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Development of an Improved Roadside Barrier System—Phase I

This digest summarizes the findings of Phase I of NCHRP Project 22-16, "Development of an Improved Roadside Barrier System." Although the project panel decided not to proceed with Phase II, the Phase I research provides a summary of the state of the art on the use of various guardrail systems, defines strengths and weaknesses of the current systems, and provides recommendations for changes to the strong-post w-beam barrier. This digest is based on a draft final report prepared by a research team lead by Dr. Karl Barth, West Virginia University.

INTRODUCTION

The objective of NCHRP Project 22-16 was to develop a new, nonproprietary roadside barrier system capable of meeting *NCHRP Report 350* crash test requirements and more cost-effective than the most commonly used strong-post w-beam (SPWB) barrier. Specifically, a new barrier should provide for increased safety, reduced life-cycle costs, lower maintenance needs, and greater installation flexibility.

The first phase of the project included a literature review, a survey of state departments of transportation (DOTs), the establishment of basic functional requirements for a new roadside barrier system, and the development of preliminary design concepts and analyses. This digest summarizes the efforts in Phase I of this project.

Although the project panel decided not to proceed with Phase II, the Phase I research developed a summary of the state of the art in the use of various guardrail systems, defined strengths and weaknesses of the current systems, and developed recommendations for changes to the SPWB barrier.

The roadside safety literature was reviewed to ascertain the current knowledge of the strengths and weaknesses of the SPWB barrier and what improvements other systems may offer. Information reviewed included research publications and reports, domestic and foreign patents, and *NCHRP Synthesis 244: Guardrail and Median Barrier Crashworthiness*.

The latest thinking of design and maintenance professionals in the DOTs was obtained through a detailed survey conducted during the early part of 2000. The survey obtained information on the strengths and weaknesses of SPWB and of other currently used barrier systems. The engineers were asked where they see a need for improvement and how they ranked the importance of the different possible functional enhancements. Forty-four states responded to the survey.

FUNCTIONAL REQUIREMENTS

Background

The SPWB is composed of w-shaped, 12-gauge, galvanized steel rails attached to steel or wood posts with steel, wood, or recycled plastic blockouts to minimize wheel snagging. The midpoint rail height is 529 mm (20.8 in.) in most states, but 554 mm (21.8 in.) in a few states and 550 mm (21.7 in.) in *A Guide to Standardized Highway Barrier Hardware* (hereafter referred to as the "Hardware Guide") *(1)*. These midpoint heights correspond to top-of-rail heights of 685 mm (27 in.) and 710/706 mm (28 in.).

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Steel and wood posts are each regularly used, with a W150x12.6 wide-flange section being the most common shape for steel posts. Rectangular 150x200-mm posts are the most common wood size, but other sizes and shapes are used. The posts are "strong" in the sense that they tend to transmit large forces to the soil in order to dissipate energy from the impacting vehicle. The strength of the barrier also depends on the strength of the soil and the embedment depth of the posts.

State-reported embedment depths vary from 760 mm (30 in.) to 1,320 mm (52 in.), with 1,120 mm (44 in.) being the most common depth. The Hardware Guide recommends an embedment depth of 1,100 mm (43.3 in.). Most states use the Hardware Guide–recommended post-spacing of 1,905 mm (6.25 ft).

The design dynamic deflection is the expected distance the barrier deflects when impacted by a typical "design" vehicle. For a barrier to perform properly, there must be adequate clear area behind the barrier to allow for the dynamic deflection. SPWB is categorized as a semirigid barrier and has typical design dynamic deflections of 800 mm (31.5 in.) for steel-post systems and 700 mm (27.6 in.) for wood-post barriers. Dynamic deflections for design reported by the state DOTs range from 610 mm (24 in.) to 1,675 mm (66 in.), with 915 mm (36 in.) being the most common value *(2)*.

The highway environment is constantly changing, and unfortunately the SPWB guardrail is now perceived to have some serious performance problems. The range of passenger vehicle sizes is much wider now than it was 40 years ago, when the SPWB began to be widely used. Whole new types of vehicles have emerged that did not even exist 10 or 15 years ago. Minivans are common on today's highways, yet they first emerged on the market only in 1987. Sport utility vehicles (SUVs) have emerged from their humble beginnings as work vehicles to become a major segment of the passenger vehicle and even luxury vehicle market. The vehicle fleet almost completely replaces itself every 10 or 15 years, resulting in a relatively rapid change in the characteristics of vehicles in the population. Roadside hardware, however, is usually installed and often forgotten. Particular installations may experience a service life of two or three decades, resulting in hardware designed for one generation of vehicles having to accommodate a newer, much different generation of vehicles.

While the SPWB guardrail has performed well for many decades, it was designed for a fleet of vehicles that is gone. Crash performance problems have emerged in recent years that suggest that the SPWB guardrail does not perform as well for today's vehicle fleet as it did for the fleet of 30 years ago. In developing an improved guardrail system, the characteristics that contributed to the SPWB guardrail's long successful service should be retained, while the performance problems that have emerged in recent years should be corrected.

Desirable Characteristics of SPWB—Literature Review

The SPWB guardrail has endured for decades because it is an effective guardrail system with reasonably modest installation cost that can be used in a wide variety of roadside situations. The desirable characteristics of the SPWB as found in the literature search are described below.

Design Flexibility

SPWB guardrails can be used in a wide variety of design situations: they can shield fixed roadside objects and steep slopes, they can be used at bridge approaches where there is relatively little room for lateral deflection, they can be used in guardrail envelopes (i.e., bullnoses) that enclose bridge piers, and they are flexible enough to redirect small cars safely while being stiff enough to redirect larger full-size passenger cars and pickup trucks. A wide variety of guardrail terminals and guardrail-to-bridge rail transitions have been developed for the SPWB guardrail to provide holistic solutions to many specific roadside design problems. Roadside designers can use the SPWB guardrail in a wide variety of applications; this ability simplifies the maintenance and repair of guardrails, since fewer parts must be stockpiled and personnel can be trained to repair and install fewer systems.

Cost

SPWB guardrails are not the least expensive guardrails to install, but they are relatively low cost, especially considering the wide range of applications where they can be used. Although cost information is difficult to obtain and is subject to variations caused by geographic areas, availability of contractors, supply of materials, and other economic factors, Ray and McGinnis have estimated that the SPWB guardrail generally costs about $40 per meter. Any improved guardrail system would have to be characterized by a similar installed cost in order to supplant the SPWB guardrail in the marketplace.

Simplicity

The SPWB guardrail is a relatively simple structure assembled from a few highly standardized, readily available components familiar to most construction trade workers. Up until recent years, the design was very stable and states had nearly a half century of experience in installing and maintaining these systems. Installation and repairs are easily accomplished with simple hand tools and a post driver.

Performance

Until recently, the SPWB guardrail was considered to have good crash performance with a wide range of vehicles. The crash test performance observed with small and large passenger sedans has generally been considered acceptable *(3)*.

Undesirable Characteristics of SPWB—Literature Review

The publication of *NCHRP Report 350* in 1993 introduced new crash tests to the matrix of tests needed to assess the performance of longitudinal barriers. Perhaps the most important change with respect to longitudinal barriers was the replacement of the 2,040-kg passenger sedan of *NCHRP Report 230* with a 2,000-kg, full-size pickup truck. When tested according to the *NCHRP Report 350* guidelines, many common guardrail systems either failed the new pickup truck test (e.g., the G4 [1S], G2, and G9 guardrail systems) or passed only marginally (e.g., the G4 [2W]). While *NCHRP Report 350* exposed a number of problems that had been unrecognized before, many of the same problems had been noted in earlier full-scale crash tests with nonstandard test vehicles like vans and pickup trucks *(3)*.

The following sections identify some of the undesirable crashworthiness characteristics of the SPWB guardrail system.

Wheel-Post Snagging

Wheel snagging is not a new phenomenon and has been observed in tests with a variety of vehicles when striking SPWB guardrails *(3)*. Wheel snagging in the pickup truck test (i.e., *NCHRP Report 350* Test 3-11), however, has emerged as a serious problem on most SPWB guardrail systems. In a test of the SPWB guardrail with steel wide-flange posts and blockouts, the pickup truck wheel snagged hard against the post, resulting in the vehicle rolling over. The W150x14 steel section commonly used for posts and blockout is very weak in lateral torsional buckling. In an impact, the post and blockout collapse in lateral torsional buckling, allowing the impacting wheel to make hard contact with the post. This problem has been addressed for the steel W150x14 post system by using wood or recycled plastic blockouts, but there is still significant wheel-post contact that causes the redirected pickup truck to experience potentially unstable motions.

A test with the SPWB guardrail using 150x200-mm wood posts and blockouts was judged to pass the requirements of *NCHRP Report 350*, but even this passing test was characterized by significant wheel-post interaction *(4)*. In fact, the snagging in this test was hard enough to remove the impact side wheel from the vehicle altogether. Some researchers believe that the real difference between these two tests (e.g., the steel versus wood post and blockout) is that if the impact side wheel is removed, the vehicle will not roll over, whereas if the wheel is not removed, the vehicle will roll over. In either case, there is significant interaction between the wheel and the post that is not desirable.

Splice Failure and Guardrail Rupture

Guardrails have been observed to rupture at times in some guardrail crash tests *(5)*. This rupturing has occurred for both weak- and strong-post w-beam guardrails. Ray and Hopp have also observed this behavior in the field *(6)*. There are several theories about why guardrails occasionally rupture. Some agencies believe that the 12-gauge, w-beam guardrail does not provide enough tensile capacity and have, therefore, required installation of 10-gauge rail on all SPWB guardrails. Some researchers have suggested that ruptures are caused by tearing on the edge of the rail. One manufacturer is proposing a new rail shape with a rolled edge that is thicker to prevent tearing along the edges. Recently, Ray et al. have performed finite element simulations and laboratory tests that indicate that the complex biaxial state of stress at the splice location is responsible for many of the guardrail ruptures *(5)*. Guardrail rupture should be examined, and methods for minimizing the chance of tearing the guardrail should be included in any new improved guardrail system.

Guardrail Height

The standard height for SPWB guardrail installations has typically been 685 mm above the ground. This height has generally resulted in good performance with small and large passenger cars.

Newer vehicles, however, present more demanding impact conditions for the SPWB guardrail. Bumper heights on pickup trucks and SUVs are often just below or at the top corrugation of the w-beam rail. Several attempts have been made to develop different shapes that provide protection for a wider range of vehicle types (i.e., bumper heights). The first such attempt was the development of the thrie-beam barrier in the 1970s *(8)*. The thrie beam is 197 mm wider than the w-beam, so it can accommodate a wider range in bumper heights. Other recent examinations of the rail shape include the development of the Buffalo rail, where the location of the corrugations was modified to maximize the area that will be effective in capturing the bumper *(7)*.

Connections

Originally, SPWB guardrails were installed with a rectangular washer under the head of the post-rail connection bolt. This type of installation was recognized to be a problem many years ago when the rail would be pulled to the ground in collisions characterized by large lateral deflections. As a result, the FHWA recommended that rectangular washers not be used in order to allow the rail to separate from the post when the lateral deflections are large *(8)*.

The elimination of the rectangular washer has largely eliminated the problem of override due to the post being carried to the ground, but performance of SPWB guardrail connections may still not be ideal. Since the post rotates in the soil, there is a geometric tendency for the post to pull the rail down as it deflects laterally. The rail also tends to rotate about its longitudinal axis, resulting in the face of the rail becoming less vertical as the post rotation increases.

Ideally, the rail should remain at the same height throughout the collision event. One attempt to solve this problem resulted in the design of the modified thrie-beam guardrail *(9)*. The modified thrie beam features a very deep blockout with a triangular wedge cut out of the bottom. During an impact, the wedge closes, keeping the guardrail essentially vertical during the impact.

Energy Dissipation

SPWB guardrails manage energy primarily by changing its direction. Although some energy is dissipated in deforming the guardrail, thereby rotating the posts in the soil and deforming the vehicle, much of the kinetic energy is redirected back into or parallel to the traveled way. This redirection of kinetic energy results in vehicles being redirected at relatively high speeds and sharp angles after successful collisions. For example, a small passenger car striking a SPWB guardrail will usually be redirected with relatively little loss of velocity. This redirection is beneficial from the standpoint of the vehicle occupant's interaction with the vehicle interior (e.g., the redirection will result in good occupant risk values), but it may place the driver in the undesirable position of not being in control of the vehicle when it leaves the barrier and re-enters the busy travel lanes of the highway.

There have been several attempts to manage the impact energy of the vehicle through energy dissipation rather than redirection. The self-restoring barrier was developed in a series of projects in the early 1980s *(10)*. A relatively heavy rail section was hinged from the top of the post such that in an impact, the vehicle had to lift and rotate the rail. This lifting action dissipated energy by doing work against gravity. The system was successfully crash-tested and was even installed at several high-collision locations, but it never became widely used in part because it was difficult to maintain in the field *(11)*.

The collapsing tube bridge rail was another concept for dissipating energy and thereby reducing the exit speed and angle of an errant vehicle *(12)*. A steel tube was placed between the w-beam rail and the concrete bridge parapet. An errant vehicle would deform the ring and thereby dissipate energy.

Strengths and Weaknesses of SPWB—Survey of DOTs

A survey of the 50 U.S. DOTs was conducted in 2000 to collect information needed to establish the functional requirements for a new barrier system. Forty-four states (88% of those that were sent surveys) responded to at least one part of the survey. Separate surveys were sent to design and maintenance groups to incorporate the different viewpoints of the two groups.

TABLE 1 Strengths of SPWB as reported by DOTs

Strengths of SPWB	Design	Maintenance	Total
Low installation costs	20	12	32
General availability	12	4	16
Good in-service performance	9	4	13
Low repair costs	7	5	12
Good ability to redirect vehicles	5	7	12
Easily constructed	7	4	11
Small dynamic deflection	7	4	11
Requires little maintenance	4	6	10
Familiar with system	0	8	8
Barrier is forgiving	4	2	6
Minimal number of parts	1	5	6
Versatility of system	4	1	5
Contains vehicles well	2	3	5

Table 1 summarizes the strengths of SPWB as reported by the state DOTs through the survey. Thirty-four states provided design strengths for SPWB, and 31 states provided maintenance strengths. Thus, a maximum of 65 responses is possible for an individual strength. The survey allowed for multiple strengths to be submitted, and many states provided more than one strength for the SPWB.

Table 2 summarizes the weaknesses of SPWB as reported by the state DOTs through the survey. Thirty-six states provided design weaknesses for SPWB, and 33 states provided maintenance weaknesses. Thus, a maximum of 69 responses is possible for an individual weakness.

Installation cost was seen as the most important strength of SPWB, with approximately half (32) of the responders listing it as a strength of the current SPWB system. The SPWB is less expensive to install than box-beam, thrie-beam, or concrete barriers, but is more expensive than weak-post w-beam or cable barriers. Reported installation costs for SPWB in 1995 ranged from \$26/m (\$8/ft) to \$127/m (\$39/ft), with typical costs being \$40/m (\$12/ft). In the recent survey, 1998 installation costs averaged \$47.5/m (\$14.5/ft). A small, but significant, number of responders (8) listed installation costs as a weakness, indicating that SPWB was expensive to install. Most of these states use cable and/or weak-post w-beam barriers, which are less expensive than SPWB. One of the states (accounting for two of the eight negative responses) reported SPWB costs at \$115/m (\$35/ft), more than double the average cost.

The second most reported advantage of SPWB is its general availability and the concomitant familiarity that results from its widespread use. Twelve designers and four maintenance professionals listed availability as a strength, while eight maintenance professionals and no designers listed the familiarity of the system as an advantage. However, these

TABLE 2 Weaknesses of SPWB as reported by DOTs

Weaknesses of SPWB	Design	Maintenance	Total
Excessive repair costs	9	8	17
Needs expensive end treatments	7	7	14
Problems with snow	6	6	12
Problems with maintenance	6	4	10
Poor aesthetics	6	3	9
Sensitive to bumper height	7	2	9
Difficult to use on slopes	5	4	9
Expensive to install	4	4	8
Excessive dynamic deflection	6	2	8
Reset after pavement overlays	2	6	8
Not crashworthy with large vehicles	5	2	7
Requires strong soil	5	1	6
Difficult to repair	0	6	6
Causes substantial damage to vehicles	4	2	6
Problems with curbs	4	1	5
Requires shoulder beyond barrier	2	3	5
Restricts sight distance	2	2	4
Causes serious injuries	2	2	4
Does not redirect vehicles well	3	1	4
Problems with mowing grass	0	4	4

advantages should apply to any barrier system that is used extensively and cannot be attributed to any specific functional advantage of SPWB.

With regards to the roadside barrier performance of SPWB, the DOT comments were mixed. Thirteen responders indicated good in-service performance as a strength of the system, and only one responder listed poor in-service performance as a weakness. Twelve responders listed ability to redirect vehicles as an SPWB strength, but four listed it as a weakness, probably reflecting the barrier's known problems with redirection of pickup trucks and other large vehicles. Similarly, SPWB's ability to contain vehicles was listed as a strength by only five responders and as a weakness (i.e., not crashworthy with large vehicles) by seven responders.

The reviewers' opinions on the amount of dynamic deflection associated with SPWB were also mixed. Eleven responders indicated that small deflections were a strength of SPWB, while eight indicated that dynamic deflections were excessive. Nine of the 11 responders listing dynamic deflection as a strength for SPWB were from states that use cable barriers, which have much larger deflections than SPWB does.

The goal of roadside safety is to provide the motorist with a forgiving roadside. Only six of the responders listed SPWB as a forgiving barrier, while an equal number of responders listed substantial damage to vehicles as a weakness of SPWB. Furthermore, four responders indicated that SPWB causes serious injuries. Thus, while SPWB may be more forgiving than concrete, it does not provide enough forgiveness to satisfy all of the DOT engineers.

The biggest weakness of SPWB as reported by the DOTs is excessive repair costs. Interestingly, while 17 responders listed high repair costs as a weakness, 12 indicated low repair costs as a strength. Responses on both sides of this issue were fairly evenly split between designers and maintenance professionals, and no strong bias from states using flexible barriers was observed. A similar pattern was found on the question of maintenance. Ten responders (4 designers and 6 maintenance professionals) believed that maintenance requirements for SPWB were minimal, while 10 other responders (6 designers and 4 maintenance professionals) believed that the SPWB was a maintenance problem.

The ease to construct SPWB was listed as a strength by 11 responders (7 designers and 4 maintenance professionals), but 6 responders (all maintenance professionals) indicated that repairs were difficult. Five maintenance professionals liked the fact that SPWB requires a minimal number of parts. The fact that heavy equipment is generally needed to make repairs is one of the reasons that repairs are considered troublesome. Also, the need for proprietary or expensive end terminals was listed as a weakness by 14 responders, the second most reported weakness.

The heavy usage of SPWB would imply that it is a versatile system suitable for many applications. Indeed, 5 responders listed SPWB's versatility as a strength; however, many of the weaknesses reported point out its limitations. Foremost of the complaints is SPWB's problems with snow. Overall, snow problems emerged as the third most reported weakness (12 responders) behind repair costs and end treatments. Given that many states do not have enough snowfall to be concerned with this issue, the relative importance of this weakness for states that have a lot of snowfall is much greater than indicated by the raw score.

Other weaknesses relate to the system's lack of versatility as far as where it can be used: the difficulty of using SPWB on slopes (indicated by 9 responders), the need to reset SPWB height after pavement overlays (indicated by 8 responders), SPWB's need to have strong soil (indicated by 6 responders), SPWB's incompatibility with curbs (indicated by 5 responders), and the perceived need to have the shoulder extend beyond the barrier (indicated by 5 responders). From a vehicle standpoint, 9 responders mentioned the SPWB's sensitivity to bumper height as a weakness.

The system's appearance is a concern to a number of DOTs, with 9 responders listing aesthetics as one of its weaknesses. (However, one responder mentioned aesthetics as a strength of the SPWB.) Finally, problems with mowing grass (4 responders) and with restricting sight distance (4 responders) were attributed to the SPWB.

Strengths and Weaknesses of Other Barriers—Survey of DOTs

Examining the strengths and weaknesses of other barriers provides insights for the characteristics to include in a new barrier as well as those that should be avoided. Unfortunately, it is not possible to incorporate all of the good features of the existing barriers without inheriting some of their weaknesses.

The flexible, weak-post systems (cable and weak-post w-beam) are the most forgiving and least expensive barriers. Cable barrier is the least expensive ($26/m, $8/ft) barrier to install (17 responders) and was reported to be the most forgiving (14 responders). However, the softness of the system that cushions the vehicle and occupants results in large design dynamic deflections (22 responders) of 3.35–3.65 m (11–12 ft). Such large deflections and the concomitant required clear space behind the barrier restrict the usage of the barrier. Additionally, cable barriers were reported to have high maintenance requirements (22 responders) and large repair lengths (15 responders) after impacts. Other strengths of cable barriers reported include their compatibility with snow (7 responders), their aesthetics (7 responders), and their reconstructability (4 responders).

The weak-post w-beam, used in only six states, has strengths and weaknesses similar to cable barriers. The barriers are inexpensive ($40/m, $12/ft), which was mentioned as a strength by 9 responders. The barriers are forgiving (9 responders) and have design dynamic deflections of 2.44 m (8 ft). Reported weaknesses are large deflections (9 responders), repair costs (8 responders), long repair lengths (5 responders), and only Level 2 certification (5 responders). Modifications have been made to the weak-post w-beam guardrail recently, and the modified system now meets *NCHRP Report 350* Level 3 requirements.

Box-beam barriers are not used in many states and do not appear to offer any features that should be incorporated in the new barrier. Three states mentioned low repair costs as a strength, but seven listed high repair costs as a weakness. High installation costs ($70/m, $21/ft) were reported as a weakness by 9 responders.

Thrie-beam barrier is used more widely than box beam, and several states commented on thrie beam's strengths and weaknesses. Installation costs were cited as a weakness by 14 responders and as a strength by 9 responders. Installation costs in 1995 ranged from $39/m ($12/ft) to $328/m ($100/ft), with a typical value of $82/m ($25/ft). In 1998, the average cost reported was $112/m ($34/ft). Maintenance needs were reported as a strength by 9 responders and as a weakness by 6 responders. Looking beyond the mixed evaluations of thrie-beam cost, reported strengths include its ability to redirect vehicles (8 responders), its ability to handle a wide range of vehicles (6 responders), and the general availability of the barrier from vendors (4 responders). Reported weaknesses include repair costs (9 responders), problems with snow (7 responders), and the unavailability of inexpensive transitions (4 responders).

Concrete barriers offer advantages because of their rigidity and durability, but carry with them disadvantages associated with their rigidity. Reported strengths of concrete barriers included low maintenance (27 responders), ability to redirect vehicles (15 responders), ability to withstand minor hits without the need for repairs (14 responders), long life expectancy (14 responders), ability to contain vehicles (11 responders), zero dynamic deflection (10 responders), strength (9 responders), in-service performance (8 responders), and constructability (7 responders). Constant slope barriers were reported by 5 designers to be able to accommodate pavement overlays.

The most widely reported weakness of concrete barriers is installation cost (24 responders). Installation costs for concrete roadside barriers in 1995 ranged from $30/m ($9/ft) to $492/m ($150/ft), with typical values of $100/m ($30/ft). Installation values in 1998 for most states ranged from $80/m to $115/m ($24/ft to $35/ft), but one state reported costs of $984/m ($300/ft).

Other reported weaknesses for concrete barriers include problems with snow (15 responders), problems with pavement overlays (11 responders), unforgiving nature (8 responders), high repair costs (8 responders), sight distance restrictions (6 responders), heavy damage to impacting vehicles (5 responders), problems with small cars (5 responders), glare problems (5 responders), problems with redirecting vehicle (4 responders), and availability of inexpensive end treatments (4 responders).

The review of existing barriers establishes that there is no perfect barrier available. The most forgiving barriers carry with them the need for large clear areas to provide for their large dynamic deflections. The low-deflection barriers are expensive and are not particularly forgiving to the errant motorist. The open barriers are more adaptable in areas with snow than are the more solid barriers. Flexible barriers require longer sections to be repaired after impacts than more rigid barriers require. Rigid barriers can survive minor hits without the need for repairs, but when they are damaged, repairs can be very expensive. All *NCHRP Report 350* approved barriers provide "acceptable" containment and redirection capabilities.

Functional Requirements for the New Roadside Barrier—Survey of DOTs

In the survey of the state DOTs, responders were asked to rate various proposed characteristics of the new barrier on a 7-point scale varying from +3 for very desirable to -3 for very undesirable, with 0 for "does not matter." The information from this part of the survey provides guidance on which characteristics should be emphasized in the new barrier and where tradeoffs in characteristics should be made if necessary.

The functional characteristics were separated into seven

TABLE 3 Functional requirements for new roadside barrier—survey of DOTs

	Crashworthiness	**Economy**	**Versatility**	**Repairability**	**Maintainability**	**Compatibility**	**Durability**
Required	Meets NCHRP 350 Level 3 Guidelines						
	Causes fewer serious injuries than SPWB						
Very Desirable	Reduces severe injuries by 50% or more from SPWB	Reduces repair costs by 50%	Serves wider range of vehicle sizes & types	Damaged components easily replaced			
		Reduces terminal installation costs by 50%		Reduces repair time by 50%			
		Reduces transition installation costs by 50%		Uses terminals that can be easily installed correctly			
Moderately Desirable	Reduces severe injuries by 25% or more from SPWB	Reduces LON installation costs by 25%	Usable in tight radius conditions	Can be repaired without heavy equipment	Multiple manufacturing sources for components	Compatible with existing inventory	Lasts 25% longer before replacement
	Performs better in TL-3 crash tests than SPWB	Reduces repair costs by 25%	Usable with curbs	Reduces repair time by 25%	Fewer overall parts, fewer non-standard parts	Reduces sight distance blockage	Withstands 30-mph impact without repairs
	Reduces PDO crashes by 25% or more from SPWB	Reduces terminal installation costs by 25%	Usable with flexible & rigid pavements		Easily adjusted after pavement overlays	Permits free passage of drifting snow or sand	Resists corrosion from salt & hostile environments
		Reduces transition installation costs by 25%	Usable in poor soils			Reduces headlight glare	
			Reduces clear space by 25%				
			Usable on side slopes of 1V:6H or flatter		Allows easy mowing of grass		
Slightly Desirable	Offers similar products for different NCHRP test levels		Usable on side slopes of 1V:4H or flatter		Less susceptible to frost heave	Modifiable appearance for aesthetics	Withstands 10-mph impact without repairs

TABLE 3 continued

	Crashworthiness	Economy	Versatility	Repairability	Maintainability	Compatibility	Durability
Slightly Undesirable	Increases PDO crashes by 10%	Increases LON installation costs by 25%	Increases clear space requirements by 100%		Requires 25% more storage space for components		
		Increases transition installation costs by 25%					
Moderately Undesirable	Increases PDO crashes by 25%	Increases terminal installation costs by 25%	Increases clear space requirements by 200%	Increases repair time by 25%			
		Increases LON installation costs by 50% (design)					
		Increases repair costs by 25%					
Very Undesirable	Increases severe injuries by 10%	Increases LON installation costs by 50% (maintenance)					

LON = length of need.
PDO = property damage only.

categories: crashworthiness, economy, versatility, reparability, maintainability, compatibility, and durability. Table 3 shows the analysis of the DOT responses to this section of the survey. Averages of the ratings provided by the responders were used to prepare Table 3. The responders were told to use their experience with the SPWB as their reference point for questions that required a base point (e.g., increases repair time by 25%, reduces length of need [LON] installation costs by 25%).

One requirement is that the new barrier must meet at least *NCHRP Report 350* Test Level 3 guidelines. Another requirement is that the new barrier should be expected to cause fewer serious injuries and fatalities than the SPWB. Making the new barrier less expensive than the SPWB without increasing its effectiveness would not produce the desired "significant" improvements in cost-effectiveness.

The DOTs considered reducing severe injuries by 50% or more as "very desirable." Even increases as small as 10% in severe injuries were indicated to be "very undesirable." Other aspects considered "very desirable" include reductions of 50% in repair costs, terminal installation costs, and transition installation costs. The responders would like the new barrier to serve a wider range of vehicles, be simple to repair, and have terminals that can be installed correctly without a lot of trouble.

The "moderately desirable" traits that the DOTs specified include better crash-test performance and greater versatility in use such as in tight radius conditions, with curbs, with both flexible and rigid pavements, with poor soils, and on side slopes of 1:6 or flatter. Responders would like to be able to repair the barrier without heavy equipment, be able to purchase it from multiple manufacturers, and have it easily adjustable after pavement overlays. Also, the new barrier should be compatible with existing inventory, consist of fewer parts, allow for better sight distance, permit the free passage of drifting snow and sand, reduce headlight glare, last 25% longer before replacement, withstand 30-mph impacts without repairs, and resist corrosion from hostile environments.

Functionalities that the DOTs considered only slightly desirable include providing a family of similar products meeting the various *NCHRP Report 350* test levels, being usable on slopes of 1:4, being less susceptible to frost heaving, and being modifiable in appearance for aesthetic purposes.

TABLE 4 Proposed functional requirements for new roadside barriers

Function	Proposed Requirement	Comments
Safety Performance Functional Requirements		
NCHRP 350	Must meet Report 350 Test Level 3	No strong indication for higher level
Wheel Snagging	Minimizes or prevents wheel snagging	
Guardrail Rupture	Minimizes or prevents barrier rupture	
Dissipate Energy	Dissipates impact energy	
Constant Barrier Height	Barrier remains at essentially the same height throughout the impact	
Vehicle Types	Can accommodate a variety of vehicles from the 820C to the 2000P test vehicles as well as intermediate passenger cars and SUVs	
Forgivingness	Results in a more forgiving impact to vehicle occupants	50% reduction in injuries is desirable
Cost Functional Requirements		
Installation Cost	Costs about $50/m to install	25% increase only slightly undesirable
Terminal/Transition Cost	Cost/availability of terminals and transitions	Costs up to 50% more are acceptable
Repair Costs	Costs about $700 per collision to repair	50% lower is desirable. No repair for minor hits.
Durability	System should have an expected design life of at least 20 years	Up to 25% increase is desirable
Maintainability Functional Requirements		
Maintenance	No routine maintenance required	
Repair Time	Repairs can be made quickly without blocking lanes. No heavy equipment needed for most collisions.	0–50% shorter
Complexity	Same number or fewer parts as SPWB	
Overlays	Accommodate 50–100 mm overlay without need for expensive adjustment of height	No adjustment needed or adjustment is easy
Constructability	Low probability of construction errors	

TABLE 4 continued

Function	Proposed Requirement	Comments
Site Versatility Functional Requirements		
Dynamic Deflection	Dynamic deflection should be about 1.0 m	100% increase only slightly undesirable
Weather	Allow free passage of blowing snow and sand	
Aesthetics	System is aesthetically pleasing. Its appearance can be modified in sensitive applications.	
Curbs	Can be used with a variety of curbs	
Side Slopes	Performs well even when installed on slopes	
Sight Distance	Barrier does not obstruct sight distances	
Horizontal Curves	Can be used on horizontal curves including small radius curves and intersection openings	
Soil Conditions	Can be used in a variety of soil conditions without adverse effect on performance	

Characteristics considered to be only slightly undesirable are ones that may need to be considered as tradeoffs to achieve some of the very desirable traits. DOTs seem willing to accept increases in property damage only (PDO) crashes of 10%, increases in LON installation costs of 25%, increases in clear space requirements of 100%, increases in transition costs of 25%, and increases in required storage space of 25%.

Proposed Functional Requirements for a New Roadside Barrier

The extensive survey sent to the state DOTs was designed to provide information to help the research team develop the functional requirements for a new barrier system. It is quite likely that a new barrier will not be able to meet all of the desired features indicated by the design and maintenance engineers in the DOTs. However, at least the survey has provided helpful information on which characteristics the DOTs feel should be emphasized and where tradeoffs can be made if necessary.

Table 4 summarizes the proposed functional requirements for a new roadside barrier system. The requirements are specified using the existing SPWB barrier as the benchmark. The functional requirements were developed by combining the results of the state DOT survey and the critical literature review of the SPWB. The list of functional requirements can be further categorized into four groups: safety performance, cost, maintainability, and site versatility functional requirements. Any new guardrail concept can be judged on the basis of the functional requirements listed in Table 4.

Summary

The previous sections have outlined several desirable and undesirable characteristics of the SPWB guardrail. An improved system would be unlikely to supplant the SPWB guardrail if it did not retain the good characteristics of the SPWB guardrail while eliminating the problem areas. Compared with the SPWB guardrail, an improved guardrail system should

- Have a similar installation and repair cost,
- Provide the same level of design flexibility,
- Be simple to install and repair,
- Reduce the chance of wheel-post interaction (i.e., wheel snagging),
- Reduce the chance of guardrail rupture,
- Accommodate a wide range of bumper heights,
- Manage energy through energy dissipation as well as redirection, and
- Retain the same rail height throughout the collision event.

A system with these characteristics would significantly improve the performance of guardrails installed on roadways while retaining the low cost, design flexibility, and simplicity of SPWB guardrails. The functional requirements of a new system have been presented based on both a survey of state DOTs and a critical review of the full-scale, crash-testing literature.

DESIGN IDEAS

The following sections present specific design concepts for improving the performance of guardrail systems. Some concepts are intended to improve the performance of existing guardrails by modifying components, whereas other concepts are entirely new. Many of the concepts could be combined, but they are discussed in the following sections individually for the sake of clarity.

The first section contains design ideas that are minor improvements to the existing SPWB system. In general, these improvements are easily made and relatively inexpensive, but may not result in dramatic gains in cost-efficiency or safety performance. The second section contains design ideas that are more significant departures from the existing system, although they still are based on the traditional basic design principles for guardrails. The third section contains design ideas that are radically different from the existing system. Such ideas are likely to be associated with higher costs, but may provide the dramatic increase in safety performance that is desired.

Minor Improvements to the SPWB

This section presents design concepts that are generally minor variations in the existing SPWB design. The advantages of such minor variations is that they are generally low cost, are fairly easy to incorporate into existing systems and designs, and improve on already proven design philosophies of guardrail design. The disadvantage is that the opportunity for large improvements in either cost-efficiency or safety performance is limited.

Center-Span Splices

The issue of guardrail rupture and splice failures have been discussed at a variety of forums in the roadside safety community in recent years. Engstrand et al. published a paper in 2001 dealing with the issue *(13)*, and Engstrand completed a thesis partly developed to an exploration of the splice failures using both component tests and finite element analysis *(14)*.

While Engstrand's work was performed to improve the performance of the weak-post w-beam guardrail, the results are equally applicable to the SPWB guardrail. When splices are located at the post, they experience complex multiaxial states of stress. These complex stresses can sometimes lead to unexpected failures. Splices in metal-beam guardrails should always be placed at midspan (e.g., between the posts) where the loading on the splice is simple tension and single-curvature bending. Implementing this idea would simply involve punching the post-rail attachment slot at 952.5-mm spacing rather than the current standard 1,905-mm spacing. Aside from some inconvenience in some repair operations where the new and old splice pattern would have to be integrated, there are no disadvantages to this approach and essentially no additional long-term costs. While rail ruptures are infrequent in the field, this design change would drastically reduce the chance of ruptures at essentially no incremental cost.

Deeper Blockouts

One of the major deficiencies of existing SPWB guardrails is their tendency to snag the impacting wheel of an errant vehicle, especially pickup truck front wheels. Steel blockouts have been shown to collapse, allowing the wheel-post contact to be very hard, resulting in the vehicle rolling over. Even impacts with solid blockouts (e.g., either wood or recycled blockouts) result in significant wheel snagging and erratic post-impact trajectory. Typical wood blockouts used today on the G4(2W) and modified G4(1S) are 200 mm deep. Although crash tests with SPWB guardrails with solid rectangular blockouts pass the appropriate *NCHRP Report 350* tests, the behavior exhibited in those tests is recognized to be marginal.

Karlsson investigated a variety of strategies to reduce the likelihood of wheels snagging in SPWB guardrail impacts *(15)*. One particular option she investigated was using 250-mm-deep solid wood or recycled plastic blockouts. Finite element simulations have shown that increasing the blockout depth to 250 mm dramatically reduces the chance of contact between the wheel and post. The impulse experienced by the wheel decreases as the blockout depth increases. The impulse experienced by the wheel falls to virtually zero when the blockout is greater than 250 mm deep. Using deeper blockouts on existing strong-post guardrail designs is an inexpensive method for reducing the likelihood of wheel-post contact.

Tubular Steel Post

Typical steel posts made of wide flange sections (i.e., I sections) fail in lateral torsional buckling. The torsional failure often occurs early in the impact event, leaving the twisted portion of the post where the wheel of the vehicle can snag on it. This failure mode also limits the lateral strength of the guardrail and pulls the guardrail to the ground when deflections are large. Tubular sections (either rectangular or circular) are much stronger in torsion. A tubular section would fail in bending at much higher lateral loads than the wide flange section. Tubular sections should increase the lateral stiffness and eliminate the lateral torsional buckling failure. A W150x14 wide flange section (the section typically used in the G4 [1S]) has a strong-axis section modulus of 91,200 mm^3. The same gross section modulus can be obtained in a 127-mm-diameter pipe section or a 127x102x6.4 rectangular tube.

The above idea is already taking hold in the marketplace. The HALCO X-post, for example, is a tube section that is made by mechanically joining a hat section and a flat plate made of 12-gauge guardrail steel *(16)*. The tubular section has bending strength adequate for lateral impact loadings, but it does not fail in lateral torsional buckling as the W140x14 steel post does. This particular tubular section is also less expensive to produce. In addition, the X-post is a cold-formed section that can be manufactured by guardrail manufacturers, whereas the W150x14 is a hot-rolled section that must be purchased from the large steel mills.

Summary

All of the above ideas can be combined into one new variation of the SPWB system. The system would consist of

- 12-gauge w-beam guardrail,
- Tubular steel posts spaced at 1,905 mm,
- Splices at midspan, or
- 250-mm-deep wood or recycled plastic blockouts.

The estimated cost of this new system is shown in Table 5. Standard recycled plastic or wood blockouts cost between \$3.75 and \$4.00 each. Since a 250-mm-deep blockout uses 25% more material, it is reasonable to assume that the blockout would cost 25% more, or approximately \$5.00 per blockout. The tubular steel posts, as described earlier, could be less expensive than existing hot-rolled wide flange sections if cold-rolled material were used. Based on the HALCO X-post, each post would cost \$2.00 less per post than the current W150x14 steel post. Relocating the splices in the midspan has no cost associated with it aside from a one-time cost associated with manufacturers' retooling to punch the slots at the midspan. The installation costs are expected to be exactly the same as for the existing steel-post SPWB, since exactly the same techniques would be used. This incremental improvement on the SPWB system would, therefore, cost about \$32.00 per meter, a few dollars less than the existing SPWB system. Both the steel and wood versions of the SPWB have essentially the same installed cost because the savings in materials for the wood-post system are usually offset by the slightly higher cost of driving wood posts.

A system very similar to the one proposed here has recently been crash-tested *(17)*. The Midwest Guardrail System uses deeper blockouts, relocates the splice to the midspan, increases the rail height, and lengthens the post-rail slots. The system passed the required tests for *NCHRP Report 350* Test Level 3.

Major Improvements to the SPWB

This section describes three major revisions of the SPWB barrier system. While all three design concepts are still based on the traditional philosophy of controlled redirection, implementing these concepts would involve more significant changes to the manufacture, installation, and maintenance of guardrail systems.

Popout Post Guardrail

The basic concept behind the popout guardrail post is to provide a post that has essentially the same lateral stiffness as conventional guardrail posts, but that includes a displacement "fuse" that would allow the post to separate from a foundation either if the post or the rail were directly contacted by the wheel of the impacting vehicle or if the post deflected more than a prescribed amount. The post is made up of two steel tubes. The upper section, or post, slides into a foundation tube that is driven into the ground. The distance that the upper tube slides into the lower tube and the tightness of the fit control the lateral deflection at which the posts separate. The popout post concept is illustrated in Figure 1. A standard w-beam guardrail is used, but no blockouts

TABLE 5 Cost breakdown for an improved SPWB system

Materials	*Unit Cost*	*Quantity*	*Total Cost*
Tubular post	12.00	2	24.00
250-mm-deep recycled blockout	5.00	2	10.00
Splice bolts and nuts	0.35	8	2.80
300-mm rail-to-post bolt	1.00	2	2.00
12-gauge AASHTO M180 w-beam guardrail	25.00	1	25.00
Total material costs for 3.8-m section of guardrail			**63.80**
Material cost per meter of guardrail			16.71
Estimated installation cost per meter of guardrail			15.00
Total installed cost per meter of guardrail			31.71

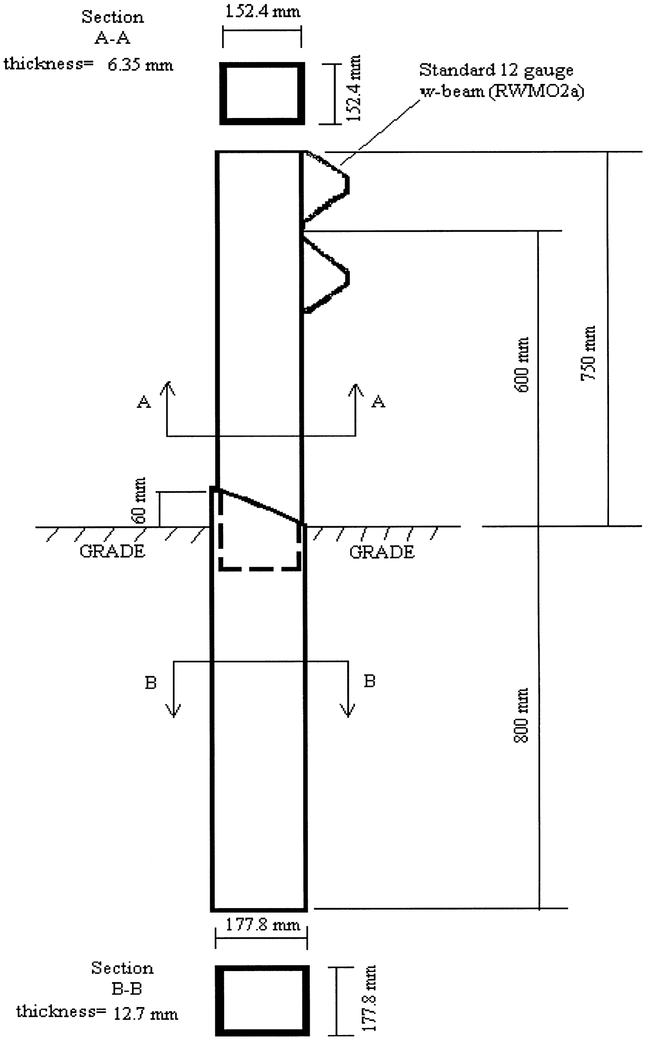


Figure 1. Popout post cross section.

are required, since the post will release before the vehicle wheel can contact the post. The rail is attached to the post with a connection that separates from the post before being dragged to the ground.

Finite element simulations were used to explore the relationships between the size of the tubes, amount of insertion, post spacing, and other important design variables. The best performance so far has been for a post that is a 152.4x152.4x6.35-mm tube and a foundation tube that is 177.8x177.8x12.7 mm.

Once the most promising geometry was identified using the single post simulation, a simulation of a full-scale crash test with a 2,000-kg pickup truck striking the prototype guardrail at 100 km/h and 25 degrees was performed. The post spacing in this model was 3,810 mm, and the post was inserted into the foundation to a depth of 60 mm. Although the system contained and redirected the vehicle, the posts popped out too easily, allowing the vehicle to deflect the guardrail a little over 2 m. A series of parametric simulations was performed varying the insertion depth. The best performance was for the 165-mm insertion. The dynamic deflection was a little less than 1.0 m, which is similar to a typical SPWB guardrail dynamic deflection (i.e., about 900 mm). All the posts popped out before the wheel contacted them, and the vehicle was smoothly redirected without the pitching and rolling that generally occurs in full-scale tests of the SPWB. When the insertion depth was increased to 200 mm, the post no longer would pop out, but would instead locally buckle at the top of the foundation tube. It appears that the width of the foundation tube (i.e., 177.8 mm) is approximately the upper limit for insertion that still allows the popout mode to predominate.

The popout post guardrail concept appears to be a feasible alternative to typical SPWB guardrail systems. The system has dynamic deflection characteristics similar to the standard w-beam guardrail and avoids the possibility of snagging the impacting wheel of the vehicle that so often results in post-impact instability.

Table 6 shows the estimated costs for the popout post

TABLE 6 Cost breakdown for the popout post guardrail system

Materials	*Unit Cost*	*Quantity*	*Total Cost*
152x152x6.35 tubular post	17.00	1	17.00
178x178x6.35 tubular foundation tube	20.00	1	20.00
Splice bolts and nuts	0.35	8	2.80
Rail-to-post bolt and nut	0.50	1	0.50
12-gauge AASHTO M180 w-beam guardrail	25.00	1	25.00
Total material costs for 3.8-m section of guardrail			**65.30**
Material cost per meter of guardrail			17.18
Estimated installation cost per meter of guardrail			15.00
Total installed cost per meter of guardrail			32.18

guardrail system. The post and foundation tube costs were estimated based on the price of hot-rolled structural tubing. This type of steel section tends to be relatively expensive. It would probably be possible to reduce this cost by using cold-formed steel sheet with welded seams. The post and foundation are spaced at 3.8 m rather than the 1.9 m of the typical SPWB system, so even though each post-foundation costs a little more than twice what a W150x14 steel post costs, only half as many are used. Additional cost savings come from not needing a blockout or a backup plate. The installation cost is estimated to be essentially the same as for the steel SPWB system. The material and installation costs are, therefore, just 10% less than the existing system.

The primary benefit of using the popout post system is improved performance. The cost is only slightly improved, and while there are some maintenance and repair advantages, there is no increase in system versatility.

Z-Post Guardrail System

The Z-post concept is similar to the popout post concept in that it attempts to retain the overall lateral stiffness of the existing w-beam guardrail while preventing the possibility of destabilizing wheel snagging. The post cross section is shaped like a Z, as shown in Figure 2. The post is 240 mm deep and 200 mm wide and is made using standard 12-gauge, zinc-coated steel plate (i.e., AASHTO M-180 type material). The cross section provides the same strong-axis section modulus as a standard W150x13.5 guardrail post, as shown in Figure 2.

When loaded by the guardrail laterally, the post responds much like a standard guardrail post because it has similar inertial properties. If the post is struck directly by the impacting wheel of the vehicle, however, the post collapses flat and can be easily pushed over by the rolling wheel. This collapsing feature minimizes the likelihood of the vehicle snagging on the guardrail post and thereby minimizes the likelihood of vehicle instability during the vehicle redirection. Since there is little possibility of snagging, blockouts are not required. Backup plates are not required because of the curved corners of the Z-post.

A finite element model of a single post mounted in soil was developed and used to explore the strength and collapse modes of the shape for a variety of geometries. The cross section shown in Figure 2 was selected as the most promising based on these simulations.

Once the most promising geometry was identified, a model of a complete guardrail was assembled. Initially, a

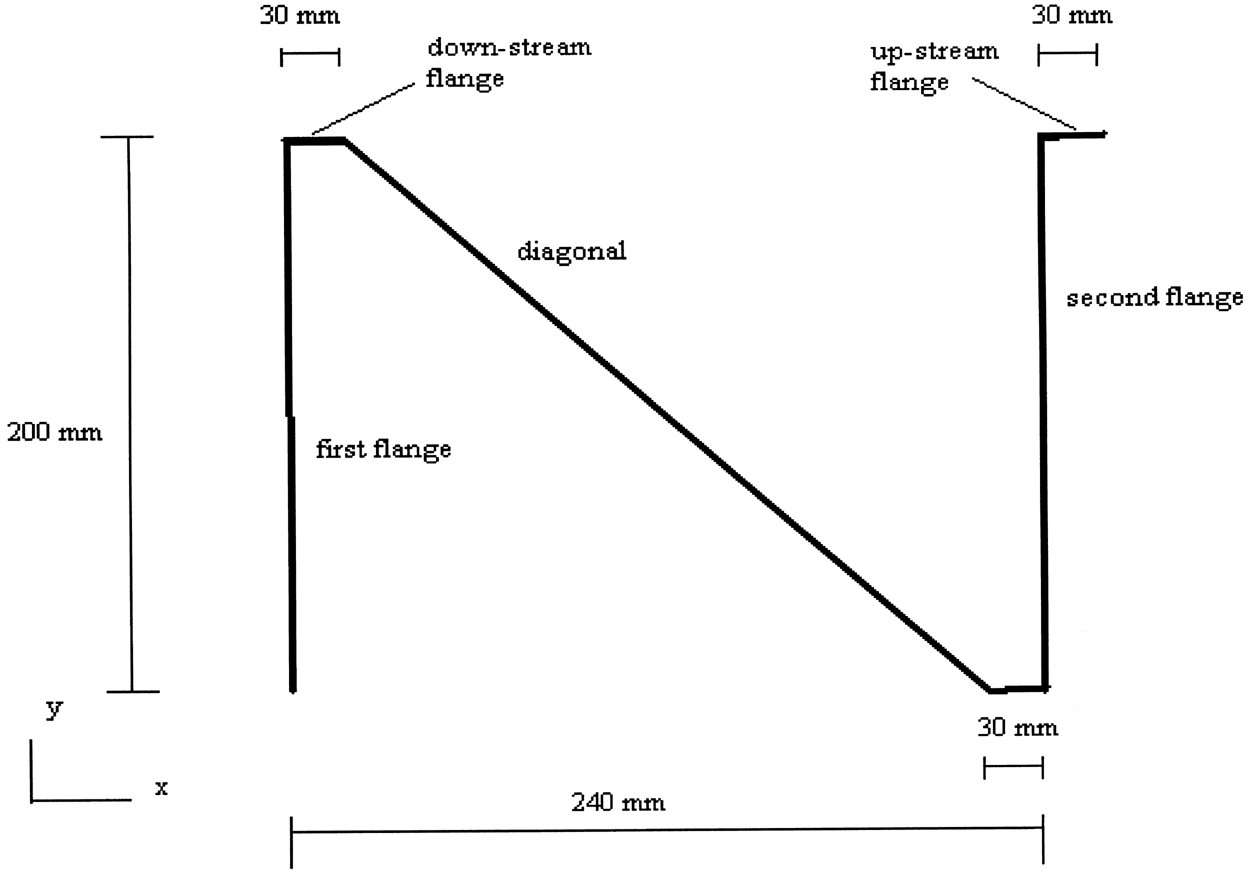


Figure 2. Sketch of the Z-post.

post spacing of 3,810 mm was used. Simulations of a 2,000-kg pickup truck striking the prototype barrier at 25 degrees and 100 km/h predicted that the vehicle would be contained, but the dynamic deflections were too large. The post spacing was reduced to 1,905 mm, the spacing used on typical SPWB guardrails. The resulting dynamic deflection was a little less than 1 m, similar to the existing SPWB guardrail system.

The Z-post guardrail system appears to be a feasible concept for a new strong-post guardrail. The lateral stiffness of the system is similar to existing w-beam guardrails, but the novel post shape reduces the likelihood of hard wheel snagging. The ability to run down the post without large interaction forces allows the vehicle to be smoothly redirected with relatively little roll and pitch.

Estimated costs for the Z-post system are shown in Table 7. The post is made using the same 12-gauge galvanized steel that is used in making the w-beam rail. The post could be fabricated with a very similar roll-forming process so the cost of the Z-post is based on proportioning the cost and size of the posts and rails. This process results in an estimated cost for each Z-post of $19 for an 1,800-mm-long post, $5 more expensive than the current steel post. It may be possible to optimize the shape of the post further and thereby decrease the cost, so this estimate should be considered an upper-bound estimate. Blockouts and backup plates are not required, reducing the cost of materials. It is assumed that the Z-post system would have installation costs similar to other steel-post guardrail systems.

Based on the finite element analyses and cost estimates, the system has some significant performance advantages over the SPWB. The cost rating of the system is barely better than the existing SPWB, and the maintenance and versatility ratings are the same as the existing system. This system would require that damaged posts be removed from the ground much like the existing SPWB, so in terms of maintenance and repair effort, it is assumed to be quite similar to the existing system.

Leaf-Spring Guardrail System

The leaf-spring post is a variation of an older guardrail concept, the self-restoring barrier (SERB). The SERB used a very stiff tubular thrie beam. The rail was suspended from hangers on large 250x250-mm wood posts. When struck by a vehicle, energy was dissipated by lifting the heavy tubular thrie-beam rail, thereby doing work against gravity. As the vehicle was redirected, the rail returned to its preimpact configuration under the restorative influence of gravity *(18)*.

Like the SERB, the leaf-spring guardrail uses a heavy tubular thrie-beam rail system. This system is very stiff, since it is a closed cross section and since it is relatively heavy. Instead of being suspended from posts as in the SERB system, the rail is attached to a leaf-spring post. The leaf-spring post is made up of four strips of steel that are rolled to a 700-mm radius, as shown in Figure 3. The strips are clamped at three locations such that they form a leaf-spring similar to the leaf-springs used on the rear suspension of most trucks and vans. When the spring is loaded at the guardrail attachment, the leaves straighten as they are pushed back.

The leaves dissipate energy through elastic deformation of the leaves needed to unbend the prerolled steel plates. Since these deformations are elastic, the post will resume its preimpact shape once the vehicle has been redirected. This post also has the desirable feature that the rail height increases slightly as deflections become larger.

A finite element model of this system has been used to explore the performance of this system in impacts with a 2,000-kg pickup truck at 25 degrees and 100km/h. Early simulation experiments resulted in a system that was much too stiff. Finite element analyses could be used to find the best combination of leaf-spring geometry, post spacing, and other guardrail properties.

The leaf-spring post concept appears to be a feasible alternative for a guardrail system, although there are still a number of significant design issues to be addressed. The potential for a self-restoring barrier that can smoothly redi-

TABLE 7 Cost breakdown for the Z-post guardrail system

Materials	*Unit Cost*	*Quantity*	*Total Cost*
Cold-formed, 12-gauge Z-post	19.00	2	38.00
Splice bolts and nuts	0.35	8	2.80
Rail-to-post bolt and nut	0.50	2	1.00
12-gauge AASHTO M180 w-beam guardrail	25.00	1	25.00
Total material costs for 3.8-m section of guardrail			**66.80**
Material cost per meter of guardrail			17.58
Estimated installation cost per meter of guardrail			15.00
Total installed cost per meter of guardrail			32.58

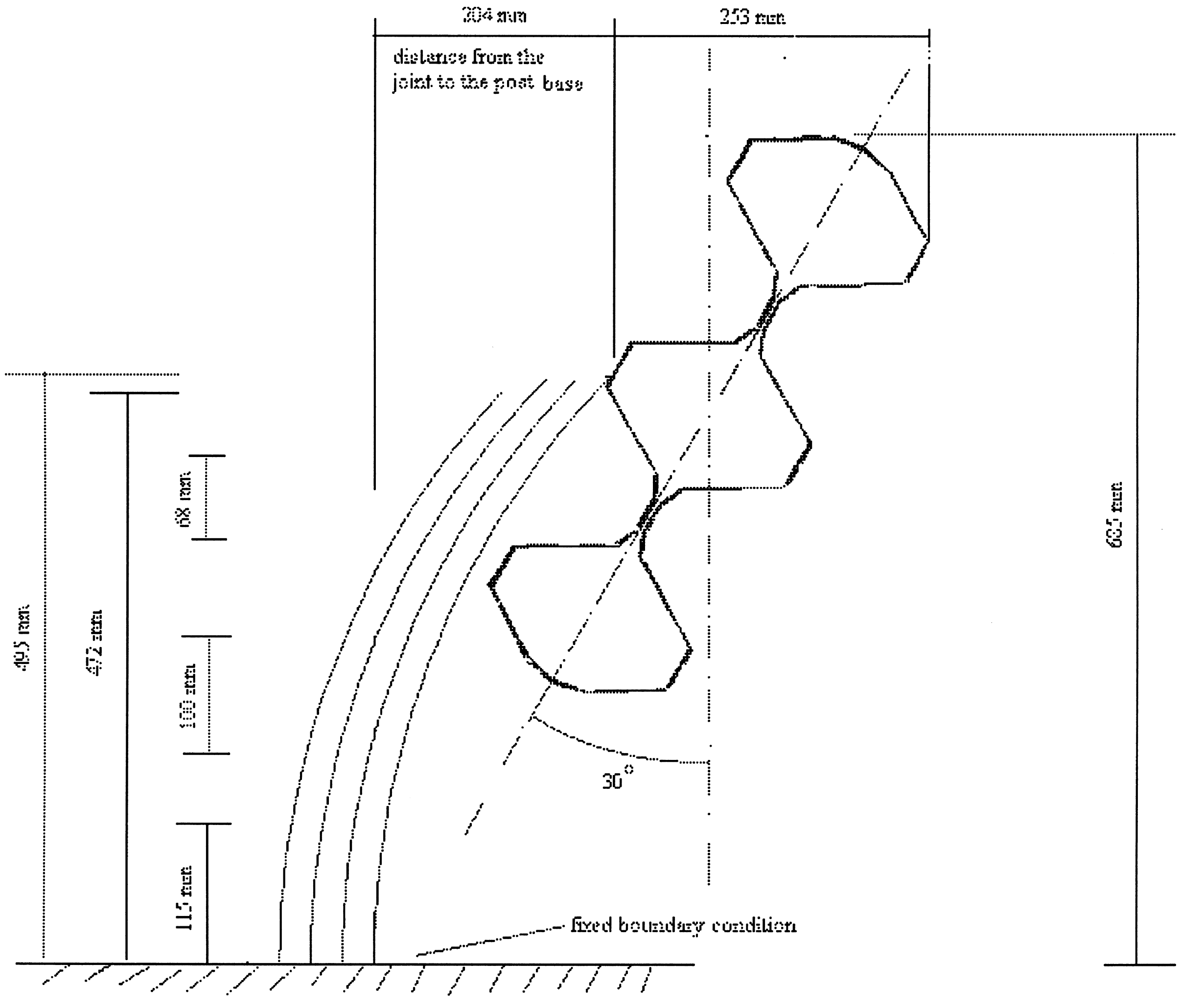


Figure 3. Cross section of leaf-spring post.

rect a pickup truck appears to be quite good, although additional work on optimizing the performance of the system must be done.

It is difficult to estimate the cost of the leaf-spring barrier without first performing additional design work. The posts are expected to be quite expensive, since they are heavy, require cold-rolling to a specified radius, and must be supported in a relatively stiff foundation. The tubular thrie beam alone would cost three times as much as the standard w-beam rail element, and there would be additional connection hardware. Even if the design were optimized, it is expected that the cost of the system would still be more than twice that of the existing SPWB system.

This system has significant safety performance benefits, since it dissipates energy, minimizes the chance of snagging and rupture, and provides a constant barrier height. The cost rating was zero, or no change from the current system. While the installation cost is expected to be much higher, the repair and maintenance costs are expected to be much lower. The system was not judged to offer any particular improvements in versatility.

New Concepts

This section describes a post and rail concept produced from honeycomb fiber-reinforced polymer (HFRP) sandwich construction. The proposed system builds on some advantageous characteristics of the "major improvements to the SPWB barrier system" and offers the potential for better performance; lower installation, maintenance, and repair costs; and better versatility for modifications, additions, and transitions to conventional systems. However, it is likely that the cost of this new concept will be much higher than that of conventional systems.

HFRP Sandwich Materials

Fiber-reinforced polymer composite materials in general offer great advantages in relation to conventional materials: high stiffness and strength per unit weight, nonconductive and nonmagnetic characteristics, high energy absorption under impact and cyclic loads, and (more importantly) the ability to tailor the fiber-resin material architecture for specific applications. Sandwich composite materials consist of top and bottom face sheets with honeycomb or foam cores and are considered to have the most efficient configuration to provide high stiffness and strength per unit weight, which is the major reason for being widely used in aircraft, satellite, and other military applications. Recently, an HFRP sandwich panel, with sinusoidal core extending vertically between face sheets, has been successfully used for highway bridge decks and fish culture tanks *(19)(20)*. The geometry of the HFRP panel is shown in Figure 4. Explicit solutions and finite element modeling have been discussed, and experimental results in bending and torsion correlate well with analytical and numerical solutions *(21)(22)(23)*. Further studies for general core configurations (tubular, hexagonal, square, etc.) and core optimizations have also been presented *(24)(25)*.

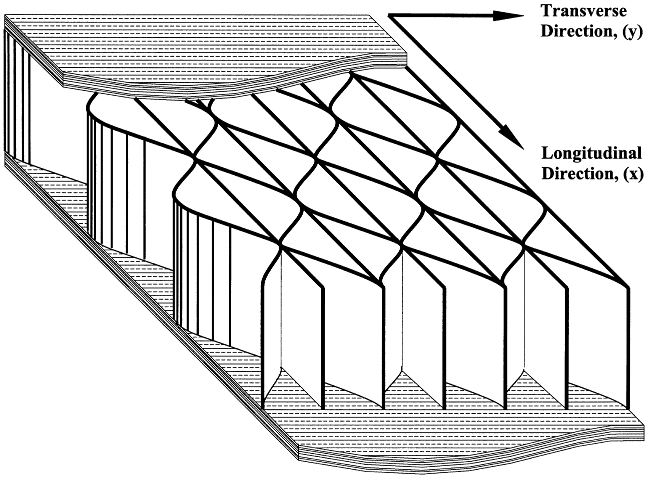
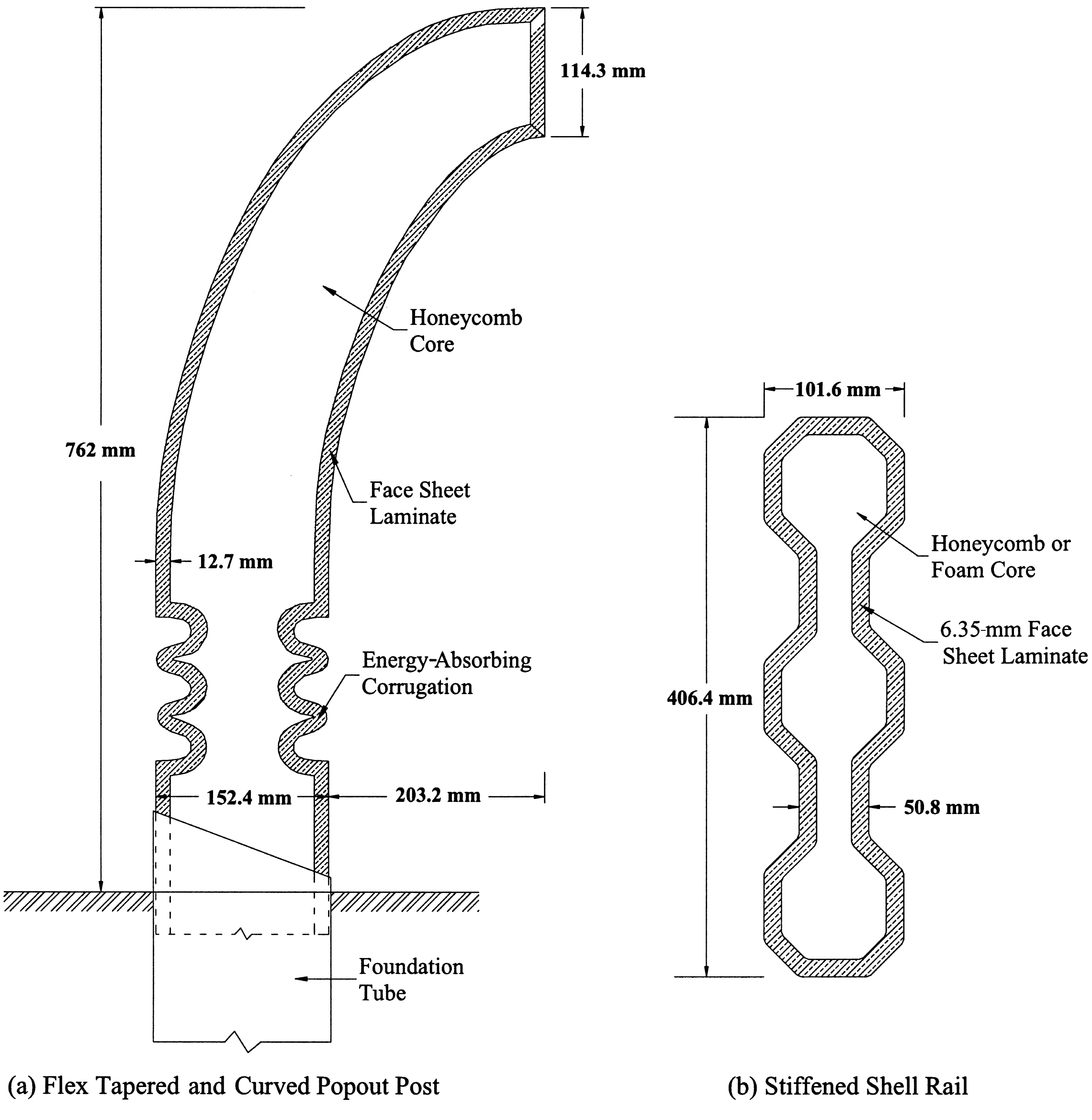


Figure 4. Configuration of HFRP sandwich panel.



(a) Flex Tapered and Curved Popout Post

(b) Stiffened Shell Rail

Figure 5. HFRP post and rail concept.

For applications to guardrail systems, the same technology as the panel shown in Figure 4 can be used, with appropriate selection of materials, face sheet fiber architecture, and either particular honeycomb geometry or foam for the core. The proposed HFRP post and rail concept includes a flex tapered and curved popout post (see Figure 5[a]) and a stiffened shell rail (see Figure 5[b]).

HFRP Post

The post (see Figure 5[a]) consists of a tapered and curved sandwich cross section with an energy-absorbing corrugation near the base and the ability to pop out from a foundation steel tube (similar to the popout concept; see the "Major Improvements to the SPWB" section). The rectangular cross section can effectively resist lateral-torsional buckling and avoid wheel snagging. The tapered section permits savings in materials, since the post acts as a cantilever beam with maximum stresses at the bottom. The curved section extends outward from the interior face of the post approximately the same distance as the blockout thickness in the existing SPWB design. The advantage of a curved post is its ability to dissipate energy by straightening as it is pushed back by an impact load; as discussed later in this section, this behavior reduces the bending displacement of the post. The objective of the accordion-like corrugation at the base of the post is to dissipate energy by a hinging effect; thus, the research team envisions that under minor impacts, the post would flex and return to its initial position without damage, requiring no repairs. Under a major impact, the post would undergo considerable deflection and eventually pop out from the foundation tube, and because of the post's light weight, the post would be able to be suspended from the HFRP rail. The dimensions are tentatively 152x152 mm at the base and 114x114 mm at the tip, and finite element optimization studies with geometric and material nonlinear dynamic models will be needed to define the fiber-resin configuration and geometric dimensions.

To arrive at the final tentative geometry of the proposed post, finite element models were evaluated for linear response of cantilever sections under a nominal transverse tip load of 4.45 KN. The models included a straight 152x152-mm cross section, a tapered cross section from 152 mm at the base to 114.3 mm at the tip, a tapered and flex section, a tapered and curved section, and finally the proposed tapered and curved flex section. The models were created using eight-node solid elements with equivalent orthotropic material properties, as defined by Davalos et al. *(21)*. A comparison of static tip deflections indicated that while there is not much difference between the straight and tapered sections, the tapered and curved section provides considerably more stiffness because of the straightening of the section as it bends. When the base corrugation is added, the deflection increases to the approximate level of the straight or tapered sections without corrugations, but, as intended, the accordion-type corrugation absorbs the additional deformation effectively.

HFRP Rail

The rail is conceived as a stiffened sandwich shell, with tentative dimensions as shown in Figure 5(b). The larger depth of 406 mm or more in comparison to the standard w-rail can probably sustain impacts from heavy and/or high center of gravity (CG) vehicles if a proper hinge connection is designed to attach the rail to the post such that the rail would maintain constant height or raise slightly as the post straightens at the tip and flexes at the base accordion. As recommended for the steel w-rail, the HFRP rail can also be spliced at center span, possibly using an insert to attach two adjacent sections.

The rail can be designed to sustain substantial membrane or axial stresses by appropriate selection of fiber-resin combinations, including high-elongation resins if necessary. At the same time, the ribs or stiffeners of the cross-sectional geometry can be optimized to provide sufficient bending resistance under impacts. Using a static finite element analysis, the maximum displacement was 4.57 mm for a 1.9-m section assumed to be simply supported at the locations of the posts and loaded at the center with a nominal load of 4.45 KN. The rail can also be designed with corrugations along the length to dissipate axial energy. A nonlinear optimization study under dynamic loads needs to be performed to properly and effectively design the rail section.

Cost

It is difficult to estimate costs for a prototype product, which lacks the benefits of economy of scale of established commercial products. Moreover, without a numerical simulation or crash test of the whole system, such as those provided in the "Major Improvements to the SPWB" section, researchers cannot evaluate the full capabilities and benefits of the proposed system, such as larger spacing of posts. However, tentative costs can be estimated from constituent material costs and estimates from manufacturers. The weight of the flex tapered and curved popout post in Figure 5(a) is approximately 8.16 kg (18 lb), and for the configuration shown, the total cost is approximately $45 per post. The weight of the stiffened shell rail in Figure 5(b) is approximately 3.63 kg/m (8 lb/ft), and the estimated cost is about $29 per meter-length ($9 per foot-length). The estimated costs in Table 8 are based on the assumption that the HFRP posts and steel foundation tubes can be spaced at 3.8 m, as with the popout steel tube. Also, it is assumed that the same costs as for the steel popout post will be incurred for rail-splice, rail-to-post connection, and installation. The installed cost per meter of all HFRP post and rail is $61, which is about twice the cost of the steel tubular popout post and w-beam system. If the HFRP post is used in a hybrid system with a steel w-beam rail, the installed cost per meter drops to $39, which is comparable to the cost of $32 for the steel tubular popout system. When considering the all HFRP guardrail system, one should keep in mind that production

TABLE 8 Cost breakdown for the HFRP post and rail system

Materials	*Unit Cost*	*Quantity*	*Total Cost*
HFRP flex tapered and curved popout post	45.00	1	45.00
178x178x6.35 tubular foundation tube	20.00	1	20.00
Splice hardware	2.80	1	2.80
Rail-to-post connection hardware	0.50	1	0.50
HFRP stiffened shell (3.8 m = 12.00 ft)	108.00	1	108.00
Total material costs for 3.8-m section of guardrail			**176.30**
Material cost per meter of guardrail			46.39
Estimated installation cost per meter of guardrail			15.00
Total installed cost per meter of guardrail			61.39

costs can decrease when dealing with large quantities; also, the potential for using recycled thermoplastics that can be obtained in large quantities from automobile parts (fenders, hoods, and bumpers) can significantly decrease bulk materials costs.

Functional Requirements

It is assumed that this system will meet or exceed *NCHRP Report 350* Test Level 3, and either tests or analyses must validate that the dynamic deflection is about 1 m. While the cost disadvantage is apparent, there are several potential benefits offered by this new concept. The safety performance for this system is one of the highest of the systems considered, about the same as the leaf-spring system, but it is a much simpler, more practical, and more economical design. The higher material cost is offset by the ease of repair and favorable durability offered by composites. The cost of developing and integrating the design with terminal concepts is expected to be high. It was estimated that there is no difference in constructability because the much lighter post and rail components will allow installation without the need of lifting equipment, and this benefit should offset the relatively higher complexity in relation to the SPWB system. The versatility is the result of improved aesthetics and response with poor soil conditions by the addition of soil plates to the foundation tube. In summary, the proposed HFRP system can offer significant advantages over the current SPWB system, but it is necessary to demonstrate by full-scale simulations that the proposed system can meet *NCHRP Report 350* Test Level 3.

RECOMMENDATIONS

A variety of design concepts were presented in the previous section. The design concepts were rated according to a scheme based on the priorities developed from the survey of states.

Popout Post Guardrail System

The concept with the highest overall ranking was the popout post guardrail system. The popout post was not the highest ranked system in terms of its likely performance, but was the best balance between expected cost and performance. The popout system addresses many of the safety deficiencies of the SPWB system while still retaining the basic cost of the existing system. The popout post has additional maintenance advantages, since the system is maintained from the ground up and repair would only rarely require re-driving foundation posts. The popout system is thought to be somewhat more versatile than the SPWB, since the foundation posts can be modified with soil plates to account for poor soil conditions.

While the popout post is more than a minor variation in the SPWB system, it uses the same basic design philosophy used in most guardrail systems, and it uses materials and construction techniques that are well understood. The likelihood of being able to develop a system that will pass the required *NCHRP Report 350* crash tests appears to be fairly high based on the finite element simulations performed in this study. The research team recommends that this system be considered for further development.

HFRP Post and Rail Guardrail System

The HFRP post and rail system was one of the highest rated systems in terms of likely performance. The system has great potential for providing a much more effective and a more tenable guardrail system than currently exists. The system addresses all the safety performance issues identified in the ranking tables. The system also should be easier to maintain, since it uses some of the concepts of the popout post system to isolate damage to easily repaired parts. The system is also somewhat more versatile than the SPWB, since it can be adjusted to suit different soil conditions.

The primary disadvantage of the HFRP system is the high initial cost and uncertainty about the long-term, steady-state cost and performance of the system. New terminal and transition systems would have to be developed to work with this new guardrail system because the elements of the HFRP system are much different than current systems.

Development of the HFRP system would pose some challenges. HFRP materials are new to the roadside safety industry, so there is relatively little experience with these materials in impact situations. A comprehensive testing program aimed at understanding the impact response of these materials would be required prior to the development of a deployable guardrail system. This uncertainty about the material response and its production cost make the HFRP a more risky investment, although the potential benefits in terms of performance may well be worth the risk. The research team recommends that the HFRP system be considered for additional research to determine the impact response of the materials and also to develop more detailed estimates of the production costs. If the material response and costs prove to be acceptable, the HFRP may be a very promising system.

Leaf-Spring Guardrail System

The leaf-spring guardrail system is conceptually based on the SERB guardrail system. The system has been refined to remove some of the maintainability problems that were experienced with the SERB. The performance of the system is expected to be one of the highest of the concepts examined (the leaf-spring system is tied with the HFRP system for performance). The system has maintenance advantages, since it will require no repair for most types of impacts.

Like the HFRP system, the primary disadvantage of the leaf-spring system is its installation cost and complexity. While it is difficult to estimate the final steady-state production cost of the HFRP system, it is relatively easy to estimate the cost of the leaf-spring system because the leaf-spring system uses readily available common materials and construction methods where the costs are well known. From an examination of the concept, the research team is nearly certain that the resulting system would be very expensive to install. While this high expense may be appropriate for specific high-crash locations, the leaf-spring guardrail system would not likely be able to compete with the SPWB, even recognizing its superior performance. For this reason, the research team recommends that the leaf-spring system not be considered for further research.

Z-Post Guardrail System

The Z-post guardrail system resolved a number of safety performance issues, and its cost is expected to be comparable to the existing SPWB system. The main disadvantage to this system involves maintenance and repair. Since the post is designed to collapse before contact with potentially snagging wheels, even minor crashes may damage a large number of posts, which would then require repair. The repairs would require removing damaged posts and redriving new posts. This need for extensive repair resulted in a low score for maintainability, which reduced the overall rating.

Since the Z-post system uses well-understood materials and construction techniques, it is highly likely that a system could be designed that would meet the requirements of *NCHRP Report 350*. The maintainability issues, however, would probably preclude the Z-post system from ever successfully challenging the SPWB system in the marketplace.

Improved SPWB System

While the performance improvements for the improved SPWB were the smallest in the group of concepts considered, it is still an improvement over the existing SPWB, as reflected by the positive score. The cost, maintainability, and versatility are all expected to remain essentially the same as the existing system.

The improved SPWB system features a variety of relatively minor improvements that are already being incorporated in new guardrail designs. The research team believes that many and perhaps most of these ideas will be integrated into existing guardrail system designs without any additional research. The implementation and research costs are small enough that manufacturers and states should be able to integrate these ideas into existing systems.

Summary

Five concepts for new or improved guardrail systems were developed in this project:

- An improved SPWB guardrail system,
- The popout post guardrail system,
- The Z-post guardrail system,
- The leaf-spring post guardrail system, and
- The HFRP post and rail guardrail system.

The concepts were examined using a variety of techniques, including finite element analysis, structural design, and engineering judgment. The concepts were then ranked according to a scheme based on the priorities derived from a survey of the states. The popout post and HFRP post and rail systems ranked most highly based on a combined score that included performance improvements, overall cost, maintainability, and system versatility.

FINAL REPORT

The agency's final report, which was distributed to NCHRP sponsors (i.e., the state DOTs), is available for loan on request to the National Cooperative Highway Research Program, Transportation Research Board, 500 Fifth Street, NW, Washington, D.C., 20001.

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