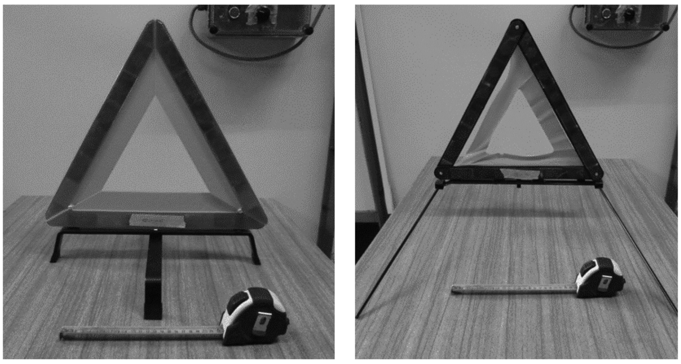

Fig. 1 Different types of emergency warning triangles. The enveloping triangle side length is 0.45 m for both types

composed of an outer retro-reflecting strip and an inner fluorescent strip, the whole supported at a certain height above the surface of the carriageway. The open centre and the fluorescent and retro-reflecting strips shall be bounded by concentric equilateral triangular contours". Fig. 1 shows two different triangles that meet the geometric requirements.

A large number of studies have been performed in order to determine aerodynamic forces and wind loads on flat plates of different shapes, the results of which are reported in classical texts such as Hoerner (1965). Full scale measurements of wind loads on road signs have been carried out by Quinn *et al.* (2001a). These and other studies report that the plate shape in the case of discs and low aspect ratio rectangular and triangular plates appears to have no significant effect on the magnitude of the normal wind force coefficient. On the other hand, height above the ground can have an influence on the drag coefficient. Letchford (2001) reports a complete investigation of wind loads on rectangular sideboards and hoardings in the turbulent boundary layer.

The forces acting on flexible surfaces, such as sails, have received much investigation (Viola and Fossatti (2008) present a good review). Nevertheless, the particular geometry of rigid-flexible warning triangles, as one of those studied in this work, presents characteristics of both rigid and flexible surfaces and their interaction. However, it is difficult to find in the literature specific studies on similar bodies. The central triangular hole of warning triangles is another characteristic that affects its aerodynamics by completely modifying the downstream recirculation region. Some work on perforated plates that study these modifications has been carried out, for instance, by Yaragal *et al.* (2002).

Surface roughness has an enormous influence on many important physical phenomena such as contact mechanics, sealing, adhesion and friction, see Persson *et al.* (2005). Therefore one can see the importance of stating the surface roughness required for the stability test. Nevertheless, surface roughness extends in a spectrum of wavelengths and not all affect the friction in the same way. UN Regulation 27 states that "The advance-warning triangle shall be set up in a wind tunnel, on a base measuring about 1.50 m by 1.20 m formed of a road surface as normally used by the competent authorities. This surface shall be characterized by its geometric roughness $HS = 0.5$ mm ± 0.05 mm, which shall be defined and determined by the so-called ′sandy beach′ method."

As seen, the only requirements for the base surface, besides being that "normally used by the competent authorities", is its geometric roughness, which characterizes the material's macrostructure. In the particular case of rubber friction, many attempts have been made to relate it to the so-called 'sand filling number' on road surfaces. The sand filling number is the amount of very fine-grained sand needed to fill out all the road surface cavities in a given surface area. Studies of Persson *et al.*

(2005) found no correlation between the sand filling number and rubber friction on dry road surfaces. In light of modern rubber friction theories, this result is not unexpected since the rubber friction depends on the power spectrum for *all wavevectors*, while only the long wavelength components contribute appreciably to the sand filling number. It is expected that the friction between asphalt and other materials as plastic or metal will not show a high correlation either. Nevertheless other studies do find correlation between friction and skid resistance of pavements in not only the macro- but also the microtexture of the road (Fenech 2000, Asi 2007), making this a subject of current research. In this work some simple computations are made in order to determine the static friction coefficients between the triangle base legs and the asphalt base, from the measured drag coefficients and the wind velocity that made the triangles slip away.

For the determination of aerodynamic loads, we tested two commercially-available advance warning triangles, one completely rigid and the other one with a flexible fabric inner area, in order to obtain their normal and tangential force coefficients at different angles of incidence and at different distances from the ground and the total drag they must overcome without slipping or overturning in the wind stability test. With these results and the weight and dimensions of 9 different warning triangles, an average static friction coefficient between the asphalt base and the triangle base is determined.

Among these and other requirements stated by Regulation 27, the triangles must pass a “mechanical solidity test”, in which a force is applied to the apex and the elastic deflection must not be larger than a specified value. In general, the moment that the base of the triangle experiences as it reaches this elastic deflection limit is found to be smaller than the one required to overcome the wind stability test, which appears to be more conservative in terms of mechanical resistance.

This work does not pretend to be an exhaustive study of warning triangle aerodynamics, but rather to present some arguments that we consider should be taken into account for future revisions of the Argentinean code, and perhaps for UN Regulation 27.

2. Warning triangle dimensions and tests

“Advance-warning triangle” stands for the device in the form of an equilateral triangle, intended to be on board vehicles and to be placed on the roadway in order to signal, by day and at night, the presence of a halted vehicle. Its shape and dimensions must be those shown in Fig. 2.

Among other tests, warning triangles must accomplish:

- *Test of stability against wind:* “The advance-warning triangle shall be set up in a wind tunnel, on a base measuring about 1.50 m by 1.20 m and placed on a road surface as normally used by the competent authorities. This surface shall be characterized by its geometric roughness $HS = 0.5$ mm $\pm$ 0.05 mm, which shall be defined and determined by the so-called “sandy beach” method. When set up in this manner, the advance-warning triangle shall be subjected for 3 minutes to an air stream exerting a dynamic pressure of 180 Pa (about 60 km/h under normal conditions) parallel to the supporting surface, in a direction which seems to be most unfavorable for the stability. The advance-warning triangle shall neither overturn, nor shift. Slight shifting of the points of contact with the road surface by not more than 5 cm, however, shall be allowed. The triangular part of the device shall not rotate by more than 10° around a horizontal axis or a vertical axis from its initial position.”

A word of caution must be introduced at this point. The criterion for the wind velocity of

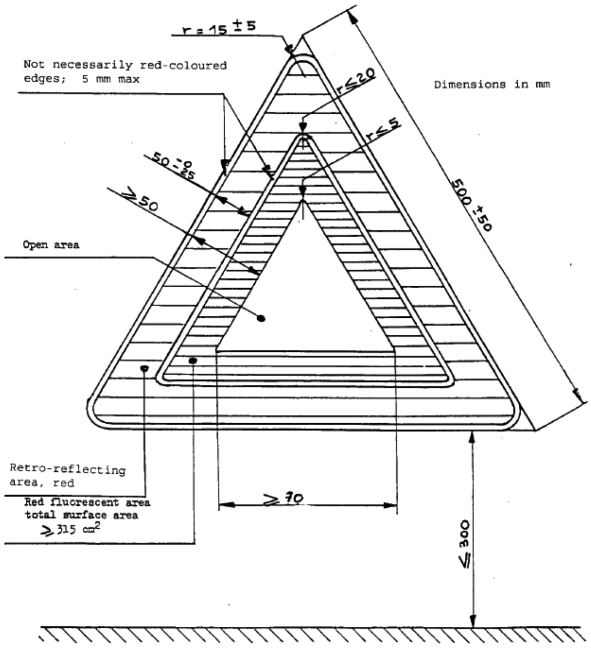

Fig. 2 (from UN Regulation 27). Shape and dimensions of advance warning triangles

approximately 60 km/s (16.7 m/s) seems to be based on the air speed induced by large passing vehicles, probably adding the effects of wind. It is worthy to point out, nevertheless, that field measurements of pressure, wind velocity and aerodynamic loads on traffic signals caused by passing vehicles on a highway are much smaller, generating static pressure fluctuations in a range between -40 Pa and + 20 Pa, Quinn *et al.* (2001b). This is considerably lower than the 180 Pa required by the Regulation.

- *Mechanical solidity test:* "When the advance-warning triangle has been set up as required by the manufacturer and its bases are firmly held, a force of 2 N shall be applied to the apex of the triangle parallel to the supporting surface and normal to the lower side of the triangle. The apex of the triangle shall not move more than 5 cm in the direction in which the force is exerted. After the test, the position of the device shall not be significantly different from its original position."

3. Methodology

Experiments were carried out at the Boundary Layer and Environmental Fluid Dynamics Laboratory (*LaCLyFA*) at the Faculty of Engineering at the Universidad Nacional de La Plata, Argentina, in order to determine the drag and side force coefficients of standard warning triangles of two types, and to derive from them normal and tangential force coefficients.

The wind tunnel at the Aeronautical Department is equipped with an electronic speed control, which allows speeds of up to 20 m/s. It is a closed section tunnel with a test section 1.40 m wide, 1 m high and 7.2 m long, powered by a 50 *HP DC* electric motor with an axial flow, adjustable pitch blade propeller. The natural turbulence intensity of the wind tunnel in the range of velocities for

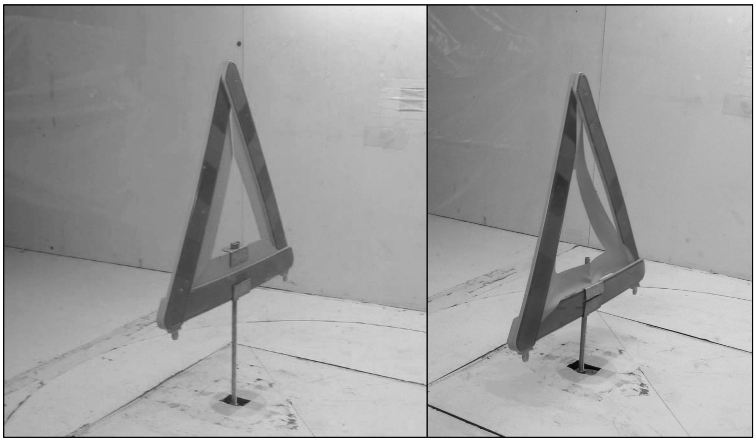

Fig. 3. Rigid (left) and rigid-flexible (right) emergency warning triangles

these experiments was below 2%. The Reynolds number based on the triangle's side and wind velocities between 5.72 m/s and 17.3 m/s was between 171000 and 519000. Blockage ratio was 6.3%, based on the outer triangle's enveloping area. No blockage correction was applied. The warning triangles were mounted vertically in the test section, on a two-channel aerodynamic balance (load cells and V-Shay 2310 bridges) placed under the tunnel floor. No boundary layer was simulated because the floor effects were confined to the natural boundary layer of the 7 m long test section. The tests to determine the aerodynamic coefficients were carried out only on the triangles, without their bases and the asphalt base, in the configuration shown in Fig. 3. The tests to determine triangle stability and failure wind velocity were performed with the triangles mounted on their commercial bases (two examples shown in Fig. 1) and standing on the asphalt surface. Failure velocity and failure type (sliding or overturning) were determined for 17 different commercial warning triangles. From the failure velocity and weight of those triangles that slid an average friction factor between the asphalt and base legs was computed.

Two different types of triangles were tested for aerodynamic coefficients, with different fluorescent areas: one triangle with a rigid plastic inner surface and another one with a flexible inner surface (Fig. 3). Their side length of 0.45 m is the lower limit allowed by Reg. 27 (Fig. 2). Both triangles have the same external dimensions and the same open area / total area ratio.

The asphalt base for the certification test and the determination of friction coefficients was provided by the Pavement Laboratory of the National University of La Plata. The average geometric roughness was 0.48 mm. The "sandy beach method" in six different points gave values between 0.46 mm and 0.52 mm, all of them within the required range of 0.5 mm ± 0.05 mm.

4. Results

4.1 Measured force coefficients

Aerodynamic normal and tangential force coefficients were computed from drag and side forces measured at different heights from the ground and at different angles of incidence, rotating the triangle on its vertical axis. Results are shown in Table 1. H is the height of the base of the triangle.

Table 1 Normal force coefficients for both rigid and rigid-flexible warning triangles

Rigid triangle, C_n				
H(m) \ angle (deg)	**90**	**60**	**45**	**30**
0.05	1.28	1.20	1.12	0.91
0.1	1.39	1.33	1.29	1.02
0.15	1.39	1.29	1.27	1.09

Rig-Flex. triangle, C_n				
$H(m)$ \ angle(deg)	**90**	**60**	**45**	**30**
0.05	1.71	1.51	1.42	1.07
0.1	1.70	1.54	1.40	1.03
0.15	1.51	1.37	1.28	0.97

Three measurements were performed for each condition, with deviations from the average value not larger than 7%. Tangential force coefficients did not exceed the value of 0.1 and were neglected in this analysis. No noticeable Reynolds number effects were found in the tested range.

Normal force coeffient, C_n, is defined as

$$C_n = \frac{F_n}{\frac{1}{2}\rho V^2 A_{ref}} \tag{1}$$

F_n is the measured normal force, A_{ref} the enveloping triangle area (the central hole is not subtracted), ρ and V the air density and wind velocity.

It is clear from the results that the concave shape adopted by the flexible strips significantly increases the normal force. However, this is a common configuration for warning triangles, probably adopted because of economical reasons, since it fulfills the optical and geometrical requirements with cheaper materials.

The influence of height above the ground in these tests is not conclusive. The obtained results are consistent with others reported in the literature. Hoerner's classical text (1965) reports normal force coefficients around 1.17 for circular and square flat plates, and no appreciable reduction in disks with central holes of less than 25% hole/disk diameter ratio. More recently, Quinn *et al.* (2001a) report drag coefficients between 0.98 and 1.40 for different road signs of triangular shape, obtained by field measurements for Reynolds numbers comparable with those of these tests. The large range can be due to the influence of atmospheric turbulence intensity and length scales, which are known to modify the base resistance of bluff bodies, Tieleman *et al.* (2003).

4.2 Friction coefficients and triangle stability

Fig. 4 shows a simple sketch of the forces acting on a car warning triangle placed on an asphalt base.

W is the triangle weight (base included), D is the aerodynamic drag, F_r the friction force, $N1$ and $N2$ the normal force supported by the rear and front legs, respectively, h the height of the center of

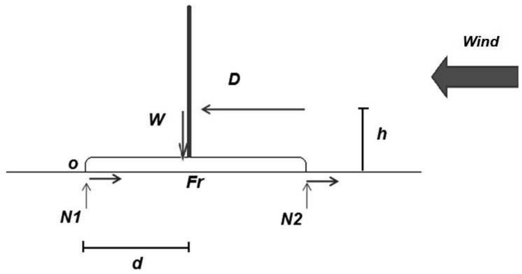

Fig. 4 Sketch of forces acting on an emergency car warning triangle (seen from the side)

pressure and d the distance between the center of gravity and the rear leg(s) tip(s).

Equilibrium equations state that for a force up until the triangle is about to slide, static friction must equal drag, so

$$\sum F_x = 0 \Rightarrow Fr = \mu W = D = C_D P_d A_{ref} \tag{2}$$

Here μ is the static friction coefficient between asphalt and leg tips, P_d the dynamic pressure and A_{ref} the reference area, which is the total area of the enveloping triangle, as defined in section 4.1. Also the sum of moments about the rear leg tip must be zero, until the load that makes the triangle begin to overturn, when the normal force at the front leg(s) $N2$ becomes zero

$$\sum M_o = 0 \Rightarrow Wd = Dh = C_D P_d A_{ref} h \tag{3}$$

Eq. (3) gives the clue for weight and leg dimensions of a warning triangle that meets the wind stability criteria concerning overturning.

Computation of the static friction coefficient between legs and asphalt for nine different commercially available warning triangles, from Eq. (2), considering the maximum wind velocity that they withstood before sliding, gave an average value of $\mu = 0.891$, with standard deviation $\sigma_\mu = 0.15$. Plastic or metal leg tips did not introduce appreciable differences in the computed friction coefficients. Nevertheless, legs with sharp metal tips tended to get lodged in the asphalt surface and in this case failure to pass the test was due to overturning rather than slipping.

Considering an average drag coefficients of 1.35 for the triangle and a dynamic pressure of 180 Pa, as required by Reg. 27, the friction force must be of 21.3 N in order to prevent slip. A friction coefficient of 0.891 makes a triangle with a 0.45 m side need a weight of 23.9 N or 2.44 kg to pass the test. A slight inclination not larger than 10º is allowed. At this maximum inclined configuration, the normal force supported by the base's rear leg(s) increases by 17,3% (sin(10º) = 0.173), thereby increasing the friction force by the same factor. In this case, the weight needed to prevent slipping is 20.4 N or 2.08 Kg. Required weights of this magnitude are clearly not economical for warning triangle manufacturers.

Due to the equilateral triangle's symmetry and the uniform flow, it is expected that the center of pressure coincides with the triangle's center of gravity. Although this assumption could become uncertain when the triangle is close to the ground, observing the weight, base dimensions and drag and moment computations of the 7 triangles that failed to pass the test by overturning, confirms this hypothesis, at least for the worst condition of the triangle facing the wind at 90º. The distance required between the triangle and the tips of the rear legs to prevent the triangle from overturning depends upon its weight and the height of the center of pressure, for standard triangle dimensions. This is close to 1/3 the triangle height, plus the base height. For the minimum required clearance of 0.05 m and the shortest allowed triangle side of 0.45 m, the height of the center of pressure is 0.18 m. To balance the aerodynamic moment, the required product of weight times the distance to the tips of the rear legs must be at least 3.8 Nm, increasing as the clearance distance increases. In the worst case wind-direction, for a rigid-flexible triangle with a normal force coefficient of 1.7, the product of weight times the distance to the rear support is 4.78 Nm. With a 0.5 m leg distance, and an inclination of 10°, the required weight is 9.41 N or 0.96 kg.

These calculated values agree with those measured at the Laboratory with 17 different warning triangles tested for wind stability certification, where lighter triangles normally fail to pass the test, either by slipping, overturning or deflecting by an angle larger than the allowed 10°. An exception was found for triangles that break the aerodynamic symmetry with inner strips of different flexibilities, in configurations that shift the center of pressure downward and change the direction of the resulting force, reducing the aerodynamic moment and increasing friction, allowing triangles as light as 0.5 kg to pass the test.

5. Discussion

The criterion for the wind velocity requirements of approximately 60 km/h (16.7 m/s) specified in UN Reg. 27 seems to be based on estimations of the air speed induced by large passing vehicles. It is worth pointing out, however, that field measurements of pressure, wind velocity and aerodynamic loads on traffic signs caused by passing vehicles on a highway are much smaller, actually yielding static pressure fluctuations in a range between −40 Pa and +20 Pa. In Quinn *et al.* (2001b), air speed and pressure fluctuations were measured at a distance of 1m from a passing vehicle and the aerodynamic loads on road signs were related to these pressure changes. It seems, in light of these results, that the requirement for a dynamic pressure of 180 Pa is excessively conservative and demands heavier base weights. Turbulence intensity and length scale, which are other factors that can influence base drag of bluff bodies (Lee 1990), Tieleman *et al.* (1997, 2003) and present important differences between wind tunnel and field experiments, are not taken into account for the specified wind stability tests.

Besides, the moment exerted on the triangle-base joint during the mandatory static deflection test by a 2 N load on the apex is, for a triangle of 0.5 m side, 0.866 Nm, with a maximum allowed elastic displacement of 0.05 m. On the other hand, considering $C_n = 1.35$ and the center of pressure at 1/3 of the triangle height, the moment exerted on the base of the same triangle by the required wind load is 3.8 Nm, more than four times the static test value. The wind stability specifications are certainly more conservative in terms of resistance than the requirements of the mechanical solidity test.

6. Conclusions

Two types of standard emergency car warning triangles have been tested to obtain their drag coefficients, and derive from them the friction coefficient between the legs and asphalt, plus the base height and weight values needed in order to fulfill the requirements of UN Reg. 27. These specifications are discussed taking into account field measurements of pressure and velocity induced by passing vehicles, the results of wind tunnel tests on two different types of warning triangles and the certification wind stability tests of 17 different commercial triangles.

From the measurements and analysis carried out in this work, basic design considerations can be derived for safety warning triangles that must fulfill the requirements of Reg. 27. Uncertainties are high in the friction coefficient between leg tips and asphalt. The only requirements for the asphalt base are on roughness height and not on asphalt composition, a factor that can have a considerable influence on friction forces. High friction coefficients or heavy (and expensive) warning triangles are needed for avoiding slipping off the triangle base. Another possible solution is to prevent slipping with leg tips that prick and get lodged in the asphalt surface, with adequate weight and leg dimensions as to prevent overturning for the required wind velocity. Increasing the base weight is generally not seen as good a solution as the more economic option of increasing the length of the legs, in order to avoid overturning by the wind.

Additionally, the mechanical resistance needed to withstand wind loads is remarkably higher than the one required by the mechanical solidity test, which is another aspect to be considered in future revisions of UN Regulation 27.

Either way, in light of this paper's results, it seems clear that the dynamic pressure requirements of Reg. 27 should be revised, considering that field measurements show that wind and vehicle induced air velocities unlikely reach the required values, except on very windy days, when, in any case, it is advisable to put some additional weight on the triangle base if it has to be used for an emergency.

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