Designing Edge Barriers in Parking Structures

By Mohammad Iqbal, F. ASCE, D. Sc., P.E., S.E., Esq.

*Figure 1: A car hanging precariously off Chicago Marina City Towers as part of Allstate Insurance ad campaign. Courtesy of **chicagobusiness.com**.*

Numerous motorists have died in recent years as their vehicles hit edge barriers in parking structures, breached them and plunged below (*Figure 1*). The building codes have historically required the vehicle barriers to resist a horizontal static force at a certain height above the floor level, as shown in *Figure 2*. The height pertains to the bumper height and the force roughly equals the weight of a fully loaded vehicle. For example, IBC 2006 prescribes that the vehicle barriers should resist a static force of 6,000 pounds applied at a height of 18 inches above floor. In light of the fact that taller and heavier SUVs and pick-up trucks have become popular in recent years, the IBC 2009 is expected to modify and increase bumper height requirements. Though IBC has moved in the right direction, using a single force to cover all locations may be arbitrary and inadequate to provide safe barriers.

Several types of highway and military barriers are designed to stop vehicles from veering from the roadway. To ascertain that the barriers perform properly when hit by a vehicle, they are pre-tested and certified according to their capacity. However, the barriers in parking structures are neither pre-tested nor certified. They are perceived to be low-risk because parking structures deal mostly with lighter vehicles, such as passenger cars, that move at a relatively slow speed therein. However, recent fatal incidents involving failure of the barriers caused by vehicular impacts have put the design of edge barriers under focus and raised about their inadequacy. The probability exists that the vehicles will hit the barriers head-on, endangering the occupants within and pedestrians below unless the barriers are properly designed.

This article introduces the use of energy principles to design vehicular barriers. It discusses factors affecting the magnitude of impact load under various conditions and outlines framework to formulate a rational design approach for designing vehicle edge barrier in parking structures.

Energy-Based Design Method

The kinetic energy of a moving object can be determined using the well-known equation:

$$K.E. = \frac{mv^2}{2} \qquad \text{Equation 1}$$

The expressions m and v represent the mass and velocity of a moving body, respectively. However, a vehicle crashing into a barrier presents a complex analytical problem. As a vehicle approaches a barrier, it impacts the barrier, as shown in *Figure 3*. The impact lasts a fraction of a second, and then the vehicle retreats or rebounds away from the barrier. The phenomenons are non-linear and complex. As a result of the impact, the vehicle's kinetic energy is consumed by (a) vehicle "crush" and (b) barrier deformation. The impact force on a vehicle barrier can be approximately determined by the equation:

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

Where m = the vehicle mass
v = the vehicle speed at the impact
δ_c = vehicle crush
δ_b = barrier deflection under impact

Equation 2 does not capture the peak force a barrier experiences for a few milliseconds. Rather, it provides an average force during the crush and rebound duration. The following sections discuss factors affecting the impact force.

Impact-causing Vehicle

There are several makes and models of numerous vehicles in the US, and every vehicular type has its unique characteristics. Three attributes of a vehicle that affect the frequency and severity of a potential impact on the barrier are: its curb weight, bumper height and market share. An attribute analysis of 2006 model SUV and pick-up trucks shows that Chevrolet Silverado

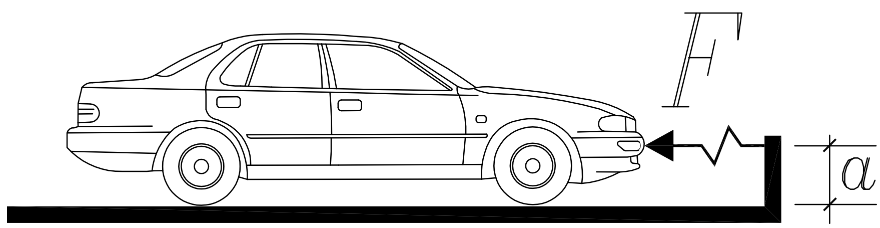

Figure 2: Barrier impact force and its arm above floor.

*Figure 3: A car crash test on a 2009 model vehicle speeding at 35 mph against a rigid barrier. Car crush = 1 ft. 11 inches (576 mm.). Courtesy of **http://nhtsa.gov**.*

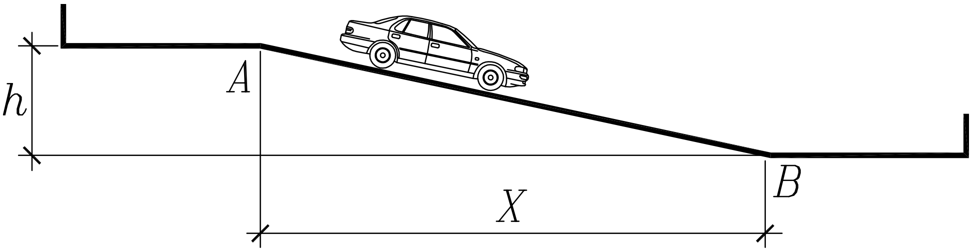

Figure 4: A passenger car rolling down a ramp.

1500 is the most likely vehicle to cause the severest impact. It weighs 5,360 pounds at curb and 6,930 pounds when fully loaded. It has a bumper height of 25 inches and over 10% share of the market. On the other hand, Hummer is the heaviest SUV, weighing 8,800 pounds at curb and 10,300 pounds when fully loaded. Its bumper height is 30 inches, but has low market share of about 1% among SUVs and pick-up trucks. It is suggested that the most popular vehicle be used in the barrier design.

Mass

Once the design vehicle is selected, the determination of vehicular mass for impact purposes needs estimation of probable weight of passengers and luggage it is likely to carry at the time of impact. A conservative approach is to assume that the vehicle is fully loaded. However, the approach may not be realistic because the vehicles that plunged thru the barriers were not fully loaded, but had just one occupant – the driver – in them. A 500 pound allowance for the weight of one occupant, gasoline and luggage seems reasonable. Therefore, the design weight for the Silverado would be 5,860 pounds It is suggested the design weight of 6,000 pounds be used in barrier design.

Speed

The most significant parameter affecting the impact force is the vehicle speed at the time of impact. The speed a vehicle can gain in a parking structure depends on the approach distance the vehicle has to accelerate. This article focuses on a driver's loss of his vehicle control when rolling down a ramp, as shown in *Figure 4*. Other situations where a driver may intentionally and recklessly accelerate his car are outside the scope of this analysis. As a vehicle rolls down the ramp, its potential energy is converted into kinetic energy. The speed gain depends on the slope and length of the ramp. Assuming the vehicle is in a stationary condition at the top of the ramp (point A) and that it moves down on its own, its speed at the bottom of ramp (point B) can be determined by the following equation:

$$m.g.h = \frac{m.v^2}{2} + \mu.m.g.s \qquad \text{Equation 3}$$

After some algebra, speed at the bottom of ramp is given by:

$$v = \sqrt{2.g.(h - \mu.s)} \qquad \text{Equation 4}$$

Where μ = co-efficient of rolling friction between the driving surface and vehicle tires.
s = length of the sloping ramp
h = ramp height

It is noteworthy that the car speed *v* is independent of its mass. The friction factor μ may vary depending on the driveway and the tires, but can be taken as 0.017 assuming a concrete surface and radial tires. See the design example later in this article to compute the vehicle speed *v*. ("*Motor Vehicle Accident Reconstruction and Cause Analysis*", Limpert, 1999)

continued on next page

Barrier Deflection

During the impact a part of vehicle's kinetic energy is transferred to, or is consumed in, deflecting the barrier. Some barrier systems absorb energy as elastic strain and distributing it to the parking structure, while others may rely on local yield mechanisms. The impact force depends on the type of barrier. The rigid barriers experience the severest impact force. The most popular types of barriers used in parking structures are:

- Cast-in-place concrete cantilever walls
- Post-tensioned concrete upturn beams
- Precast concrete spandrel beams acting at barrier walls
- Multi-strand steel cables
- Steel members and rails

Every barrier has its unique characteristics. In general, steel barriers are ductile. The steel guards employing various steel shapes are considered very desirable, as they can be readily designed to deflect and yield under load. Similarly, barrier cables exhibit flexibility and offer considerable deflection, δ_b. On the other hand, concrete walls and precast spandrels generally are neither detailed to have ductility nor expected to have ductility. The cast-in-place and post-tensioned concrete upturn beams are quite rigid when connected to columns and braced by a diaphragm. They exhibit negligible δ_b. For non-rigid barriers, δ_b can be readily determined using an iterative process.

Vehicle Crush and Rebound

When a vehicle hits a barrier, parts of the vehicle deform, bend or crush and the vehicle length decreases, as shown in *Figure 3 (page 24)*. The decrease in vehicle length after an impact is termed "car crush" and is denoted as δ_c in *Equation 2 (page 24)*. After impacting into a barrier, the vehicle rebounds and moves away from the barrier and stops. The National Highway Traffic Safety Administration (NHTSA) has tested thousands of vehicles to determine vehicle crash-worthiness. The target vehicle speed in the tests has been 35 mph. While most of the test data is not relevant to the barrier design, some is useful. A limited survey of the test results shows that, for rigid barriers, the car crush distance δ_c ranges from 1.1 feet (0.32 meters) to 2.2 feet (0.66 meters) at the impact speed of 35 mph. Assuming a second-degree relationship between car crush and impact speed, δ_c can be approximated by the following equation:

$$\delta_c = \frac{\sqrt{v}}{3}\ \text{(ft)} \qquad \text{Equation 5}$$

Where v is car speed in miles per hour. By substituting the values of δ_c into *Equation 2 (page 24)*, an impact force-velocity graph can be obtained as a design aid *Figure 5*. The IBC-prescribed force of 6,000 lbs. for edge barrier design is considerably smaller than that predicted by the energy principles as shown in *Figure 5*. Therefore, it is suggested that the code requirements should be revised to reflect the anticipated force levels using energy principles.

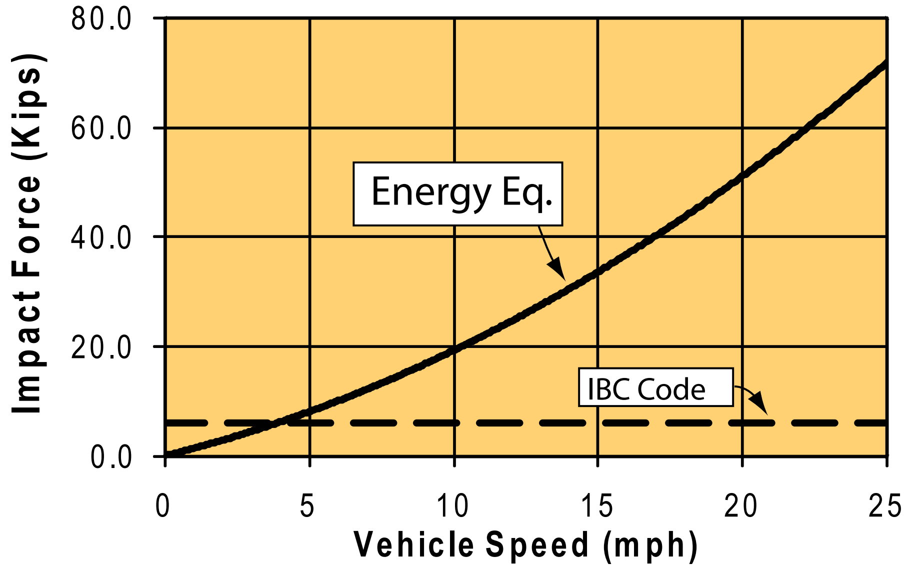

Figure 5: Impact force on a rigid barrier. Impacting vehicle weight = 6,000 lbs.

Design Example

Consider a 6,000 pound vehicle rolling down a ramp and crashing into a rigid barrier, as shown in *Figure 4 (page 25)*.

Ramp length, X = 200 feet

Story height, H = 10 feet

Coefficient of friction, $\mu = 0.017$

Assuming the car starts rolling down from point A and using *Equation 4 (page 25)*, Velocity v at B = 14.3 mph.

For rigid barriers, $\delta_b = 0$. There are two ways to determine the impact force:

Using *Equation 5*, $\delta_c = 1.26$ feet. Substituting the δ_c value in *Equation 2 (page 24)*, the force F= 31,500 pounds. Alternately, use the force-velocity graph in *Figure 5* to compute the force.

Summary

A vehicular impact at edge barriers in a parking structure involves an enormous amount of energy that needs to be absorbed by the barrier and the vehicle. The magnitude of impact energy depends upon vehicular mass and speed as well as on barrier characteristics, as illustrated by the force-velocity relationship shown in *Figure 5*. Therefore, the present IBC approach to use one force level to design barriers sited along various locations in or along the perimeter of a parking structure is improper and inadequate. In order to eliminate or curtail fatalities caused by the barrier failures, the building codes should incorporate the energy principles in edge barriers design requirements. A minimum speed of 10 mph and vehicular weight of 6,000 pounds are recommended in design. At locations in a parking structure where vehicles can gain greater speed, such as on down ramps, anticipated vehicular speed should be calculated and the barrier force requirements should be increased accordingly.▪

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