

# A Rational Method to Design Vehicular Barriers

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In an earlier STRUCTURE magazine article (October 2008), the author presented an algorithm to determine design force on a barrier during a vehicular impact. The algorithm, based on energy principle and empirical car crash data, showed that the impact force depends on four factors: mass, speed and crush characteristics of the vehicle, and the barrier stiffness. The article concluded that the impact force on a barrier during a head-on collision can be significantly larger than the code-specified force of 6,000 lbs.

A vehicular barrier is defined as an element or a system that, when placed in the path of a moving vehicle, would stop the vehicle after it collides with the barrier (Figure 1). The barrier may be active or passive, located at grade or at an elevated level. In general, vehicular barriers are used to protect life, limbs and property from intruding vehicles. In a parking structure, barriers are used at floor edges to prevent the vehicles from plunging to street below. In other structures, barriers are installed outside a building to keep vehicles from slamming into the building. Generally, the barriers are passive type, such as concrete walls, upturn beams, spandrel beams, steel guardrails, bollards and prestressed cables. If a vehicle can plow through or go over an obstacle, the obstacle is not considered an effective barrier. A barrier that either fails during an impact with a colliding vehicle (Figure 2) or flexes so much that the vehicle breaches it without stopping, is not an effective barrier. Recent fatal incidents involving failure of the barriers in parking structures during vehicular impacts and the use of vehicles to slam into buildings have put the barriers under focus and their design adequacy has become more important than ever.

A vehicle crashing into a barrier presents a complex analytical problem. In order to calculate the impact force  $F$  on a barrier, one needs to know the weight, speed and crashing characteristics of the vehicle, as well the stiffness properties of the barrier. In this respect, the International Building Council's (IBC) approach to design barriers to use a single force of 6,000 lbs. appears arbitrary and unreasonable.

## Historical Background

Designing a vehicular impact barrier is not a straight-forward task. Modern passenger

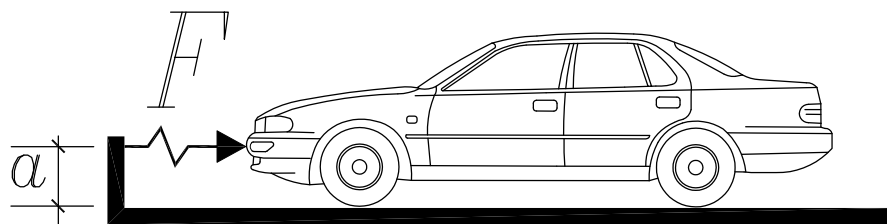


Figure 1: Barrier impact force and its arm above floor.

vehicles are made of various materials, including metals, alloys and fiber-reinforced polymer composites. The impact lasts fraction of a second and then the vehicle retreats or rebounds away from the barrier. During a collision with a barrier, metals in the vehicle body fold and collapse like an accordion causing polymer fibers to break away or de-bond from polymer matrix. An analytical model that incorporates these effects and accurately predicts how a car crushes in a crash is useful in the barrier design. The finite-element crash and crush analyses procedures have been used abundantly in automotive industry; however, the analyses require specialized software and large models consisting of several hundred thousands, if not millions, finite elements. Though the method is appealing, it may be cost-prohibitive for use in building projects.

In contrast to the above approach that relies on sophisticated analysis, the U.S. military has used field testing to design barriers used to protect its bases against enemy vehicles. The testing method presumably requires building a test barrier, subjecting it to a moving vehicle at a specified speed and then standardizing

it on a scale of 0 to 10. For example, according to the Military Field Manual, steel pipes embedded in 4 foot deep footings (Figure 3) have been approved for 4,500-pound vehicles travelling at 30 mph. The protection rating of this system is poor – 1.0 on a scale of 0 to 10. Another standardized system is a reinforced concrete retaining wall shown in Figure 4 (page 24). The wall is 21 inches thick and has been approved for 15,000-pound vehicles travelling at 30 mph, with a protection rating of 3.6. Recently, ASTM F-2656-07, *Standard Test Method for Vehicle Crash Testing of Perimeter Barriers*, has been developed to standardize testing of barriers. The method requires building a test barrier and subjecting it to a moving vehicle at the design speed. The barriers tested are then classified. The experimental procedure is definitive, but expensive.

## Proposed Design Method

In contrast, the author's approach has been to seek synergy by integrating the well-known energy principle with the available vehicular crash data to determine impact force for all types of barriers, and not limit the design to a few standardized barrier types. As explained in the previous article, the impact force on a vehicle barrier can be determined by the equation:

$$F = \frac{mv^2}{2(\delta_c + \delta_b)} \quad \text{Equation 1}$$

Where  $m$  = the vehicle mass  $[= \frac{W}{g}]$

$v$  = the vehicle speed at the impact

$\delta_c$  = vehicle crush

$\delta_b$  = barrier deflection under impact

Equation 1 does not capture the peak force a barrier experiences. Rather, it provides an average force during the crush and rebound duration that lasts a fraction of a second. The four parameters noted in Equation 1 are discussed below, with a focus on the effects of barrier stiffness on the impact force  $F$ .



Figure 2: A concrete barrier failed prematurely at impact.

## Mass

It was concluded in the previous article that a vehicular weight of 6,000 pounds should be used in barrier design in parking structures. In case the clear floor height exceeds 7 feet, a taller and heavier vehicle should be considered in designing the barrier.

## Vehicular Speed

The most significant parameter affecting the impact force is the vehicle collision speed; the impact force increases with the square of the vehicular speed. The anticipated speed depends on the distance and slope available for a vehicle to accelerate before slamming into the barrier. Further, in a parking structure, a vehicle may roll down the ramp without any aid from its engine and gain considerable speed, as its potential energy is converted into kinetic energy. A formula to compute the speed at bottom of the ramp was presented in the 2008 article.

## Vehicle Crush

When a vehicle hits a barrier, parts of the vehicle deforms, bends or crushes, and the vehicle length decreases. The decrease in vehicle length after an impact is termed "car crush" and is denoted as  $\delta_c$  in Equation 1. Based on the National Highway Traffic Safety

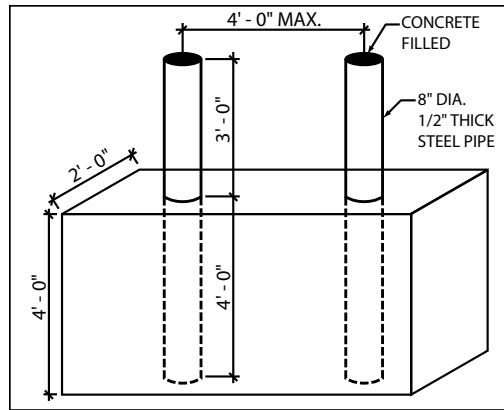


Figure 3: Steel Bollards used as Barriers for 4,500 lbs. vehicle travelling at 30 mph.

Administration (NHTSA) vehicle crash-worthiness tests, the car crush distance  $\delta_c$  can be approximated by the following equation:

$$\delta_c = \frac{\sqrt{v}}{3} \text{ (ft)} \quad \text{Equation 2}$$

where  $v$  is the car speed in miles per hour (mph).

Since vehicles are manufactured by many automakers in many models with changes made every year, the vehicle crush characteristics may change as the technology progresses. As such, the car crush data need to be updated accordingly.

## Barrier Deflection

During an impact, a part of vehicle's kinetic energy is transferred to the barrier. One barrier system may absorb energy as elastic strain while another system may rely on local yield mechanisms. The amount of energy absorbed and accompanying deformation depends on the barrier type. For barriers exhibiting linear behavior, the deflection can be represented as:

$$\delta_b = \frac{F}{k_b} \quad \text{Equation 3}$$

where  $k_b$  is the barrier stiffness. Substituting the value of  $\delta_b$  and  $\delta_c$  in Equation 1, and after some algebra, the impact force,  $F$ , can be computed using the following equation:

$$F = 0.5k_b \left[ -\frac{\sqrt{v}}{3.63} + \sqrt{\frac{2mv^2}{k_b} + \frac{v}{13.2}} \right] \quad \text{Equation 4}$$

where  $m$ ,  $k_b$  and  $v$  are in ft-lb. units.

Equation 4 can be used to plot the impact force-speed relation for a given vehicular weight. For example, Figure 5 (page 24) shows the relationship for a 6,000 pound car impacting against a barrier of stiffness  $k_b$ . Figure 5 (page 24) shows that the impact force decreases as the barrier stiffness is reduced (i.e. its flexibility increases). However, barrier rigidity cannot be reduced *ad infinitum* because, after certain reduction in stiffness, a barrier ceases

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to be effective. Concrete barriers, such as cantilever walls, upturned beams and precast spandrel beams are nearly rigid. Such barriers exhibit negligible  $\delta_b$  and, unless they fail prematurely (e.g. Figure 2, page 22), they experience the severest impact force. The steel guardrails show some flexibility and the multi-strand steel cables undergo large deformations under impact loading. However, the determination of impact force and associated deflection is not a straightforward task for a non-rigid barrier, as it may require consideration of the P- $\Delta$  effects. For example, the prestressed cable barrier system is a non-linear system that requires an iterative process to determine  $F$  and  $\delta_b$ .

## Comparison between Test Results and Proposed Design Method

Two barriers tested by the U.S. Military are analyzed to determine if the proposed method can reasonably predict the barrier design force. Since all necessary test data is not available, some assumptions are made in the comparison.

### Pipe Barrier

As shown in Figure 3 (page 22), a series of pipes cantilevering from a nearly-rigid base form a barrier to a moving vehicle. The pipes are spaced 4 feet apart. Each pipe is 8 inches in diameter and is filled with concrete. The pipes are extra strong ASTM A501,  $F_y = 36$  ksi. From the American Institute of Steel Construction's (AISC) handbook, the pipe section  $I = 106$  in<sup>4</sup>,  $S = 24.5$  in<sup>3</sup> and plastic modulus  $Z = 33$  in<sup>3</sup>. The colliding car weighing 4,500 pounds ( $m = 139.75$  ft-sec.<sup>2</sup>/lb.) impacts a single pipe barrier at 30 mph (44 ft./sec.). Its bumper height is assumed to be 18 inches. The pipe's

stiffness  $k_b = 3EI = 10^6$  lbs./in. Using Equation 5,  $F = 68$  kips.<sup>3</sup> The pipe starts yielding at  $F_y = 49$  kips when its deflection is 0.042 inch. The pipe becomes fully plastic when  $F$  reaches 56.7 kips. The contribution of concrete in resisting impact is minimal, if at all, and so it is neglected. As the pipe continues to deflect in plastic mode under load, it keeps absorbing energy. When the pipe's deflection (at the point of impact)  $\delta_b = 6.8$  inches, the vehicle would stop and rebound, leaving behind a bent pipe leaning 13.6 inches at the top. Accordingly, the load factor for the pipe is 0.83 – less than unity, which is unsatisfactory. Similarly, the Military's protection rating for the pipe barrier is very poor – 1 on the scale of 0 to 10.

### Wall Barrier

The vehicle used in testing the barrier (Figure 4) weighed 15,000 pounds ( $m = 466$  ft-sec.<sup>2</sup>/lb.). It is assumed to be a commercial truck, such as Ford F-450 with a bumper height of 21 inches. For a rigid barrier, the impact force  $F = 248$  kips. The test wall was reinforced each way, each face and was thus capable of developing yield-lines on both faces and in both directions.

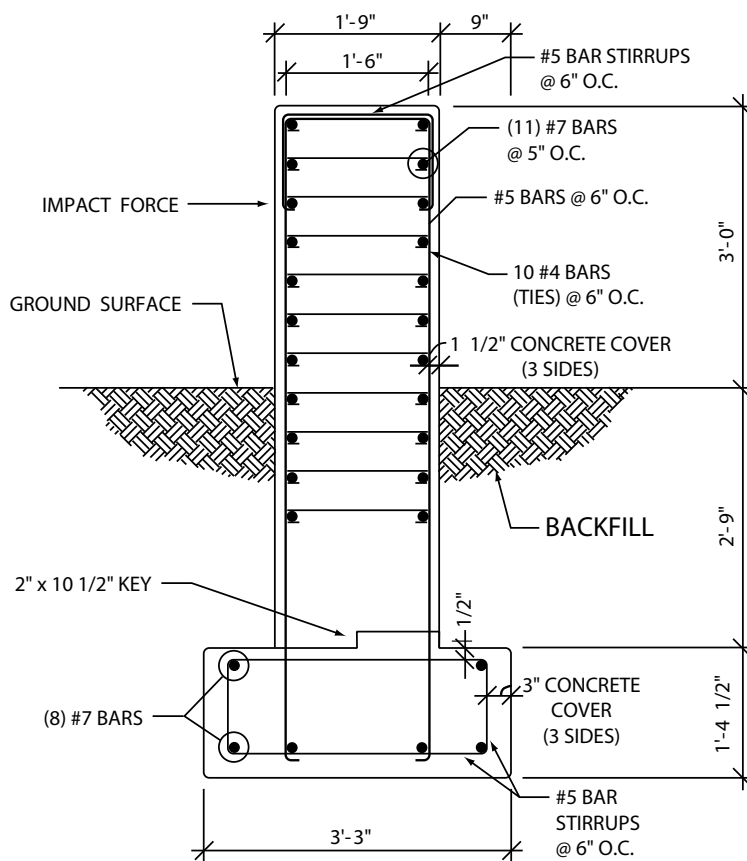


Figure 4: Concrete retaining wall used as barrier for 15,000 lb. vehicle traveling at 30 mph.

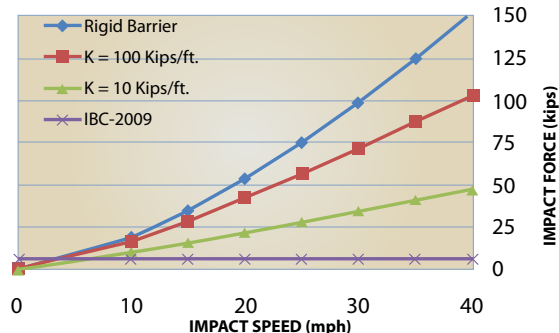


Figure 5: Vehicular Speed – Impact Force plot for a 6,000 lb. vehicle and barrier stiffness,  $k$ .

Assuming a rigid wall, fixed base and impact load spread over 30 inches long line, the wall capacity appears to be adequate at  $\phi F_n = 254$  kips. In addition, since the wall footing is narrow, it is expected to rotate under impact to absorb energy. The analysis shows that the wall will be able to stop the truck speeding at 30 mph; however, it will experience severe cracking and its base will undergo noticeable rotation. The Military's protection rating for the wall barrier is a low 3.6 on the scale of 0 to 10. The comparison of test results with the proposed design method shows that the proposed method is reliable in predicting the impact force.

## Summary and Guidelines

A frontal vehicular impact involves an enormous amount of energy. The magnitude of impact energy imparted to the barrier depends upon vehicular mass, speed and crush characteristics as well as on barrier characteristics. Both IBC and ASCE-7 prescribe a minimum design force that per-

tains to the vehicular speed of approximately 5 mph (Figure 5); they do not provide a rational basis to design a vehicular barrier. It is suggested that the building codes should require the use of energy principles in vehicular barrier design to protect public safety, and that design professionals use the following guidelines:

- 1) Select vehicular speed based on distance and slope available for acceleration, but not less than 10 mph in parking stalls.
- 2) Select vehicular weight based on the ceiling height available, but not less than 6,000 pounds in facilities with ceiling heights of less than 8 feet. When complying with ADA requirements, the vehicular weight should be increased accordingly.
- 3) Incorporate barrier deformation characteristics and load flow to avoid a progressive collapse. ■

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