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IMPROVING TRAFFIC SAFETY IN EXISTING AND NEW ROAD TUNNELS WITH THE NOVEL NDBA CONCRETE SAFETY BARRIER

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Two main elements are essential in terms of road traffic safety. The first element is accident prevention and the second is the minimization of accident severity once a crash has occurred. Concrete safety barriers have very good anti-collision performance against roadside obstacles, relatively modest construction and maintenance costs, and low dynamic deflection and therefore are widely used in tunnels. Thanks to their characteristic redirective profile these barriers can redirect errant vehicles into their original lane after collisions. However insufficient research has been done for increasing the performance of concrete barriers purposely designed for tunnel installations. This research presents the new "NDBA Tunnel" concrete safety barrier designed and constructed by the Italian Road Operator ANAS indicated to be installed in road tunnel sections for safety improvements. In Europe, road safety barriers must be designed in compliance with the European Standard EN 1317. Therefore, the barrier "NDBA Tunnel" was subject to the TB11 and TB81 full-scale crash tests according to the European EN 1317 regulation. The results prove the barrier's ability to absorb impact loads of light and heavy vehicles with a working width W2. Therefore, the NDBA concrete barrier can be installed on existing or new tunnels at a distance less than or equal to 70 cm from the facing of the tunnel wall.

Keywords: concrete safety barriers, "NDBA Tunnel" barrier, full-scale crash test, EN 1317 regulation

1. Introduction

Road tunnels frequently are the most appropriate technical solution to overcoming particular spatial and/or environmental obstacles, while also meeting the transport needs of goods and people. Urban and extra-urban road tunnels frequently easily become bottlenecks for traffic streams, above all in case of accidents with consequently congestion phenomena and environmental pollution. The economic losses generated by tunnel traffic accidents include delay time costs, vehicle damage, structural costs, etc. In addition, in the case of a traffic accident, the functionality of a tunnel can be partially or completely compromised for a certain amount of time (e.g., for hours or days). Empirical data confirm that the relative risk of accidents in tunnel sections is lower than in open road sections, but that the accident severity is much higher (Amundsen, 1994; Amundsen and Engebretsen, 2009; Amundsen, and Ranes 2000). Moreover, accident severity is higher when the vehicle crashes against the tunnel wall than when it collides against road safety barriers, on open roads (Pireddu *et al.*, 2022). Some research analysed the distribution patterns of tunnel accidents under different factor combinations (e.g. gradient and slope length, curve radius, etc.) and found that most accidents are not produced by a single factor but are affected by an average of 1.5–1.6 factors (Turner-Fairbank Highway Research Center, 2003; Xing *et al*., 2023). Accident data of Italian, Chinese and Norwegian roads, show that crash severity may be significantly higher in tunnel sections than in the corresponding open road sections (Caliendo *et al*., 2023). Research on fire accidents in Chinese highway tunnels demonstrates that the proportion of fire accidents caused by traffic accidents is significant (18.3% of the total causative factors) (Ren *et al*., 2019). Trucks and other heavy vehicles are the most dangerous vehicle types involved in tunnel accidents because they often carry combustible materials and therefore can generate disastrous consequences. In terms of collision type, Pennsylvania tunnel accidents are dominated by rear-end collisions (53.8%), followed by hit-fixed-object (28.5%), sideswipe (5.8%) and angle collisions (5.5%) (Luo and Liu, 2023). Some studies have proven that the brightness variation inside and outside the tunnel often leads to the so-called "white hole effect" and "black hole effect" at entrance and exit sections respectively, with corresponding accidents increasing in these zones (Wang *et al.,* 2019). The European Commission has published the tunnel regulation "Directive 2004/54/EC of the European

Parliament and the Council on minimum safety requirements for tunnels in the Trans-European Road Network" to improve EU tunnel safety in general (European Commission, Brussels, 2004). This Directive must be applied to all road tunnels of over 500 m length. Two main aspects are fundamental in traffic safety of tunnels: accident prevention and minimization of accident severity once a crash has occurred. Crashes with solid objects placed beside the carriageway, such as tunnel walls, cause many fatal injuries. Consequently, there is a need to consider effective road safety barriers (SB) to increase safety in tunnels. The main purpose of roadside barriers installed in tunnels is to redirect errant vehicles back to the carriageway after an impact (Brian *et al*., 2006). Therefore, safety barriers do not close down accidents but can mitigate their adverse effects (Yang *et al*., 2019). Safety barriers can be grouped based on materials (steel, cable, wood and concrete barriers) and place of installation (embankment/cut, bridge, tunnel sections, etc.). Based on their behaviour, barriers are divided into two main types: flexible (e.g. steel barrier) and rigid (e.g. concrete barrier) systems. In flexible barriers impact energy of a vehicle is absorbed by both the road safety barrier (barrier deformation) and the vehicle (vehicle deformation) (Guerrieri *et al*., 2013). Instead, in rigid barriers impact energy is dissipated to vehicle deformation, movement of barrier modules, friction between the vehicle body and the barrier surface, as well as lifting up the vehicle wheels onto the barrier. Concrete safety barriers have increased road safety since their first implementation in New Jersey, U.S., in 1955 (EUPAVE, 2012). They are characterized by long lifetimes and require almost no maintenance while presenting a relatively high degree of safety. The particular shape of a concrete safety barrier permits redirecting a vehicle into its original lane after a collision on its structure. Impact forces are opposed by a combination of the rigidity and mass of the barrier structure. Because deflection is generally irrelevant, the vehicle impact energy is in part dissipated through the redirection and the deformation of the vehicle bodywork. For low-speed and/or low-angle collisions, concrete barriers redirect the vehicles without consistent damage to the bodywork. However, in some specific conditions (e.g. vehicle type tyre conditions, vehicle speed, impact angle, etc.), concrete safety barriers can produce a vehicle rollover, which may have fatal effects on the vehicle occupants (Grzebieta *et al*., 2005). This problem arises for the particular slope and step in the lower section of concrete barriers. For this reason, several studies were devoted to optimising the profile of concrete traffic barriers (Trajkovski, 2018). In this regard, full-scale impact tests to evaluate the safety performance are required. Because concrete barriers have exceptional anti-collision performance, relatively modest construction and maintenance costs, and low dynamic deflection, they are widely used in tunnels. However, no sufficient specific studies have been conducted for improving the performance of concrete barriers specifically designed for tunnel sections.

The novelty of this research refers to the analysis of an innovative concrete safety barrier designed by the Italian Road Operator ANAS specifically for tunnel sections. The barrier, called "NDBA Tunnel", was subject to several full-scale crash tests that can simulate in a very precise way the real configuration of tunnel walls, safety barriers installation and light and heavy vehicle impacts. The results prove the barrier satisfies the current EN 1317 regulation and therefore can be installed on existing or new tunnels to better guarantee users' safety. The article is structured as follows: Section 2 explains the safety barriers classification and metrics for evaluating drivers' injury risk. Sections 3 and 4 briefly describe the NDBA safety barrier family, correlated simulations and full-scale crash tests. Sections 5 and 6 illustrate the main characteristics of the new "NDBA Tunnel" safety barrier. Finally, conclusions are given in Sect. 7.

2. Road safety barriers classification and metrics for evaluating drivers' injury risk

The project of a new safety barrier usually needs different steps: the conceptual design, static or dynamic, linear or nonlinear analyses and crash tests (Bruski *et al*. 2019). In particular, the response of the barrier must be assessed during full-scale crash tests. The goal of crash testing techniques is to assess road safety barrier performance in representative conventional-case impact scenarios. According to the EN 1317 regulation, the full-scale test type varies in function of the containment level of the safety barriers. Detailed characteristics of full-scale tests are given in Fig. 1. Moreover, to forecast the performance of new safety barriers, the EN1317 specifies the criteria for the numerical simulation. New safety barriers and other restraint systems are certified after compulsory full-scale tests, then simulations can be carried out only for evaluation and prediction objectives. Instead, if modifications to existing safety barriers are required, the certification can be obtained from numerical simulations (Li *et al*., 2021). In Europe, the marketing for restraint systems must comply with the Council Directive 89/106/EEC laying down harmonized conditions for the marketing of construction products. According to the EN 1317 regulation, safety barriers are grouped into various categories in function of the following main parameters (see Figure 1):

- *Containment level (CL):* establishes the strength of the system, essentially specifying the maximum capacity for redirecting a vehicle. Higher containment levels produce stronger restraint systems:

$$CL = \frac{1}{2} M \cdot (V \cdot sen\varphi)^2, \tag{1}$$

where M is the vehicle mass (kg), ϕ is the impact angle (rad) of the vehicle with respect to the longitudinal axis of the barrier, V is the impact speed (m/s).

Depending on the specific risk level of the road section under consideration, the safety barriers have to be chosen to guarantee a proper containment level (CL). According to this concept the CL are distinguished as in Fig. 1 and Table 1. CL may be anywhere from low to very high. At a low CL, the safety barrier has to survive an impact from a 1,300-kg car with a speed of 80 km/h and a collision angle of 8°. At a very high hazard level of the road CL, the barrier must endure an impact of up to a 38,000-kg truck with a speed of 65 km/h and a collision angle of 20° (Table 1).

- *Acceleration Severity Index (ASI):* is regarded as the most important indicator of impact on the occupants. ASI is the value of weighted longitudinal, lateral and vertical accelerations, measured at the centre of mass of the test vehicle. ASI measures the severity of the impact and assesses occupant injury risk. The greater the ASI value, the higher the injury risk is. If maximum ASI values exceed 1.0 or 1.4 in some cases, then the impact consequences for the passengers are assumed to be dangerous or even lethal.

ASI is a nondimensional function of time, calculated as follows:

$$\begin{cases} ASI(t) = \sqrt{\left(\frac{\bar{a}_x(t)}{a_x^*}\right)^2 + \left(\frac{\bar{a}_y(t)}{a_y^*}\right)^2 + \left(\frac{\bar{a}_z(t)}{a_z^*}\right)^2}, \\ ASI = \max_t [ASI(t)] \end{cases} \tag{2}$$

where:

$$a_j(t) = \frac{1}{\delta} \int_t^{t+\delta t} a_j(t) \cdot \delta t \qquad j = x, y, z; \tag{3}$$

- x, y, z: longitudinal, lateral and vertical directions in the vehicle, respectively;
- t: time variable;
- $\bar{a}_x(t)$; $\bar{a}_v(t)$; $\bar{a}_z(t)$: acceleration components related to the car's centre of gravity (CG); (values averaged over a moving time interval δ = 50 ms);
- $a_x^* = 12g$; $a_y^* = 9g$; $a_z^* = 10g$ limits of acceleration components in x, y, z directions;
- g = 9.81 m/s^2, gravity acceleration.

- Theoretical Head Impact Velocity (THIV): is used to evaluate the collision intensity, in relation to persons in the vehicle, during the vehicle impact with the safety barrier. More specifically, it is the speed with which the theoretical head strikes the inside of the cuboid space of the vehicle. THIV is calculated as follows:

$$THIV = \max_t \sqrt{v_x^2(t) + v_y^2(t)}, \tag{4}$$

in which $v_x(t)$ and $v_y(t)$ are the speeds of the theoretical head with respect to the car, in the longitudinal (x) and transverse (y) directions of the car coordinate system, respectively.

The trajectory of the hypothetical head considered and THIV value are calculated from the parameter values measured in the vehicle center of gravity (CG).

- *Post-impact Head Deceleration (PHD)* represents the head deceleration after an impact. CG accelerations measured from the instant of the contact between the occupant's head and the windshield of the car in 10-ms time intervals are considered to calculate PHD with the relation:

$$PHD = \max_t \sqrt{a_x^2(t) + a_y^2(t)}, \tag{5}$$

in which $a_x(t)$ and $a_y(t)$ are the post-impact deceleration of the theoretical head with respect to the car, in the longitudinal (x) and transverse (y) directions of the car coordinate system, respectively.

- *Working Width 'W', Dynamic Deflection 'D' and Vehicle Overhang 'O':* horizontal displacements of the road restraint system (Figure 1).

Many other metrics can be used for estimating drivers' injury risk (Chell *et al.*, 2019) such as the Theoretical Head Impact Velocity man ($THIV_{man}$), the Real Head Impact Velocity (RHIV), the Head Injury Criteria (HIC_{15} and HIC_{36}), the Head acceleration 3 ms after its maximum (G_{3ms}) and the Neck Injury Risk (N_{ij}).

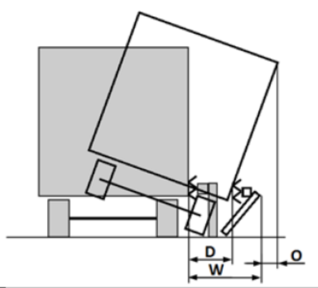
Parameter	Description	Note
CL	**Containment Level:** describes the ability to hold back colliding vehicles. Higher containment levels produce stronger road safety barriers $LC = \frac{1}{2} M \cdot (V \cdot sen\phi)^2$	Containment level characteristics: Low angle containment $\begin{cases} T_1 \\ T_2 \\ T_2 \end{cases}$ Normalcontainment $\begin{cases} N_1 \\ N_2 \end{cases}$ Highercontainment $\begin{cases} H_1;\ L_1^* \\ N_2;\ L_2^* \end{cases}$ Very High containment $\begin{cases} H_{4a};\ L_{4a}^* \\ H_{4b};\ L_{4b}^* \end{cases}$
ASI	**Acceleration Severity Index**: is a vehicle occupant severity indicator measured during homologation of road safety barriers. $ASI(t) = \max_t \left[\sqrt{\left(\frac{\bar{a}_x(t)}{a_x^*}\right)^2 + \left(\frac{\bar{a}_y(t)}{a_y^*}\right)^2 + \left(\frac{\bar{a}_z(t)}{a_z^*}\right)^2} \right]$	Three classes have been established: Class A: $0 < ASI \leq 1.0$ Class B: $1.0 < ASI \leq 1.4$ Class C: $1.4 < ASI \leq 1.9$
THIV	**Theoretical Head Impact Velocity:** describes the theoretical speed of the head, colliding with an obstacle during an impact. $THIV = \max_t \sqrt{v_x^2(t) + v_y^2(t)}$	It must be less than 33 km/h (for safety barriers).
PHD	**Post-impact Head Deceleration:** describes the head deceleration after an impact. $PHD = \max_t \sqrt{a_x^2(t) + a_y^2(t)}$	It must be less than 20 g (acceleration of gravity).
W	**Working Width**: the distance between the side of the safety barrier turned towards the traffic and the maximum dynamic lateral position of all essential parts of the system.	Eight classes have been established: $W_1 \leq 0.6$ m $W_2 \leq 0.8$ m $W_3 \leq 1.0$ m $W_4 \leq 1.3$ m $W_5 \leq 1.7$ m $W_6 \leq 2.1$ m $W_7 \leq 2.5$ m $W_8 \leq 3.5$ m
D	**Dynamic Deflection**: maximum lateral dynamic displacement of the side facing the traffic of the safety barrier	
O	**Vehicle Overhang:** where barrier deformation is limited, the barrier must support the vehicle with an overhang	

Figure 1. Metrics, definitions and safety barriers classification criteria according to Regulation EN 1317-1

Table 1. Impact energy required during crash tests in function of the containment levels

Test	Impact Speed (km/h)	Impact Angle (°)	Vehicle Mass (kg)	Containment Level (kJ)	Barrier Class	Vehicle Types
TB11	100	20	900	41	N2, H1, H2, H3	Car
TB21	80	8	1300	6	T1, T3	Car
TB22	80	15	1300	22	T2	Car
TB31	80	20	1500	43	N1	Car
TB32	110	20	1500	82	N2	Car
TB41	70	8	10,000	37	T3	Rigid HGV
TB42	70	15	10,000	127	H1	Rigid HGV
TB51	70	20	13,000	287	H2	Bus
TB61	80	20	16,000	462	H3	Rigid HGV
TB71	65	20	30,000	572	H4a	Rigid HGV
TB81	65	20	38,000	725	H4b	Articulated HGV

In some countries such as the United States, a specific procedure based on cost-benefit analysis (BCA) may be used instead (Montella, 2001). BCA techniques are usually considered as a rational procedure for assessing roadside safety action options. In BCA costs and benefits are conveyed in monetary values. The benefit/cost (B/C) ratio between two road safety options (i.e. scenario 2 and scenario 1) is calculated with the relation (NCHRP Report 492, 2003):

$$\left(\frac{B}{C}\right)_{2\text{-}1}=\frac{CC_1\text{-}CC_2}{DC_2\text{-}DC_1}, \tag{6}$$

where:

- $(B/C)_{2\text{-}1}$ is the incremental B/C ratio of scenario 2 to scenario 1;
- CC_1, CC_2 = annualized crash cost estimated for the scenarios 1 and 2;
- DC_1, DC_2 = annualized direct cost estimated for scenarios 1 and 2.

RSAP software (NCHRP Report 492, 2003), can be adopted as a useful tool for BCA evaluations. It includes an encroachment probability model that allows to estimate the estimated crash cost as follows:

$$E(C)=V\cdot P(E)\cdot P(C/E)\cdot P(I/C)\cdot C(I) \tag{7}$$

in which:

- E(C) is the estimated crash cost;
- V is the traffic volume;
- P(E) is the probability of encroachment (encroachment rate);
- P(C/E) is the probability of a crash given encroachment;
- P(I/C) is the probability of injury given a crash;
- C(I) is the cost of injury.

The model implemented in RSAP software is founded on the assumption that crash frequency is proportional to encroachment frequency, which is a function of motorway type and traffic intensity in terms of annual average daily traffic (AADT). The probability $P(C^{w\theta}_{v\psi}/E^{w\theta}_{v\psi})$ that a vehicle (of size *w*, encroaching with a given speed *v*, angle θ and orientation ψ) is within the hazard envelope and so encroaching as to impact the hazard, is obtained with the relation:

$$P(C^{w\theta}_{v\psi}/E^{w\theta}_{v\psi})=(1/5280)\cdot[L_h\cdot P(L_e\geq A)+\sec\theta\cdot\csc\theta\cdot\textstyle\sum_{j=1}^{W_e\cos\theta} W_e\,P(L_e\geq B)+\cot\theta\cdot\sum_{j=1}^{W_h} P(L_e\geq C)]. \tag{8}$$

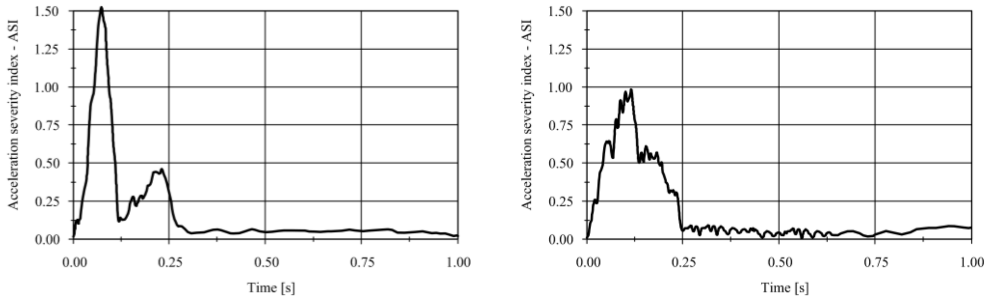
The probability P(C/E) of an impact against the safety barrier is obtained with the relation:

$$P(C/E)=\textstyle\sum_w\sum_v\sum_\theta\sum_\psi P(E^{w\theta}_{v\psi}/E)\cdot(C^{w\theta}_{v\psi}/E^{w\theta}_{v\psi}). \tag{9}$$

To choose the specific type of safety barrier to use in a certain road section, some national guidelines (e.g. the Italian guidelines D.M. n. 2367, 2004) suggest using a deterministic criterion based on traffic parameters such as AADT, percentage of heavy vehicles, road category, particular risk conditions, etc.

3. The NDBA safety barrier family

The primary objective of a road safety barrier is to restrain vehicles from an impending impact against dangerous fixed objects, and slowly dissipate the kinetic energy to the greatest possible barrier surface. The characteristic profile of a concrete safety barrier (also denominated “New Jersey”) allows redirecting an errant vehicle into its original lane after an impact against the barrier structure and protects vehicles from roadside hazards. Impact forces generated during the impact are contrasted by a combination of the rigidity and mass of the safety barrier. The deflection of concrete safety barriers is generally irrelevant. Therefore, the impact energy owned by the errant vehicle is partially absorbed through redirection and deformation of the vehicle bodywork. Instead, when the impact is characterized by low speed and/or low angle, concrete barriers can redirect the errant vehicles in the original lane without any consequent damage to the bodywork. However, due to the slope and step in the lower part of their profile, concrete safety barriers sometimes may produce the rollover of small cars. Generally, ASI values obtained in full-scale crash tests are very often greater than those of steel barriers, as shown in Figure 2.



(a) (b)

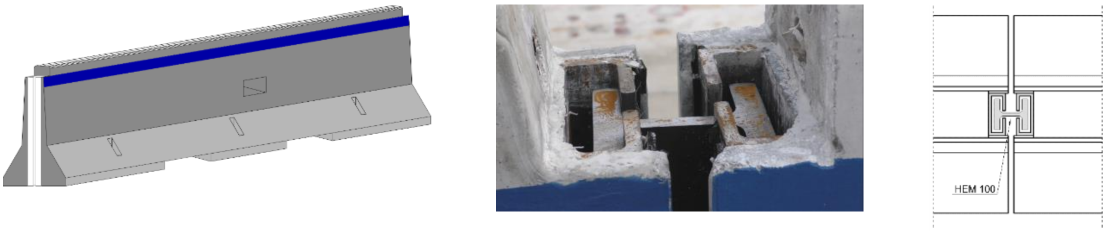
Figure 2. Examples of shape curves of ASI: a) concrete barrier, b) steel barrier

The EN 1317 regulation (EN 1317-1:2010; EN 1317-2:2010) requires that safety barriers must withstand the crash conditions summarized in Table 1 in function of the barrier class. Given this specification, it follows that the current road safety barriers are capable of withstanding only a vehicle impact. Therefore, in real-world applications, safety barriers do not guarantee any reasonable containment of errant vehicles in circumstances of multi-vehicle crashes, although the impacts happen at different points of the same barrier. However multiple vehicle impacts are rather frequent.

To solve this problem, the Italian road operator ANAS designed and patented a new type of concrete safety barrier called “NDBA” (National Dynamic Barrier ANAS) (Dinnella, 2019).

After numerical simulations in the LS-DYNA environment, the NDBA barrier was subjected to several full-scale crash tests. Two subsequent TB81 tests were completed on the same barrier. In particular, the second TB81 was carried out in the damaged barrier already subjected to a first TB81 test. The full-scale tests demonstrated that NDBA overcame two subsequent TB81 tests.

Thanks to this uncommon performance, currently the NDBA barrier is increasingly used in the Italian road network managed by ANAS S.p.A. This is also attributable to the fact that conventional concrete safety barriers commonly used in Italy have a working width W5 (Fig. 1) and therefore need a clearance distance from the hazardous obstacles higher than 2.80 m. Instead, the NDBA has a working width W2 and therefore assures lower values of “working width” than traditional barriers. Each barrier module is fabricated employing concrete of class C40/50. The barrier has maximum width and height of 68 cm and 120 cm respectively. To obtain a perfect fixed joint, two "C" steel profiles are included in correspondence of the terminal sections of each module (Figure. 3) and a vertical HEM 100 steel profile is used for connecting pairs of concrete modules. The connection system allows you to improve the barrier performance because, in case of an impact event, the instantaneous and permanent deformations result lower than those of traditional concrete barriers.



(a) (b) (c)

Figure 3. NDBA barrier module and connection system

In embankment road sections the barrier can be connected with the body of the embankment and pavement layers using six IPE 80 steel beams (placed into niches) each 78 cm long, as shown in Figure 4.

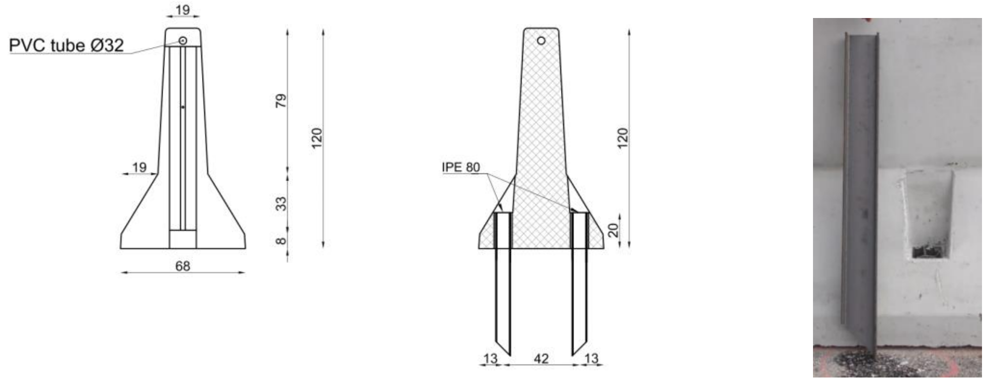


Figure 4. Anchoring system for an embankment road section

4. Simulation and full-scale crash tests

The containment performances of the NDBA safety barrier were estimated with the explicit dynamic nonlinear analysis using the LS-DYNA code (Hallquist, 2006). Furthermore, a TB11 and two subsequent TB81 full-scale crash tests were performed. As for simulations, the nonlinear equation of a vehicle motion, discretized by FEM at time “n”, can be formalized as follows (Tischer *et al.*, 2014):

$$M\ddot{x}^n = r^n - f^n - h^n, \tag{10}$$

where M is the diagonal global mass matrix, $\ddot{x}$ indicates the global nodal acceleration vector, r^n is the vector of external loads, f^ndenotes the vector of internal loads and damping, and $h^n$is the vector of forces resulting from hourglass control. The global nodal velocity vector $\dot{x}$ and the global nodal displacement to timet^{n+1}vector x are calculated with the following relationships:

$$\ddot{x}^n = M^{-1}(r^n - f^n - h^n), \tag{11}$$

$$\dot{x}^{n+\frac{1}{2}} = \dot{x}^{n-\frac{1}{2}} + \Delta t_n \ddot{x}^n, \tag{12}$$

$$x^{n+1} = x^n + \Delta t_{n+\frac{1}{2}} \dot{x}^{n+\frac{1}{2}}, \tag{13}$$

$$\Delta t^{n+\frac{1}{2}} = \frac{1}{2}(\Delta t_n + \Delta t_{n+1}). \tag{14}$$

To ensure the stability of the solution, the time step is obtained as $\Delta t = \alpha \cdot \Delta t_{crit}$ where α is the Courant number (α = 0.90 (Hallquist, 2006)) and Δt_{crit} denotes the critical time step. Δt_{crit} depends on the spatial dimension of the finite elements and material properties and characteristics (Tischer *et al.*, 2014).

The finite element (FE) models for light and heavy vehicles used during the TB11 and TB81 tests (Figure 6) were obtained from the public library of the National Crash Analysis Center (Borovinšek, 2007). Instead, the NDBA barrier in each elementary part was modelled taking into consideration the values of material properties given in Table 2 (Yang *et al.*, 2013). The speed and impact angle of vehicles against the barrier are those requested by the EN 1317 regulation and reported in Table 1. Finally, static and dynamic friction coefficients were established in function of the different parts and materials in contact during the impact.

Table 2. Materials properties adopted in “LS-DYNA” simulations (source: Yang *et al.*, 2019)

Component	Type	Unit	Default Value
Concrete	Elastic modulus	N/mm^2	3.00×10^4
	Density	kg/m^3	2.4×10^3
	Poisson ratio	-	0.2
	Compressive strength	N/mm^2	20.1
	Tensile strength	N/mm^2	2.01
Steel	Elastic modulus	N/mm^2	2.06×10^5
	Density	kg/m^3	7.85×10^3
	Poisson ratio	-	0.28
	Yield strength	N/mm^2	345
	Ultimate strength	N/mm^2	470

Based on different connection and anchoring configurations and the impact point of the heavy vehicle, three different scenarios were simulated taking into consideration the following connection and anchoring configurations and the impact point of the heavy vehicle:

1. Scenario A: the length of the HEM steel profile is identical to the NDBA barrier height. The impact is located in the centreline of the barrier module (Figure 5);
2. Scenario B: length of the HEM steel profile of 33 cm. The impact is located in the centreline of the barrier module;
3. Scenario C: length of the HEM steel profile of 33 cm. The impact is placed in the connection constraint between two barrier modules.

The simulations were performed by using the LS-DYNA 970 and a PC with an Intel Core i7 - 8700K processor.

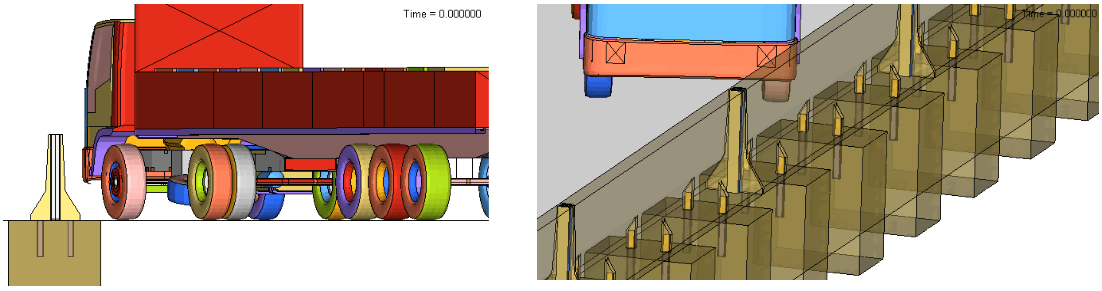


Figure 5. Simulation with LS-DYNA (Scenario A)

The simulation outcomes show that the maximum value of Working Width is 0.83 m, which corresponds to a barrier of class H4b ((CL = 725 kJ) and working width W3 (< 1.00 m) (Dinnella *et al.*, 2019). After simulations, a 72.00 m long NDBA concrete barrier was analysed with full-scale crash tests at “CSI test centre” (IMQ Group) in Bollate, Milan (Italy). A TB11 test with a light vehicle (Fiat Uno, cf. Figure 6) and two TB81 tests with a heavy vehicle (Volvo FH12) were performed. The results showed that the NDBA barrier can withstand two successive heavy vehicle impacts, according to the TB81test, with a maximum ASI of 1.26 (class B, cf. Figure 1 and Figure 7) and a working width of 0.74 m (class W2 cf. Figure 1). Considering these results, currently, the NDBA barrier is used both on new and existing roads belonging to the Italian road networks operated by ANAS. Nowadays the NDBA barrier family (Figure 8) comprises also the “NDBA bridge” and the “NDBA tunnel” to improve traffic safety of bridges and tunnels respectively.

Phase 1 Phase 2 Phase 3 Phase 4

Figure 6. Impact phases of a light vehicle during the test TB 11

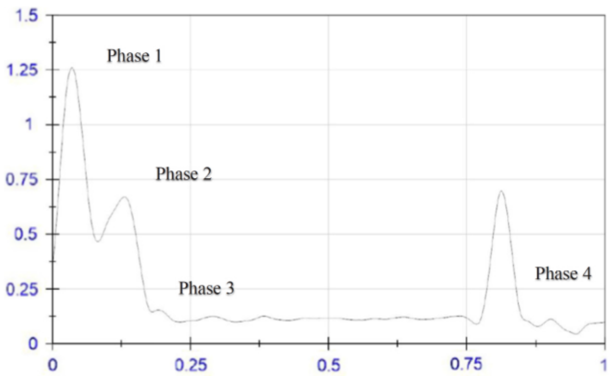


Figure 7. Values of ASI during the test TB 11

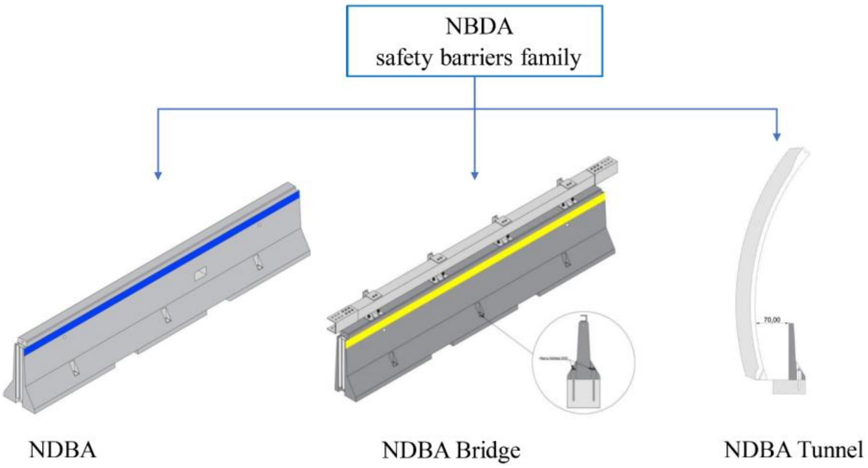
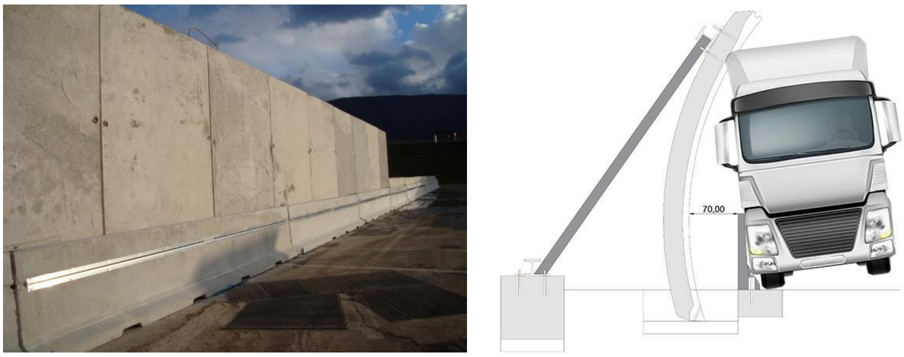


Figure 8. NDBA safety barriers family

5. The safety barrier "NDBA Tunnel"

Tunnel walls are generally protected by barriers with a redirective profile that allows redirecting a vehicle into its original lane after a collision on its structure. Usually, the redirective profile is very similar to a common concrete barrier (i.e. New Jersey barrier) but it has an asymmetrical transversal section. In Italy and other countries, the most common barriers with a redirective profile have a containment level H2. These barriers are successfully tested and certified according to European regulation EN 1317-5 which uses different criteria to assess the safety of roadside barriers, including the structural adequacy, the vehicle trajectory and the occupants' risk factors. Installing concrete safety barriers directly against a tunnel wall produces a risk for road users because safety barriers cannot translate transversally. Therefore, the severity of an impact against barriers may be very dangerous for the occupants of vehicles. Therefore, generally, it is necessary to distance the rear part of barriers by 5-8 cm from the inner profile of the tunnel walls so that barriers can absorb part of the kinetic energy that the vehicle possesses at the moment of impact, thus obtaining an ASI lower than maximum permissible value. Up to now, the crash tests carried out to analyse safety barriers specifically designed for installation in tunnel sections have been carried out by placing the concrete safety barriers in direct contact with a vertical concrete wall (cf. Figure 9a). Therefore, crash tests have traditionally been carried out under impact conditions that are very different from those found in operating tunnels.



(a) (b)

Figure 9. a) Common test conditions of barriers for road tunnels; b) Layout used for testing the "NDBA Tunnel" barrier

This test configuration currently performed, however, is not suitable for testing the barrier alone, but rather the structural system composed of the barrier and wall as a whole.

To improve traffic safety in tunnel sections, in 2023 the Italian operator ANAS designed and created a particular barrier from the NDBA barriers family, named "NDBA Tunnel" that was tested according to the requirements of the UNI EN 1317 regulation. The shape and dimensions of the "NDBA Tunnel" are shown in Figures 10-12.

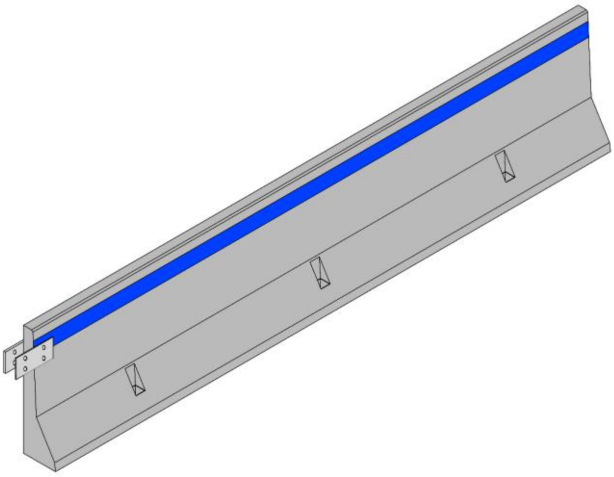


Figure 10. 3D rendering of the "NDBA Tunnel" concrete safety barrier

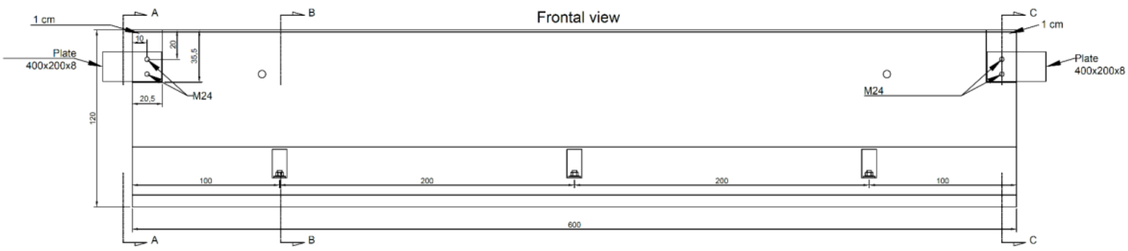


Figure 11. Frontal view of the "NDBA Tunnel" barrier (dimensions in cm)

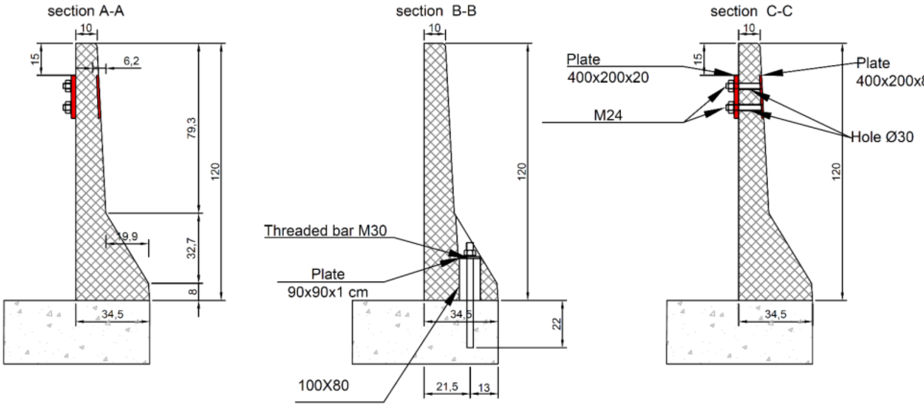


Figure 12. Sections of the "NDBA Tunnel" barrier (dimensions in cm)

The "NDBA Tunnel" barrier was tested in class H4 (therefore considering the effect of heavy vehicle impacts) within the CSI S.p.A. test center (IMQ Group based in Bollate, Milan) in conditions similar to that of real tunnel environments (cf. Figure 9b and Figure 13). The test configuration, and therefore the consequent real installation layout of the safety barrier, guarantees a proper space for positioning cable ducts between barrier and tunnel wall. To carry out the crash tests of the "NDBA Tunnel" barrier, ten curved prefabricated concrete segments were first installed to simulate the inner shape of a road tunnel. Each segment is 2.40 m long for a total length of 24 m. A system consisting of steel props and concrete blocks was used to guarantee maximum stability of the structure during the crash tests. The modular elements of the NDBA Tunnel barrier were anchored to a concrete curb (136 x 60 cm), created on the test field, through the adoption of 3 Ø30 anchor bolts inserted for 22 cm in length (cf. Figure 12). The concrete (class C40/50) modular elements were connected through two plates connected using 2 M24 countersunk head bolts. Each module is 6 meters long (maximum width 34,5 cm, height of 120 cm) and can be installed at a distance of approximately 70 cm from the facing of the prefabricated wall. The particular connection system between the different modules allows the installation of the barriers even in small horizontal radius curves.

Figure 13. Configuration of the “NDBA Tunnel” barrier before crash tests

Before proceeding with the full-scale crashes, finite element simulations were carried out which gave decidedly positive outputs. However, to obtain the certification numerous types of crash tests were carried out. In the first analysed layout, the “NDBA tunnel” barrier was positioned at a distance of 70 cm from the wall and three different crash tests were carried out, namely (cf. Table 2):

- TB 11, with 900 kg light vehicle (Figure 14);
- TB 32, with a 1500 kg light vehicle (Figure 15);
- TB 81, with a 38 t heavy vehicle (Figure 16).

In particular, the TB 32 test was performed to consider the impact of a light vehicle but with a higher mass than the one used in the TB11 test.

Figure 14. Car used in the TB11 test

Figure 15. Car used in the TB32 test

Figure 16. Heavy vehicle used in the TB81 test

Figure 17. Photos of the damaged barrier after the TB81 test

According to the EN 1317 regulation, the results have shown a containment level CL=725 kJ (H4b class), a working width W=0.74 m (class W2) and ASI = 1.26 (class B, Fig. 19) obtained from Eq. (2) and the measured light vehicle accelerations (cf. Fig. 18). To evaluate the benefit achievable with the installation of the NDBA Tunnel barrier compared to tunnels without this safety system device, other crash tests were carried out for the configuration of Figure 9b and Figure 13 where the barrier was absent. In particular, the following crash tests were performed:

- TB 11 with 900 kg light vehicle (Figure 14);
- TB 81 with 38 t heavy vehicle (Figure 16).

The results of the TB 11 test show that the value of the ASI index is higher than that found in the presence of the NDBA Tunnel barrier. The TB 81 test, however, demonstrates that after the impact, the heavy vehicle follows a trajectory that takes it to the center or even to the opposite side of the carriageway, rather than continuing its trajectory alongside the barrier as happens instead in the presence of the NDBA Tunnel barrier. In summary, the installation of NDBA Tunnel barriers can significantly contribute to raising safety levels both in one-way and two-way tunnels, preventing, after hitting the barrier, a vehicle from invading the lane opposite to the one it was originally travelling in. Finally, the NDBA Tunnel barrier can be installed at a distance from the tunnel wall between 0 cm and 70 cm (Figure 20).

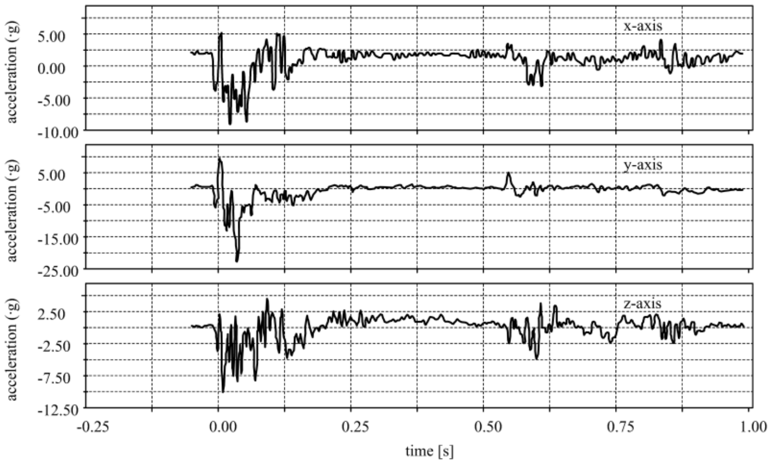


Figure 18. Measured vehicle accelerations (TB11 test)

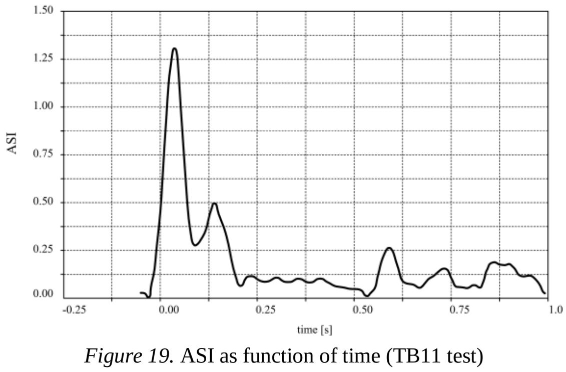


Figure 19. ASI as function of time (TB11 test)

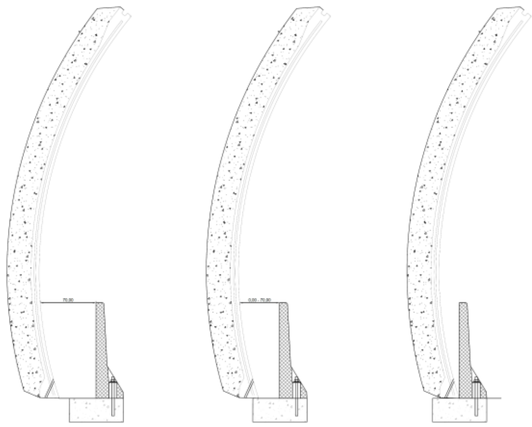
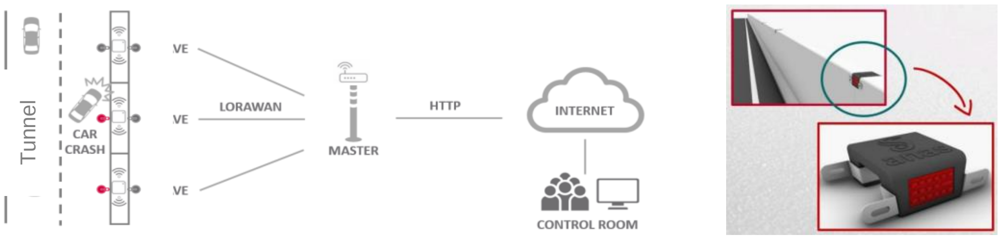


Figure 20. Installation positions of the barrier "NDBA Tunnel"

6. NDBA concrete barrier as a smart device for smart rods

"NDBA Tunnel" concrete safety barrier can be considered a smart device because, in the upper part of its structure, a real-time warning system for accidents can be applied. This component is integrated with an Accidents Monitoring System (AMS) that identifies vehicle impacts against the barrier in real time. AMS comprises the following main components: Slave sensors, LED light and Master device. The system communicates constantly with the operating control room of the road operator ANAS (Figure 21). The Slave sensors are equipped with a triaxial accelerometer that, together with an informatic platform, can detect the section of an impact and transmit an alarm to the associated Master device and the Control Room (CR). In the case of an impact, the red lights come on in all safety barrier modules before the section where the impact is detected to quickly inform road users when approaching the incident zone. Future development of this device will allow users to be informed about obstacles in the carriageway, intensity of traffic, congestion phenomena, roadworks, presence of risky curves and vehicles broken down along the road. From this point of view, the "NDBA Tunnel" barrier is a smart device and could be soon integrated into smart road facilities (Guerrieri *et al*., 2020; Guerrieri, 2021) according to the main objective of the "smart road project" launched by the Italian road operator ANAS in the year 2016.



(a) (b)

Figure 21. Accidents monitoring system for a tunnel equipped with the "NDBA Tunnel" safety barriers and LED lights

7. Conclusions

This research describes the main characteristics and performances of the new safety barrier "NDBA Tunnel" that was originally designed by the Italian road operator ANAS S.p.A. to ensure values of working width (W) compatible with the available spaces in the tunnel environment and able to pass the test TB81 of the European EN 1317 regulation (barrier of class H4b, the impact energy of 725 kJ). Each barrier module is 6 meters long and can be installed at a distance less than or equal to 70 cm from the facing of the tunnel wall. To obtain the certification, according to EN 1317 regulation, the following main crash tests were performed: TB 11 with a 900 kg light vehicle and TB 81 with a 38 t heavy vehicle. Considering that crash tests have traditionally been carried out under impact conditions that are very different from those found in operating tunnels, in this research a novel approach has been used. Ten curved prefabricated concrete segments were used to replicate the inner shape of a wall tunnel and the concrete safety barrier modules were installed at approximately 70 cm from the facing of the prefabricated wall. The full-scale crash tests prove that the analysed barrier withstands the TB 81 test. In addition, afterward the impact against the NDBA Tunnel barrier, the heavy vehicle used in the TB 81 test describes a trajectory that redirects it to the original lane. So, the use of the new "NDBA Tunnel" barriers can significantly contribute to increasing traffic safety levels in tunnels. After the interesting results shown in simulations and full-scale crash tests, extensive use of NDBA concrete safety barriers can be soon expected to improve the traffic safety of new and existing road tunnels.

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References

1. Amundsen, F.H. (1994) Studies of driver behaviour in Norwegian road tunnels. *Tunnelling and Underground Space Technology*, 9(1), 9–15.
2. Amundsen, F.H. & Engebretsen, A. (2009) Studies on Norwegian road tunnels II. An analysis on traffic accidents in road tunnels 2001–2006.
3. Amundsen, F.H. & Ranes, G. (2000) Studies on traffic accidents in Norwegian road tunnels. *Tunnelling and Underground Space Technology*, 15(1), 3–11.
4. Borovinšek, M., Vesenjak, M., Ulbin, M., Ren, Z. (2007) Simulation of crash tests for high containment levels of road safety barriers. *Engineering Failure Analysis*, 14(8), 1711-1718.
5. Brian, A., John, Coon, Reid, D. (2006) Reconstruction techniques for energy-absorbing guardrail end terminals. *Accident Analysis and Prevention*, 1–13.
6. Bruski, D., Burzyński, S., Chróścielewski, J., Jamroz, K., Pachocki, Ł., Witkowski, W., Wilde, K. (2019) Experimental and numerical analysis of the modified TB32 crash tests of the cable barrier system. *Engineering Failure Analysis*, 104, 227-246.
7. Caliendo C., Russo, I, Genovese, G. (2024) A Resilience Analysis of a Motorway Tunnel Affected by a Traffic Accident Using the Average Vehicles’ Speed as a Metric. *International Journal of Civil Engineering*, 22, 505-522. https://doi.org/10.1007/s40999-023-00903-8.
8. Chell, J., Brandani, C.E., Fraschetti, S., Chakraverty, J., Camomilla, V. (2019) Limitations of the European barrier crash testing regulation relating to occupant safety. *Accident Analysis and Prevention*, 133. DOI: 10.1016/j.aap.2019.07.015.
9. Dinnella, N. (2019) Road safety barrier. Patent (PCT), n. IB2019/058588.
10. Dinnella, N., Chiappone, S., Guerrieri, M. (2020) The innovative “NDBA” concrete safety barrier able to withstand two subsequent TB81 crash tests. *Engineering Failure Analysis*, 115, 104660.
11. European Commission. (2004) Directive 2004/54/EC of the European Parliament and of the Council on Minimum Safety Requirements for Tunnels in the Trans-European Road Network 2004. Brussels
12. EUPAVE. (2012) Concrete Safety Barriers: A Safe and Sustainable Choice. European Concrete Paving Association (EUPAVE), Brussels.
13. Guerrieri, M. (2021) Smart Roads Geometric Design Criteria and Capacity Estimation Based on AV and CAV Emerging Technologies. A Case Study in the Trans-European Transport Network. *International Journal of Intelligent Transportation Systems Research*, 19(2), 429–440.
14. Guerrieri, M., Parla, G., Corriere, F. (2013) A new methodology to estimate deformation of longitudinal safety barriers. *ARPN Journal of Engineering and Applied Sciences*, 8(9), 763-769.
15. Guerrieri, M., Maini Lo Casto, B., Peri, G., Rizzo, G. (2020) Smart vs conventional motorways: Environmental impact assessment under realistic traffic conditions. *Science of the Total Environment*, 727, 138521.
16. Grzebieta, R.H., Zou, R., Jiang, T., Carey, A. (2005) Roadside hazard and barrier crashworthiness issues confronting vehicle and barrier manufactures and government regulators. In: *Proceedings of the 19th International Technical Conference on the Enhanced Safety of Vehicles*, Washington.
17. Hallquist, J. (2006) *LS-DYNA, Theory Manual*.
18. Li, Z., Fang, H., Fatoki, J., Gutowski, M., Wang, Q. (2021) A numerical study of strong-post double-faced W-beam and Thrie-beam guardrails under impacts of vehicles of multiple size classes. *Accident Analysis and Prevention*, 159.
19. Luo, Q., Liu, C. (2023) Exploration of road closure time characteristics of tunnel traffic accidents: A case study in Pennsylvania, USA. *Tunnelling and Underground Space Technology*, 132.

20. EN 1317-1:2010. (2010) Road restraint systems – part 1: Terminology and general criteria for test methods.
21. EN 1317-2:2010. (2010) Road restraint systems – part 2: Performance classes, impact test acceptance criteria and test methods for safety barriers including vehicle parapets.
22. D.M. (2004) n. 2367, Italian Road safety barriers guidelines, 21/06/2004.
23. Montella, A. (2001) Selection of roadside safety barrier containment level according to European Union Standards. *Transportation Research Record*, 1743, 104-110.
24. NCHRP Report 492. (2003) Roadside Safety Analysis Program: Engineer's Manual, TRB, Washington, D.C.
25. Pireddu, A., Lombardi, M., Bruzzone, S., Berardi, D. (2022) Risk-based tunnel design for consequences of road accidents: the role of tunnel length. *WIT Transactions on the Built Environment*, 214, 71–81.
26. Ren, R., Zhou, H., Hu, Z., He, S., Wang, X. (2019) Statistical analysis of fire accidents in Chinese highway tunnels 2000–2016. *Tunnelling and Underground Space Technology*, 83, 452–460.
27. Tischer, M. Wehrle, E.J, Baier, H. (2014) Reduced modeling of crash barriers for design, *LS-DYNA Forum*, Bamberg.
28. Trajkovski, J., Ambrož, M., Kunc, R. (2018) The importance of friction coefficient between vehicle tyres and concrete safety barrier to vehicle rollover - FE analysis study. *Journal of Mechanical Engineering*, 64(12), 753–762.
29. Turner-Fairbank Highway Research Center. (2003) Interactive Highway Safety Design Midel: Getting Started Guide. Federal Highway Adiministration: Washington, DC, USA.
30. Wang, Q., Jiang, S., Liu, H., Ma, F. (2019) Analysis on traffic accident characteristics of urban road tunnels. *Chin. J. Underground Space Eng*., 15 (Supplement 1), 460–469.
31. Xing, R., Li, Z., Cai, X., Yang, Z., Zhang, N., Yang, T. (2023) Accident Rate Prediction Model for Urban Expressway Underwater Tunnel. *Sustainability*, 15, 10730. https://doi.org/10.3390/su151310730.
32. Yang, J., Xu, G., Cai, C.S., Kareem, A. (2019) Crash performance evaluation of a new movable median guardrail on Highways. *Engineering Structures*, 182, 459–472.