ATTACHMENT E

Hazard Penetration Considerations

N C H R P
22-12(3)
RECOMMENDED GUIDELINES FOR THE SELECTION OF TEST LEVELS 2 THROUGH 5 BRIDGE RAILINGS

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Introduction

RSAPv3 includes three general types of hazards:

1. Point hazards,
2. Line hazards and
3. Area hazards.

Point hazards are generally items like signs, trees utility poles and other roadside features that can be reasonably approximated as a point in space. Line hazards are those that can be approximated by a line including longitudinal barriers (i.e., guardrails, bridge railings, median barriers, etc.) and some special features like the edge-of-clearzone, edge-of-median and water hazards, and tree-lines. Area hazards are generally related to terrain features like slopes and ditches. Each type of hazard "performs" in particular ways. For example, a point hazard can either breakaway or not breakaway. Determining if breakaway occurs or not is simply a matter of comparing the kinetic energy of the simulated collision with the maximum strain energy of the point hazard. Thus, a 2000-lb vehicle striking a pole at 30 mi/hr has 60 ft-kips of kinetic energy. If the size of the pole indicates it has less than 60 ft-kips of strain energy capacity the pole will breakaway and if it has more than 60 ft-kips of capacity it will not breakaway.

The line hazards present a more complicated situation. A typical longitudinal barrier can result in one of five types of performance:

1. Redirection,
2. Redirection with rollover (i.e., the vehicle rolls over on the traffic side of the barrier),
3. Penetration (i.e., the vehicle goes through the barrier causing structural failure of the barrier),
4. Rollover barrier (i.e., the vehicle rolls over the barrier and lands on the non-traffic side) or
5. Vaulting (i.e., the vehicle is vaulted into the air and over the barrier and lands on the non-traffic side).

Accounting for each of these five possible performance types is important because each is associated with a different severity. Redirection, for example, is the preferred barrier performance outcome whereas the others are considered failures according to Report 350 and MASH because they are associated with higher severity crashes. If a vehicle penetrates a bridge railing, for example, it may land on a roadway below. Rollover and vaulting are often associated with vehicle occupant ejection which is always more hazardous than when the occupant is retained in the vehicle. Estimating which type of performance a line hazard results in for a particular set of impact conditions is, therefore, an important part of the RSAP severity model.

The type of barrier performance is obviously dependent on the impact conditions of the encroaching vehicle. A variety of approaches have been used in past roadside safety cost-benefit. BCAP, a program developed to do benefit-cost in the selection of bridge railings in the 1980's, used a mechanistic approach to predict penetration and rollover in truck crashes; the ABC program, an updated version of BCAP, introduced improved equations for penetration and rollover; the earlier versions of RSAP used the impact severity (IS) to help predict penetrations. In all of these cases, a simple equation for predicting rollover or penetration was used and compared to some critical value. There are two main difficulties with this mechanistic approach: (1) Vehicle dynamics are complicated and not easily reduced to one simple equation and (2) The capacity of barrier is typically not known since tests to failure are seldom performed. For these reasons mechanistic methods have not worked particularly well.

Objectives

The objectives of this task were to review the various historical methods for predicting penetration of features and to develop a new method for predicting penetration based on a probability of penetration approach using observable crash data. The following literature review section of this report discusses the strengths and weaknesses of the various mechanistic and probabilistic approaches. Then, a new methodology for predicting penetration of features is discussed which is based on a combined mechanistic-probabilistic approach.

Literature Review

Mechanistic Methods

Barrier Penetration

BCAP was a cost-benefit program that was developed to aid in the selection of bridge railings. BCAP was the basis for the guidelines published in the 1989 AASHTO Guide Specification for Bridge Railings (GSBR). [AASHTO89] BCAP estimates the force imposed on the bridge railing by each simulated collision using the estimated speed, angle and mass of the encroaching vehicle. This force estimate is then compared to the assumed capacity of the bridge railing. If the capacity is less than the impact force, the bridge rail is assumed to be completely penetrated and the vehicle is assumed to fall off the bridge. If the impact force is less than the capacity, redirection is assumed and the vehicle conditions are checked to see if rollover is likely.

The penetration model in BCAP is based on work by Olsen in NCHRP Report 149. [Olsen74] Olsen suggested that the lateral force imparted by the vehicle to the barrier could be approximated as:

$$F_{lat} = \frac{W\,V^2\,sin^2\theta}{2g(A\ \sin\theta - \frac{B}{2}(1-\cos\theta) + D)}$$

Where:

F_{lat} = The average lateral deceleration of the vehicle,
W = The weight of the vehicle in lbs,
V = The vehicle impact velocity in ft/sec,
Θ = The impact angle,
A = The distance from the front of the vehicle to the center of mass in ft,
B = Vehicle width in feet and
D = Lateral deflection of the barrier in feet.

BCAP randomly generates a set of encroachment conditions (i.e., speed, angle and vehicle type) and the lateral force can then be calculated based on those assumed impact conditions. If the lateral impact force is greater than the capacity of a barrier, the barrier is assumed to have failed structurally.

While Olsen's model is a good simple estimator it certainly has its limits. First, it is based on estimating the impact force but damage and failure is more properly related to strain energy. Unfortunately, while impact energy is easy to calculate (i.e., ½ mv^2), the strain energy capacity of a barrier is quite difficult to calculate at least in some simplified general form. Also, in developing the 1989 GSBR recommendations, it was assumed that the barrier deflection would always be zero (i.e., the D term in the equation above) but for longitudinal barriers in general, the deflection is also a function of the impact conditions. This is probably reasonable for rigid concrete barriers but it has the effect of under estimating the capacity of post-and-beam types of bridge railings and would under estimate the force for most types of guardrails. Another flaw with this penetration model, at least with respect to its use in BCAP, is that once capacity has been reached it is assumed the barrier is totally compromised when in fact the capacity load is really just the beginning of the failure process. The barrier may often contain and redirect the vehicle even though there are structural failures; in other words, reaching capacity does not necessarily mean the vehicle will penetrate the barrier.

NCHRP Project 22-08 was initiated in order to assess BCAP and validate the 1989 AASHTO GSBR recommendations. [Mak94] Unfortunately, Mak and Sicking, the principal investigators for NCHRP 22-08, found some serious short comings of BCAP itself and the assumptions that were built into the selection tables. Mak and Sicking found that BCAP seriously over predicted bridge railing penetrations and seriously under predicted rollovers; the opposite of what would normally be expected. Based on crash test experience and anecdotal information, most bridge railings "fail" due to a heavy vehicle rolling over the barrier rather than penetrating after a structural failure so the BCAP results were counter intuitive. When a series of baseline simulations were performed with BCAP mimicking the GSBR recommendations, the researchers found that BCAP predicted 32.7 percent of tractor-trailer trucks striking a PL-2 bridge railing would penetrate the bridge railing yet there were no predictions or rollover even though the center of gravity of a typical tractor trailer truck is 64 inches and the typical PL-2 barrier height was 32 inches (i.e., the c.g. of the vehicle is 32 inches higher than the top of the barrier). [Mak94] Mak and Sicking discovered several reasons for this. One reason was the algorithm used to predict rollovers resulted in unreasonably high critical

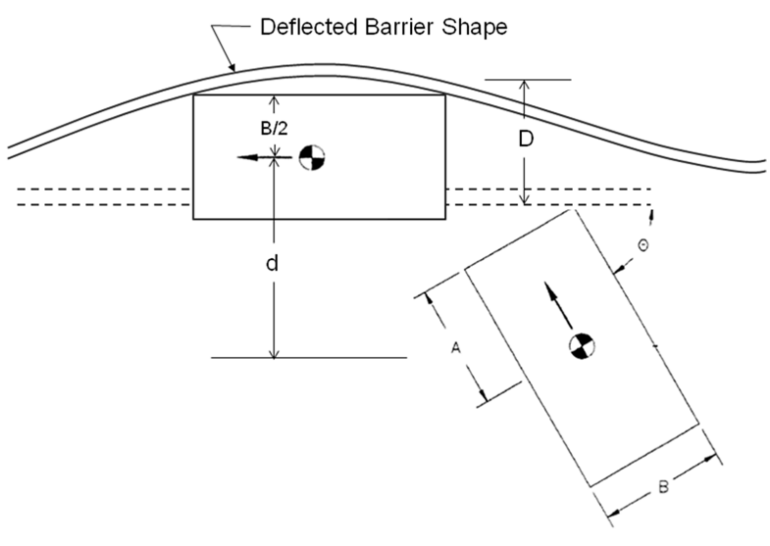

Figure 1. Vehicle and barrier geometry for calculating the average impact force according to Olsen. [Mak93]

velocities. A new rollover algorithm was proposed and implemented as will be discussed in the next section.

Another reason involved barrier capacity. BCAP estimates the forces on the barrier using the Olsen equation shown above. The equation is a simple derivation of the force based on the overall mechanics of the impact. The force in Olsen's equation is actually the *average* lateral force required to arrest (or redirect) the lateral component of kinetic energy of the vehicle during redirection and can be derived based on the energy balance equation:

$$F * d = \frac{1}{2} m v^2$$

Where in Olsen's equation the lateral component of kinetic energy is given as,

$$\frac{1}{2} m v^2 = \frac{1}{2} \frac{W}{g} (V sin\theta)^2$$

Olsen's derivation neglects frictional forces (e.g., friction between the vehicle and barrier and friction between the vehicle tires and ground) and plastic deformation of both the vehicle and barrier; thus all energy change is done through forces acting normal to the face of the barrier. The term *d* in Olsen's equation is the distance through which this force moves to absorb/transform the kinetic energy. It is assumed that the vehicle rotates about the center of gravity (c.g.) of the vehicle; thus, *d* is the total distance that the c.g. moves toward the barrier during redirection (i.e., from time of impact until the vehicle has become parallel to the barrier). Thus, *d* is defined as:

$$d = \left[A \sin\theta + \frac{B}{2} cos(\theta)\right] - \frac{B}{2} + D$$

where, as shown in Figure 1:

- $\left[A \sin\theta + \frac{B}{2} cos(\theta)\right]$ is the lateral distance from the c.g. of the vehicle to the face of the barrier
- $\frac{B}{2}$ is the width of the vehicle and
- D is the deflection of the barrier

After the impact force imparted by the vehicle is calculated, it is compared to the assumed bridge rail capacity. If the impact force is greater than the capacity, the bridge rail is considered failed. Estimating the actual capacity of bridge railings is more difficult than it might first seem. Materials are routinely assumed to be less strong and loads are routinely over estimated in design so even if the theoretical capacity is calculated it is likely a conservative value. For example, in designing concrete structures a resistance factor 0.85 is usually used for bending which essentially takes advantage of only 85 percent of the strength of concrete. Likewise, if an allowable stress design method for steel were used, 67 percent of the strength of the steel is assumed. In both cases, the designer is neglecting a significant portion of the capacity of the structure. While this makes excellent design sense, it makes it difficult to estimate the real failure conditions of the structure. BCAP assumed that PL-1 bridge railings have a capacity of 15 kips, PL-2 railings have 35 kips and PL-3 railings have 55 kips. While there are relatively few crash tests where structural failure of the bridge railing was observed, Mak and Sicking were able to find some cases where the bridge railing experience some degree of structural failure (i.e., hairline cracking, spalling, etc.). When they compared the limited crash test results to the BCAP assumptions they found that the BCAP assumptions were about half what could be supported by crash tests as shown in Table 1.

Table 1. Bridge railing capacity recommendations in BCAP and NCHRP 22-08.[after Mak94]

Performance Level	**BCAP Assumption** (kips)	**Mak/Sicking Recommendation** (kips)
PL-1	15	30
PL-2	35	64
PL-3	55	108

Adding to the difficulty is the basic assumption in BCAP that when capacity is reached, the bridge railing will totally fail and allow the vehicle to penetrate. In fact, this does not generally happen. Bridge railings can experience structural failure and sometimes will still redirect the vehicle. The failure may be cracks or spalls that, while considered serious structural damage, do not result in complete loss of structural capacity. .

Recently, Alberson and others evaluated a 32-inch high PL-2 concrete safety shaped barrier that had experienced structural failure problems in the field as shown in Figure 2. [Alberson11; Alberson04] A yield-line structural analysis was performed on the bridge railing which resulted in an estimate of the barrier capacity of 33.6 kips when loaded near a construction joint and 47.7 kips when loaded at the mid-span. The same design was then constructed and statically tested to failure resulting in a near-the-joint capacity of 35.1 kips and a mid-span capacity of 45.1 kips. The bridge railing was also subjected to full-scale Report 350 TL-4 crash tests which were passed successfully and which caused relatively minor concrete damage (e.g., hairline cracks and some gouging). As shown by Alberson's research, the capacity values suggested by the 1989 AASHTO GSBR were grossly over conservative and those proposed by Mak and Sicking were much more appropriate although it should be noted that this particular railing was chosen for investigation precisely because there had been some observed field structural failures so this particular railing probably represents the lower end of the capacity of PL-2 railings.

Figure 2. Damage to a 32" concrete bridge railing in a crash with a single unit truck in Florida. [Alberson04]

Since BCAP first assesses the capacity and then the rollover potential, the overly conservative values for capacity tended to over predict penetrations. Since the higher velocity truck impacts would tend to reach the capacity too early and the rollover algorithm was over conservative, penetrations were over predicted and rollovers under predicted.

Mak and Sicking revised the rollover algorithm (discussed in the next section) and adjusted the bridge railing capacities upward as shown in Table 1 and re-ran their analysis. In the initial BCAP runs, 32.7 percent of tractor trailer truck crashes penetrated the railing and none rolled over whereas after the improvements implemented by Mak and Sicking were made 1.2 percent penetrated and 8.9 rolled over which seemed more reasonable.

Mak and Sicking also evaluated bridge railing crash data from Texas to determine field-based penetration and rollover rates. [Mak94] Mak and Sicking found that the Texas data indicated that 2.2 percent of bridge railing crashes result in the vehicle going through (i.e., penetration) or over (i.e., roll over the barrier) and they believed that even this value was a high-side estimate due to coding errors on the police crash reports. The improved BCAP with the higher capacity limits and improved rollover algorithm resulted in an overall estimate of 10 percent going through (i.e., 1.2 percent penetrating and 8.9 percent rolling over) for the typical Texas conditions so even the improved BCAP appeared to over predict penetrations/rollover by an order of magnitude although the proportion of penetrations to rollovers appears much more reasonable.

In summary, then, BCAP and the 1989 AASHTO GSBR appear to greatly over predict bridge railing penetrations and under predict rollovers. The improvements from NCHRP 22-08 appeared to improve the results considerably although even the improved BCAP over predicts the incidence of vehicles going through or over the bridge railing.

RSAP versions 2.0.3 and before include two sets of procedures to deal with vehicle penetration of features and rollover after hitting features. For example, RSAP 2.0.3 first identifies whether an impacting vehicle would be likely to penetrate the first-struck hazard. For point hazards like breakaway objects, such as trees, wooden utility poles, and breakaway supports (i.e., Type 5 Fixed Objects Features in RSAP 2.0.3), the penetration is predicted if the impacting vehicle is above a threshold value of kinetic energy calculated as:

$$KE = \frac{1}{2}\, m\, V^2$$

where

KE = Kinetic energy of impacting vehicle (joules=kg*(m/s)^2)
m = Mass of impacting vehicles (kg)
V = Impact speed (m/s)

Similarly, longitudinal barriers (RSAP Type 7 Features) are predicted to be penetrated when the impact severity (IS) of an impact is higher than the containment limit for the barrier test level. The IS value is calculated as:

$$IS = \frac{1}{2}\, m\, (V \sin\theta)^2$$

where

IS = Impact severity
m = Mass of impacting vehicles (kg)
V = Impact speed (m/s)
θ = Impact angle (deg)

If feature penetration is predicted, RSAP calculates the energy gained or lost in impacts with roadside features that are penetrated. For roadside features other than side-slopes, the energy associated with the capacity or containment limit of the feature is subtracted from the vehicle's initial kinetic energy (or its lateral component in the case of a guardrail). A new speed for the vehicle is then calculated on the basis of the remaining energy and this new speed is used for the next impact. A roadside slope, provided it is not very steep, would not be expected to affect the vehicle's kinetic energy appreciably; however, the resultant rise or drop in the vehicle's center of gravity during slope traversal would affect the vehicle's potential energy. Thus, the potential energy associated with traversing a roadside slope is added (or subtracted if going uphill) from the initial kinetic energy of the vehicle to determine a new speed for the next impact. Further, RSAP 2.0.3 estimates the crash severity of the first feature struck as well as any subsequent features in the vehicle's path. The highest severity of any feature in the vehicle's path is then utilized in the calculation of crash cost.

Several recent research projects are revisiting the question of barrier capacity. Alberson's work on a 32-inch New Jersey safety shaped bridge railing has already been discussed earlier. Bligh is currently doing work on quantifying the impact forces on TL-4 and TL-5 barriers as a part of NCHRP 22-20(2). Ray is currently compiling barrier strength calculations as well as crash test data for several common closed-profile concrete bridge rails for use in establishing a relationship between theoretical barrier capacity and probability of penetration as part of NCHRP 22-12(3). [Ray, 2011].

Preliminary information from Bligh's study, regarding MASH TL-4 impacts, is shown in Figures 3 – 7 and in Table 2. Impact force values were derived using the 50-milisecond average accelerations collected from vehicle-mounted accelerometers in full-scale crash tests on concrete safety shapes of different heights. Interestingly, the initial impact (i.e., front of the SUT) does not seem to be greatly affected by the barrier height but the second impact (i.e., rear "tail slap") is strongly affected; the 42-inch high safety shape has a second impact force that is 25 percent higher than the 36-inch tall safety shape because there is less roll of the vehicle which directs more of the force to the barrier. Bligh has also performed some recent MASH TL-5 tests on different barrier heights with similar interesting results as shown in

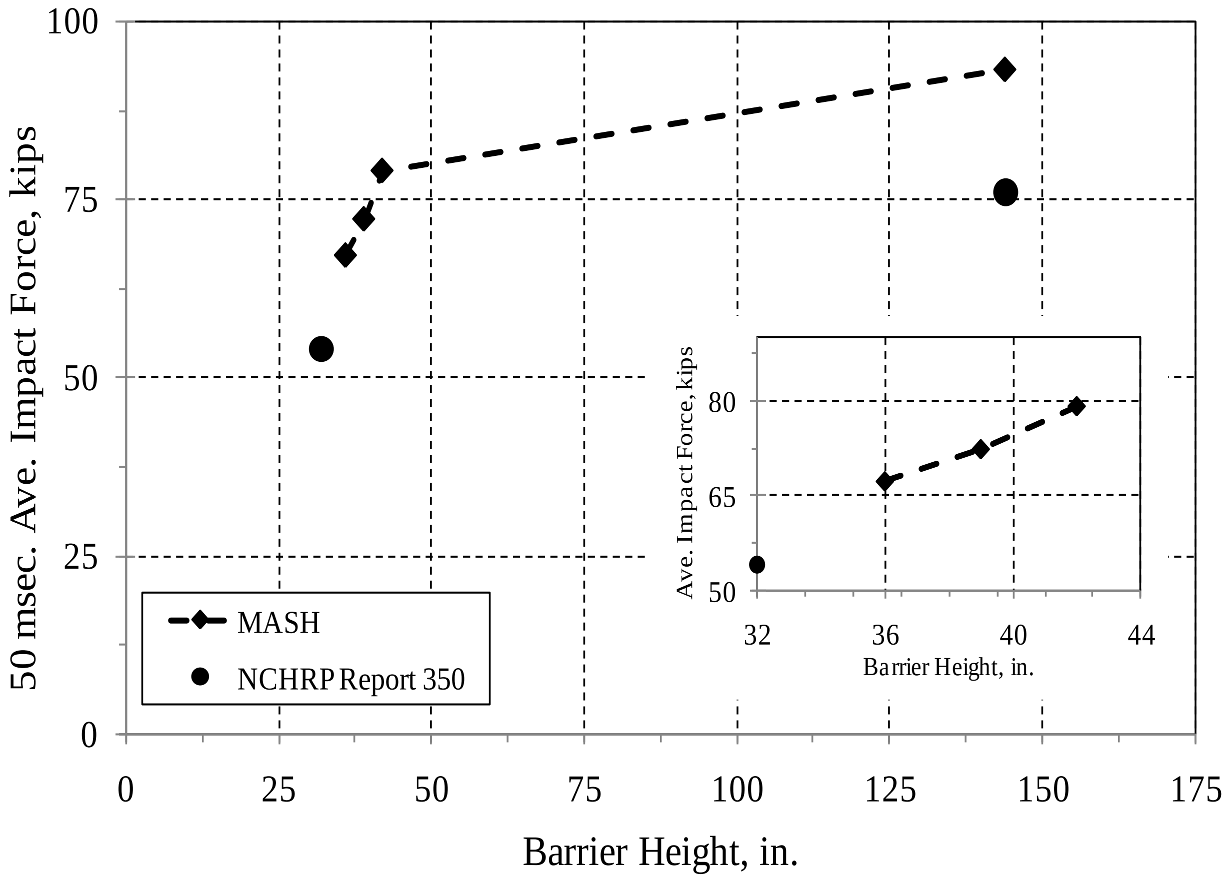

Figure 7: Variation of maximum TL-4 impact force for different barrier heights [Bligh, 2011]

Table **3** and Figure 8. These barrier resistance forces were calculated based on FE simulations compared to the results of crash tests.

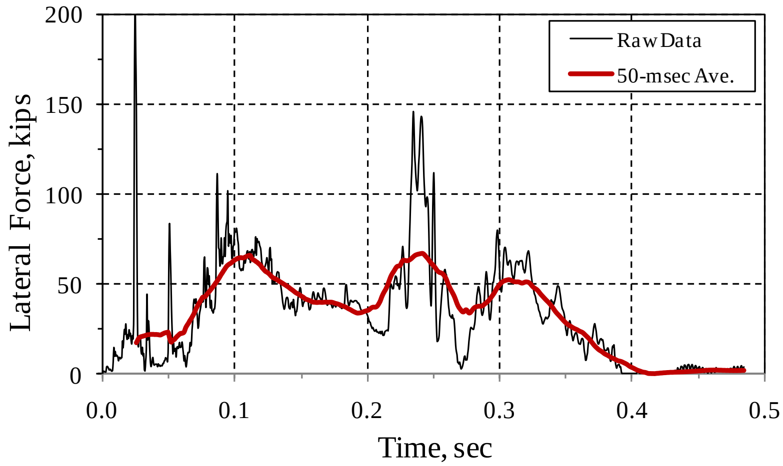

Figure 3. Raw Data and 50 msec. Impact force on the 36 in. (0.91 m) Tall Barrier. [Bligh11]

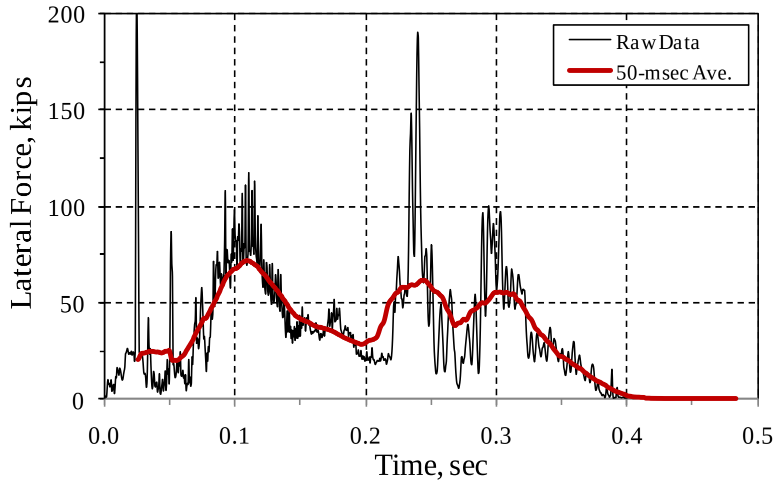

Figure 4. Raw Data and 50 msec. Impact force on the 39 in. (0.99 m) Barrier High. [Bligh11]

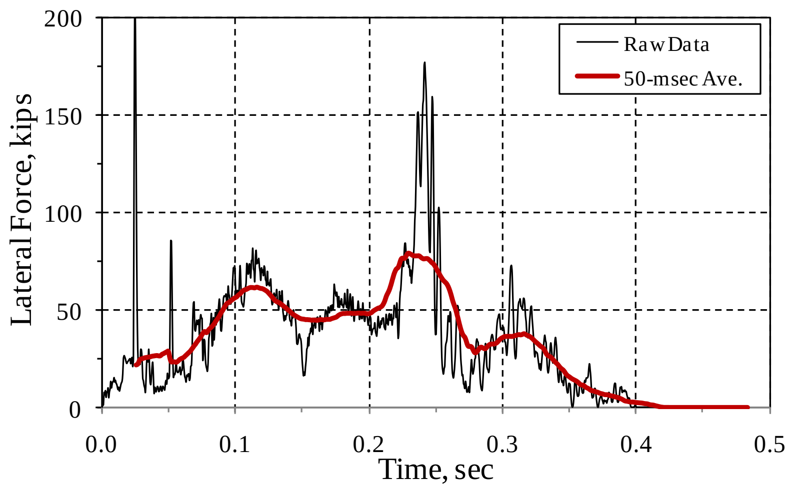

Figure 5. Raw Data and 50 msec. Impact force on the 42 in. (1.07 m) Barrier High. [Bligh11]

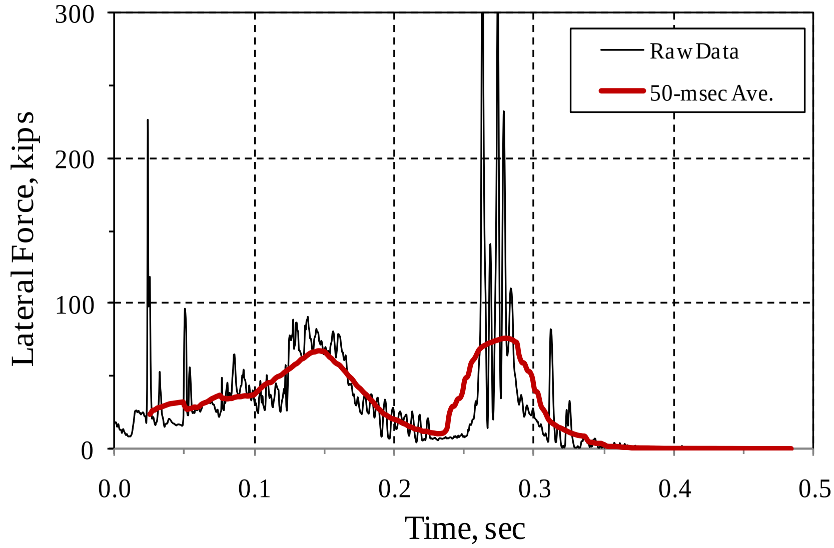

Figure 6. Raw Data and 50 msec. Impact force on a Tall Vertical Wall. [Bligh11]

Table 2. MASH TL-4 SUT Test Impact Forces of Concrete Safety Shapes of Different Heights. [Bligh11]

	50 msec Average Impact Force	
Bridge Rail Height (inches)	1st Impact	2nd Impact
36	67	65
39	72	64
42	62	79
200 (i.e., tall wall)	92	93

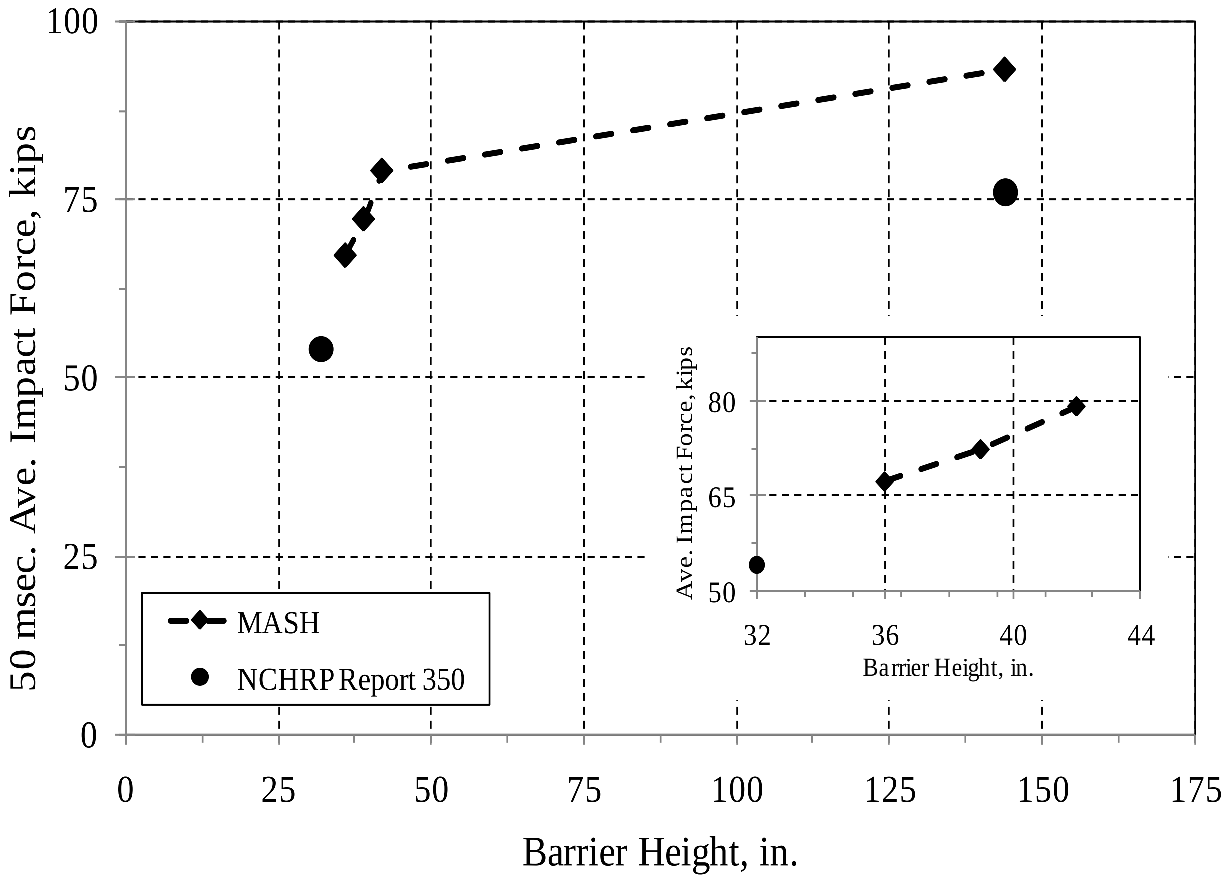

Figure 7: Variation of maximum TL-4 impact force for different barrier heights [Bligh, 2011]

Table 3. MASH TL-5 Tractor Trailer Test Impact Forces for Concrete Safety Shapes of Different Heights. [Bligh11]

	50 msec Average Impact Force		
Bridge Rail Height (inches)	1st Impact	2nd Impact	3rd Impact
42	50	105	95
48	50	250	230
54	50	250	275
200 (i.e., tall wall)	50	280	450

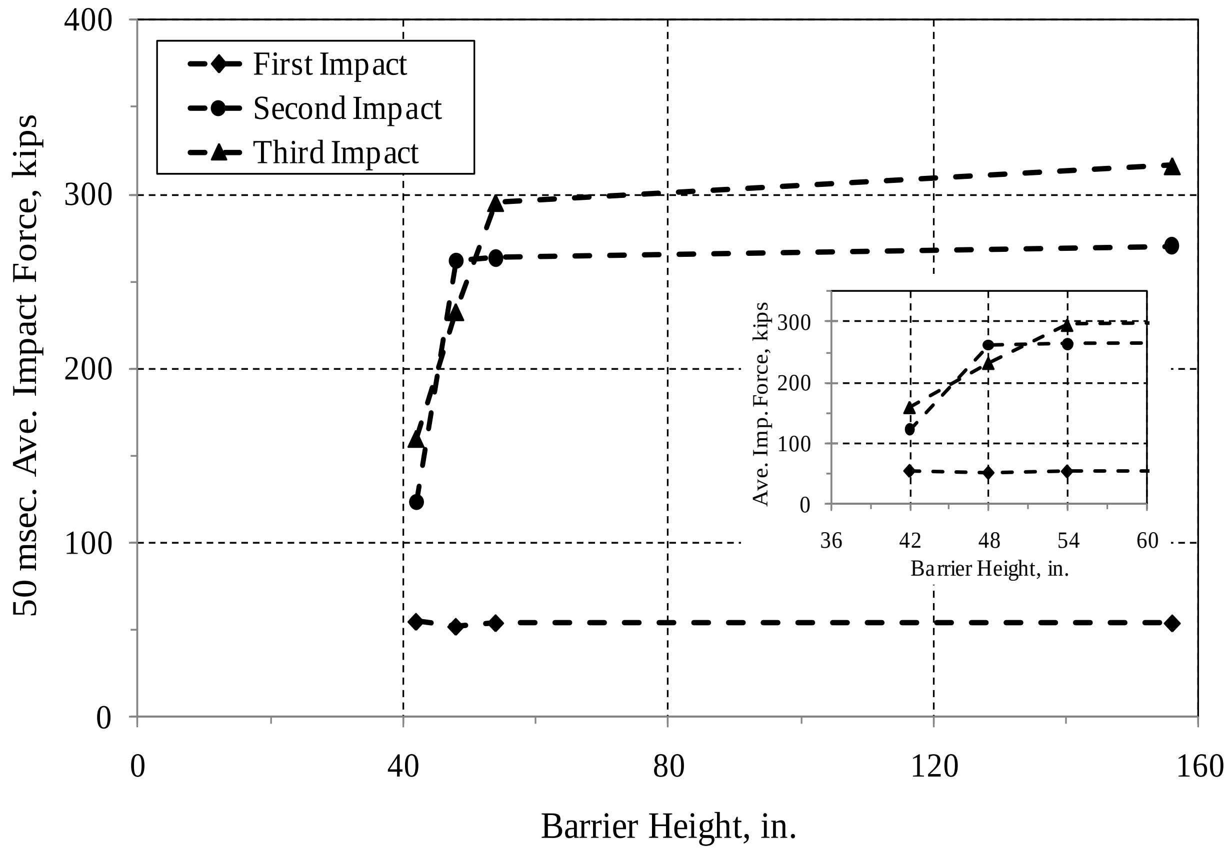

Figure 8: Variation of TL-5 lateral impact force for different barrier heights [Bligh, 2011]

Rollover and Vaulting

BCAP also included a rollover algorithm to predict if trucks would roll over the bridge railings. The rollover algorithm only is activated if the bridge railing is not penetrated. BCAP first checks to see if the penetration capacity has been reached. If capacity has been exceeded, the vehicle penetrates the railing. If capacity has not been exceeded, the vehicle is assumed to be redirected and the rollover algorithm is checked. The rollover condition in the original BCAP is:

$$V_{cr} = \frac{\sqrt{\frac{g}{2}\left[\frac{5B^2}{4}+\frac{H_{cg}^2}{144}+\frac{(H_{cg}-H_b)^2}{36}\right]\left[\sqrt{\frac{B^2}{4}+\frac{(H_{cg}-H_b)^2}{144}}-\frac{(H_{cg}-H_b)}{12}\right]}}{\frac{(H_{cg}-H_b)\sin\theta}{12}}$$

Where:

V_{cr}= The velocity in ft/sec that the vehicle would rollover,
g = The acceleration due to gravity (i.e., 32.2 ft/s^2),
H_{cg} = The height of the vehicle center of gravity in ft,
H_b = The height of the barrier in feet and
Θ = The impact angle.

This formulation assumes that the vehicle forces act at the center of gravity of the vehicle and that the barrier forces act at the very top of the barrier.

Mak and Sicking also reviewed the rollover algorithm in project 22-08. They found that this equation yields critical velocity estimates that are much too high so BCAP seldom predicted a rollover. Mak and Sicking modified the model by assuming the barrier forces act at the vehicle axle rather than top of the barrier and that the truck would rotate about the top of the barrier when the truck deck settled onto it during the rollover. The improved impulse-momentum model is given by:

$$V_{cr} = \frac{\sqrt{\frac{2g}{12}[(d+H_b-H_{cg})]}}{R\sin\theta}\left[\frac{H_{cg}-H_b}{12}+\frac{12R^2}{(H_{cg}-H_f}\right]$$

Where the terms are as defined before with the addition of:

d = Distance from the vehicle c.g. to the bottom edge of the truck frame in inches,
H_f = Height of the center of the truck axle in inches,
R =The radius of gyration of the truck and its load about the bottom corner of the truck frame.

This model was validated to some extent with HVOSM and NARD and resulted in lower critical velocities and more rollovers in the BCAP analyses which was the objective. As discussed earlier, the improved rollover algorithm and adjustments to the barrier capacity performed by Mak and Sicking greatly improved the estimates of BCAP but BCAP still predicted more crashes than comparison to the real-world data available at the time indicated.

Both of these rollover models completely ignore the effect of barrier shape on vaulting over the barrier and rollover on the traffic side of the barrier by vehicles with c.g. heights lower than the barrier height. For example, many passenger cars vault or rollover safety shaped barriers even though the height of the passenger car c.g. is lower than the barrier height. The reason is that the shape of the barrier in some shallow angle impacts has the effect of launching the vehicle over the barrier. This is not accounted for in either model.

Some types of roadside features, such as longitudinal barriers, could cause impacting vehicles to rollover, which has a higher severity than a redirection-impact. Since the actual mechanisms involved in rollovers are not well understood, RSAP 2.0.3 incorporates two simple rollover algorithms to identify impact conditions under which a vehicle is likely to rollover in front of (i.e., on the traffic side of) a barrier and rollover the top of a barrier. The rollover routines incorporate simplified impulse and momentum calculations and are primarily intended to be accurate for analyzing heavy truck impacts. These rollover equations have been inherited from the NCHRP 22-08 project that developed improved impulse momentum equations for BCAP. The key truck and impact parameters used in the "roll in front of the barrier" algorithm are the truck's center of gravity height and width, barrier mounting height and impact angle. For the "roll over the top of the barrier" algorithm, additional parameters are used including distance from vehicle center of gravity location to the extreme bottom corner of truck frame, height of truck axle center, and the radius of gyration of truck and load about the bottom corner of truck frame. Higher severities are assigned to rollover impacts than non-rollover impacts.

Rollover of heavy trucks when hitting longitudinal barriers is the only rollover event currently considered by RSAP 2.0.3. These rollovers involving longitudinal barriers are part of the rollovers initiated by hitting fixed- and non-fixed objects, which represent a relatively small fraction (less than 14 percent) of total rollover cases on high speed roadways (i.e., roadways with posted speed limits $\geq$ 45 mph). Other types of rollovers not considered by RSAP 2.0.3 include those initiated by "soft soil" (68 percent) and slope of ditches and embankments (13 percent). [Miaou04] It is suggested in RSAP Engineer's Manual that this deficiency of RSAP could be mitigated by users through some adjustments of the impact speed-SI relationships to reflect the probability of injury due to rollovers. Since rollover crashes tend to be much more severe than other types of crashes, especially for those crashes involving unbelted occupants, they should be given a high priority in updating the impact-severity relationships for RSAP.

Statistical Methods

The methods discussed in the previous sections were mechanistic in that they used some simplified version of the equations of motion of the vehicle and the law of energy conservation to estimate the forces on barrier and vehicle. While mechanistic methods have the advantage that they are grounded in the physics of the problem, getting a simple closed-form solution usually involves making many broad assumptions about the impact which may or may not be correct. Very accurate predictions about vehicle dynamics can be obtained using finite element analysis or vehicle dynamics analysis but these require extensive input and long runtimes to develop an answer which would not be feasible in the context of RSAP where tens of thousands of simulated encroachments are needed. Simple one-equation models like those used in BCAP and RSAP 2.0.3 simply are not adequate to capture the full range of vehicle dynamics.

An alternative approach is to use the statistics of real-world crashes. The advantage is that a complete understanding of the physics of the problem is not required since the data represents the real events. The disadvantage is that such methods require that there be crash data available in sufficient quantities to develop meaningful statistical models. The following sections discuss statistical methods of predicting penetration and rollover.

Barrier Penetration

Penetration can also be observed in the field and, depending on the form of the police reports, can sometimes be deduced from the police-level crash data. One particular example where there is a fairly large amount of data on the barrier performance is low-tension cable median barriers. Several states have reported the effectiveness of cable median barriers in terms of the percentage of crashes that were contained by the barrier. If the barrier prevented the vehicle from crossing to the opposing lanes of traffic, then it was considered to be effective in containing the vehicle. Some of the data in Table 4 represents fairly limited data collection, but several of the states have been collecting cable median barrier crash data for nearly a decade and have collected over 400 cases. In general, it appears that the vehicle is prevented from crossing over into the opposing lanes of traffic in about 95 percent of the cases (i.e., about 5 percent penetrations assuming that rollover on a cable barrier is unlikely). The states listed in Table 4 have all used cable median barriers and studied their effectiveness. In all cases, with the exception of Utah, it was found that less than seven percent of police reported crashes penetrate the barrier. The States with the most police-reported cases all show penetration rates of less than 5.3 percent. Considering the collective results of all the states, that is, the total number of penetrations divided by the total number of collisions (i.e., 162 / 6221), results in a 2.6% penetration rate.

Table 4. Performance of cable median barriers in various States. [Ray09, MacDonald07]

State	**Collisions** (No.)	**Penetrations** (No.)	**Penetrations** (%)
AR	490	25	5.1
IA	20	0	0.0
NC	71	5	7.0
NY	99	4	4.0
MO	1,402	67	4.8
OH	372	4	1.1
OK	400	1	0.2
OR	53	3	5.7
RI	22	0	0.0
SC	2500	10	0.4
UT	18	2	11.1
WA	774	41	5.3

The State of Washington probably has the most complete information on cable barrier crashes and has performed assessments of low-tension cable median barrier, high-tension cable median barrier and concrete safety shaped median barrier performance in 2007 through 2009. [MacDonald07, Hammond08, Hammond09] As summarized in Table 5, six percent of low-tension cable median barriers allowed the vehicle to penetrate and cross the median compared to 3.7 percent for high-tension cable median barriers and 2.2 percent for concrete safety shaped median barriers. The severe and fatal injury percentage for each barrier type is also included in Table 5. Interestingly, vehicle contained in the median and those that cross the median appear to have very similar severe and fatal injury percentages. This study by Washington State, therefore, shows the penetration percentages of three different types of barriers.

Table 5. Barrier Performance in Washington State.

Barrier Performance	Low-Tension Cable			High-Tension Cable			Concrete		
	No.	%	A+K %	No.	%	A+K %	No.	%	A+K %
Contained in Median	742	85.9	1.1	560	71.5	0.9	441	34.0	
Redirected	70	8.1	0.1	194	24.8	0.4	828	63.6	
Crossed the Median	52	6.0	1.4	29	3.7	0.9	28	2.2	
Total	864	100.0		783	100.0		1,297	100	

MoDOT performed an in-service evaluation of its cable median barriers in 2005. [MoDOT06] Data analysis from 1999 to 2005 yielded 1,402 crashes involving cable median barriers. Successful performance was defined as "the vehicle does not make it to the opposing travel lanes," whereas failure indicated that the vehicle penetrated the barrier and entered the opposing lanes. By this definition, 95.2 percent of the cable median barrier crashes were considered successful in that they prevented a cross-median event so at least 4.8 percent of the cases resulted in a barrier penetration.

Information such as that shown above could be used in RSAP to assign a particular percentage or probability of penetration for each type of barrier. Table 5 seems to indicate that about six percent of vehicles penetrate a low-tension cable median barrier, 3.7 penetrate a high-tension cable median barrier and 2.2 penetrate a concrete safety shape. Of course, a crash study like the one above would be required to determine the appropriate percentages for use in RSAP.

The cable barrier example is interesting in that the penetrations of cable barriers are seldom ever capacity related. Generally, vehicles penetrate cable barrier by going under, through or over the cables which does not load the barrier to its structural capacity. This points out that there are two types of penetration failures – capacity related failures and non-capacity related failures that are usually more associated with vehicle and barrier geometry.

Rollover and Vaulting

Rollover and vaulting has also been studied for some types of barriers and can be used to estimate expected rollover and vaulting rates. For example, in 1990 Mak and Sicking reported on a study aimed at examining rollover and vaulting on concrete safety shaped median barriers and bridge railings. [Mak90] As shown in

Table **6**, 157 of the 1835 collisions (i.e., 8.6 percent) rolled or vaulted over the concrete safety shaped barrier. When the vehicle rolled over or vaulted the barrier, there were more than twice as many severe and fatal driver injuries as when the vehicle did not rollover or vault the barrier so the severity adjustment when rollover occurs would be 2.0.

Table 6. Driver injury in concrete safety shape collisions.

Severity	**Non-rollover**		**Rollover**	
	No.	%	No.	%
F	2	0.1	2	1.3
A	100	6.0	18	11.5
B	406	24.2	70	44.6
C	182	10.8	18	11.5
PDO	988	59.5	49	31.2
Total	1678	100.0	157	100.0

Mak and Sicking were also able to deduce many other characteristics of concrete safety shape rollovers and vaults. For example, vehicles weighing around 2000 lbs were almost twice as likely to rollover in a collision with a concrete safety shape than a vehicle weighing around 4000 lbs. When a vehicle struck the safety shape at a high speed (i.e., greater than 50 mi/hr) and small angle (i.e., less than or equal to 10 degrees), the odds of rolling over or vaulting were more than 13 times higher than when the vehicle struck at somewhat lower speed and higher angle. Mak and Sicking's analysis indicates that for concrete safety shapes, the proportion of rollovers and vaults can be estimated at roughly nine percent and rollover and vaulting are associated with specific types of impact conditions (i.e., high speed coupled with low angle and low vehicle mass).

In the context of using RSAP, a probability model could be developed for concrete safety shaped barriers that predicts the probability of rollover or vaulting given the simulated speed, angle and vehicle weight of a particular encroachment. While this would be useful and probably highly accurate, it would require that such a relationship be developed for every type of line-hazard in RSAP which may be difficult for some types of seldom used or newly developed barrier types.

Summary of Literature Review

Each method for assessing the probability of barrier performance has its strengths and weakness with respect to use in RSAP as shown in Table 7.

Table 7. Strengths and weakness of the mechanistic and statistical approaches to penetration/rollover/vaulting.

Mechanistic		Statistical	
Strength	Weakness	Strength	Weakness
Based on physics	Capacity of barriers is seldom known *a priori.*	Based on real-world data so likely to be accurate.	May not be data available for many types of barriers, especially new or specialty barriers.
Useful for barriers with unknown field performance.	Simple equations for prediction are not very accurate.	Easy to compute and implement in RSAP.	May not be able to determine the impact conditions most associated with performance.
Based on impact conditions and structural assessment.	Complex simulations are not practical and would be difficult to implement.		
Simple equations would be easy to implement.			

Penetration-of-Features Model in RSAPV3

The research team has explored the strengths and weaknesses of both the mechanistic and probabilistic approaches and has determined that the best compromise considering accuracy, implementation and model development is to use a combined mechanistic-probabilistic approach, which will be discussed in more detail in the following sections.

Since crash reconstruction data does not accurately distinguish between barrier penetrations caused by (1) structural failure, (2) rolling over the barrier and (3) vaulting, those events have been combined into a single variable denoted by the acronym, PRV (Penetration/Rollover the barrier/Vault). The penetration model can be modified when a sufficient amount of penetration data becomes available; however, it will first be necessary to ensure that future crash reconstruction data clearly distinguish between these three separate crash events.

Probability of Penetration

Current Model

The basic approach for determining the probability of PRV in RSAPV3 is based on the following criteria:

- **Criterion A:** If the *structural capacity* of the barrier is less than the *impact severity* (IS) [Olsen,], then penetration occurs:
  - The probability of PRV is set to 1.0 for that trajectory case,
  - The post-PRV velocity is computed based on amount of kinetic energy expended in penetrating the barrier and
  - Redirection on the traffic side is not considered.
- **Criterion B:** If the *capacity* of the barrier is greater than the *kinetic energy* (KE) of the vehicle then all the kinetic energy of the vehicle would have been expended before the vehicle could "break through" the barrier. In other words, even if the trajectory was allowed to penetrate, the resulting post-penetration velocity would be zero. Thus:
  - The probability of PRV is set to zero for that trajectory case and
  - The probability of redirection and the probability of rollover after redirection, however, are based on crash statistics and those values are used to "weight" the crash cost of any subsequent collisions.
- **Criterion C:** If, however, the barrier capacity is greater than the impact severity and is less than the kinetic energy of the impacting vehicle, then:
  - The probability of PRV, the probability of redirection, and the probability of rollover after redirection are all based solely on crash statistics and those values are used to "weight" the crash cost of any subsequent impacts.

This approach is summarized in Figure 9 below. Note that the relationship between IS and KE is defined by:

$$IS = KE * sin^2\theta$$

Where θ is the impact angle with respect to the longitudinal orientation of the hazard. Criterion B can then be redefined as:

$$\frac{KE}{Capacity} = \frac{(\frac{IS}{sin^2\theta})}{Capacity} \leq 1$$

Or

$$\frac{IS}{Capacity} \leq sin^2\theta$$

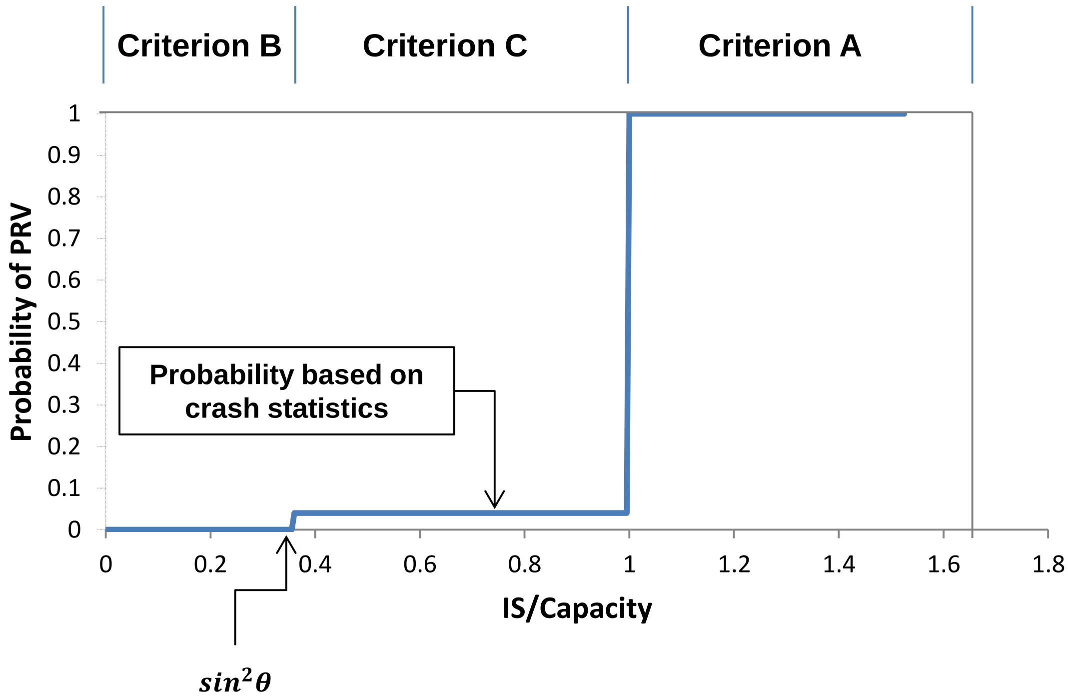

Figure 9: Illustration of the basic approach for determining the probability of PRV in RSAPV3

As discussed earlier, BCAP and RSAP (versions 2.0.3 and earlier) ignore the effect of barrier shape on vaulting over the barrier and rollover on the traffic side of the barrier by vehicles with c.g. heights lower than the barrier height. These events are accounted for in the procedure above when criterion C is met.

For *Point* hazards, however, the impact angle is always assumed to be 90 degrees (in RSAPV3); thus IS = KE and only Criterion A and Criterion B are evaluated. That is, penetration of Point hazards is based solely on the mechanics of the collision.

Alternative Penetration Model

The research team recognizes that there should not be such a drastic transition from the relatively low probability of penetration derived from crash statistics (e.g., 4% in Figure 9) to the 100% probability of penetration at barrier capacity, as defined in the current model. It is reasonable, however, to assume that for very low impact speeds and angles (i.e., low *IS* values) the probability of penetration would, correspondingly, be very low and would increase gradually as the impact conditions approached the capacity of the barrier. Also, the probability of penetration when impact conditions are at barrier capacity should not be 100%, but should continue to increase toward 100% as the impact conditions continue to increase beyond barrier capacity.

Figure 10 illustrates a possible representation of such a model, which is based on a hyperbolic tangent function defined by:

$$P(Penetration|collision) = 0.5 * \tanh\left[\left(\frac{IS}{Capacity} - A\right) * B\right] + 0.5$$

Where *A* defines the point of symmetry of the curve and *B* controls the rate of change in probability (i.e., the steepness of the curve) as the curve approaches and passes through the point of symmetry of the curve. As the value of *B* decreases, so does the slope of the curve at the point of symmetry. Figure 10 shows a possible probability function using the above equation with *A* = 1 and *B* = 4. In this case, the theoretical capacity of the barrier is the point of symmetry.

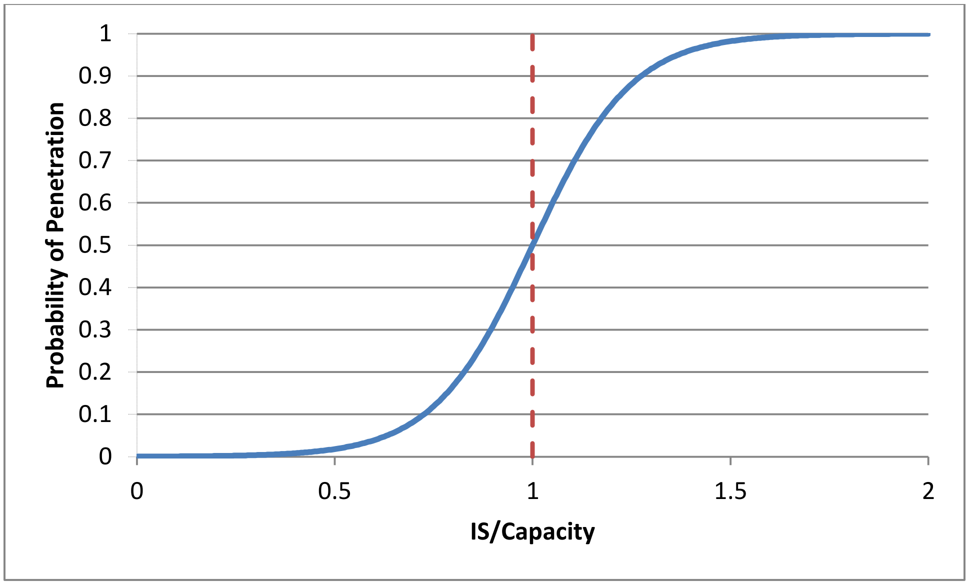

Figure 10: Illustration of an alternative approach for determining the probability of PRV in RSAPV3

Note that the probability of penetration derived from crash statistics generally represents the average probability from all crashes and includes a large range of impact conditions and vehicle classes. The research team is not aware of any studies that have been conducted to develop statistical models of penetration based on impact conditions (e.g., speed, angle, energy, *IS*, etc.) or vehicle class (e.g., passenger vehicles, single unit trucks, tractor-semitrailer, etc.), but such models could be readily implemented into the penetration subroutine in RSAPV3 if such data becomes available in the future.

Consideration of Heavy Trucks

As previously discussed, penetration is not guaranteed when impact conditions are just beyond the threshold of barrier capacity. For example, the current model will allow a large percentage of heavy trucks to penetrate since the impact severity (IS) in those cases often exceed barrier capacity. However, it has been shown in full-scale tests that even though the barrier suffered significant structural damage during impact the truck was safely redirected. This may be in part due to the fact that tractor-trailer vehicles are articulated and generally result in three peak loads on the barrier corresponding to 1) initial impact of the tractor against the barrier, 2) simultaneous impact of the rear tandem axles and front of trailer against the barrier and 3) impact of the trailer axles against the barrier.

Note that the calculation of *IS* basically assumes that the total mass of the vehicle is concentrated at the point of impact and does not account for the relationship between the stiffness of the structure and the distribution of mass along its length which effectively overestimates the loads imparted to the barrier. This is particularly true for articulated vehicles where the impact is distributed over three separate peak loadings and the magnitude of these peak loads are further affected by kinematic response of the vehicle; for example, tractor-trailer vehicles tend to roll over on top of the barrier during redirection which reduces the lateral impact forces imparted to the barrier. Also, the highest load is generally associated with the impact of the trailer axles; however, the momentum of the vehicle moving along the length of the barrier tends to pull the trailer away from the damaged region and penetration is, thereby, often avoided. In such cases, an accurate characterization would require a multi-degree of freedom representation of the vehicle which would be too computationally demanding for use in RSAP.

Since different classes of vehicles tend to interact differently with longitudinal barriers, RSAP results could be improved if the probability of penetration was based on vehicle class and impact conditions (e.g., *IS*). An important task in another ongoing NCHRP Project (i.e., Project 22-12(3)) is to collect barrier capacity data for closed-profile concrete bridge rails and to establish the likelihood of barrier penetration in collisions based on impact conditions (e.g., mass, velocity, impact angle), barrier height and test level. That task is still underway so final results and conclusions are not yet available; however, of the 48 full-scale crash tests of bridge rails and median barriers that have been reviewed in that project, the test vehicle was contained and redirected in every case, with only one exception (i.e., test 4348-2) in which the trailer rolled over the barrier.

In most cases the barriers were tested at impact forces below their calculated strength capacity. In no case, however, was the damage sufficient to allow penetration of the vehicle – even when posts sheared from the bridge deck (Test ACBR-1). The tests involving concrete parapets and safety shape barriers with theoretical strength capacity less than or equal to 61 kips resulted in estimated impact forces exceeding the theoretical strength capacity by as much as 1.4 times. The results were inconclusive regarding validity of the theoretical barrier capacity for those with theoretical strength capacity greater than or equal to 129 kips, since most of the tests resulted in estimated impact forces less than the theoretical capacity of the barriers. In all these test cases, the damage to the barrier was reported as either “minimal” or “cosmetic”.

Crash Cost Associated with Barrier Penetrations

Sicking reported that in collisions with longitudinal barriers those cases that resulted in the vehicle rolling over or vaulting the barrier were more than twice as severe as those cases where the vehicle did not rollover or vault the barrier; based on those findings, the severity adjustment in RSAP 2.0.3 was set to 2 when the vehicle rolled over the barrier. RSAPV3, on the other hand, does not explicitly assign a higher “blanket” severity to PRV collisions. When a trajectory penetrates a line hazard such as a bridge rail or median barrier, RSAPV3 will continue to evaluate the trajectory for subsequent interaction with hazards beyond the barrier. The crash cost of each of those collisions is computed according to the hazard severity rating of each hazard and the impact speed. The collective costs are then summed to determine the total crash cost of the overall crash event.

For example, if a vehicle penetrates a median barrier and then crosses over the median into opposing traffic lanes, the total crash cost is the cost of the collision with the median barrier *plus* the crash cost associated with crossing the median edge into on-coming traffic. Similarly, if a vehicle penetrates a bridge rail and then falls off the bridge, both incidents are analyzed separately and the total crash cost for that encroachment is the sum of the two collision events. However, depending on the given trajectory path, secondary collisions may not occur, or there may be cases where secondary collisions occur but at very low speeds. In those cases, the penetration would have little or no effect on the overall crash cost of the encroachment.

In summary, RSAPV3 computes crash costs as the sum of all collisions events (i.e., initial impact and subsequent impacts) that result from a given trajectory case. This approach effectively increases the overall crash cost when penetration and vaulting occur. The validity of this model will be determined by comparison with crash data in Task 6C2.

Summary and Conclusions

The research team has explored the strengths and weaknesses of both the mechanistic and probabilistic approaches and has determined that the best compromise considering accuracy, implementation and model development is to use a combined mechanistic-probabilistic approach.

While mechanistic methods have the advantage that they are grounded in the physics of the problem, getting a simple closed-form solution usually involves making many broad assumptions about the impact which may or may not be correct. Simple one-equation models like those used in BCAP and RSAP 2.0.3 simply are not adequate to capture the full range of vehicle dynamics, and it is not practical to incorporate detailed nonlinear dynamic impact analysis to investigate vehicle trajectory and collision due to the extensive computations that are typically required in such an effort; particularly in the context of RSAP where tens of thousands of simulated encroachments are needed.

A major flaw with most mechanistic penetration models is that once capacity has been reached it is assumed the barrier is totally compromised when in fact the capacity load is really just the beginning of the failure process. The barrier may often contain and redirect the vehicle even though there are structural failures, as was determined by Plaxico and Ray in Project 22-12(3) in their review of 48 full-scale crash tests on concrete bridge rails and median barriers. In other words, reaching capacity does not necessarily mean the vehicle will penetrate the barrier.

Another deficiency in the existing mechanistic models is that the effect of barrier shape on vaulting over the barrier and rollover on the traffic side of the barrier by vehicles with c.g. heights lower than the barrier height is generally ignored. For example, many passenger cars vault or rollover safety shaped barriers even though the height of the passenger car c.g. is lower than the barrier height. The reason is that the shape of the barrier in some shallow angle impacts has the effect of launching the vehicle over the barrier.

These weaknesses in the mechanistic approach lead the research team to strongly consider the probabilistic approach. The advantage of a statistical approach is that a complete understanding of the physics of the problem is not required since the data represents the real events. The disadvantage is that such methods require that there be crash data available in sufficient quantities to develop meaningful statistical models.

The approach adopted for use in RSAPV3 is a combined mechanistic-probabilistic approach where the probability of penetration is determined based on three basic criteria:

- **Criterion A:** If the *structural capacity* of the barrier is less than the *impact severity* (IS) [Olsen,], then penetration occurs and post-penetration velocity is computed based on amount of kinetic energy expended in penetrating the barrier. In this case redirection on the traffic side is not considered.
- **Criterion B:** If the *capacity* of the barrier is greater than the *kinetic energy* (KE) of the vehicle then all the kinetic energy of the vehicle would have been expended before the capacity of the barrier was breeched. In this case the probability of penetration is set to zero. However, redirection and possible rollover after redirection are both possible outcomes and are determined based on crash statistics.
- **Criterion C:** If, however, the barrier capacity is greater than the impact severity and is less than the kinetic energy of the impacting vehicle, then the probability of penetration, redirection, and rollover after redirection are all based solely on crash statistics.

The increase in crash cost that is generally associated with penetration is accounted for in RSAPV3 as the collective sum of all collisions resulting from a given encroachment. That is, if a vehicle penetrates a barrier and then encounters a second hazard (e.g., median edge, bridge drop-off, tree-line, etc.), each incident is analyzed separately and the total crash cost for the encroachment is the sum of the all associated collision events. However, depending on the given trajectory path, secondary collisions may not occur, or there may be cases where secondary collisions occur but at very low speeds. In those cases, the penetration would have little or no effect on the overall crash cost of the encroachment. The validity of this model will be determined by comparison with crash data in Task 6C2.

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