Development of Guardrails for High-Speed Collisions

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The installation of guardrails in Japan is conducted according to the Guideline of Guard Fences (October 1972) and has served to prevent or alleviate accidents around the country by keeping vehicles from leaving the road. However, since the guideline was first promulgated, traffic characteristics in Japan have changed considerably: the total extension of national expressways is much longer, the performance of vehicles has been improved dramatically, traffic on national expressways is faster, and vehicles are larger. Consequently, the severity of a guardrail collision tends to be much higher than before, and this trend is expected to continue in coming years. For this and similar reasons, a number of investigations and experiments were carried out in 1990 and 1991 to develop new types of guardrails for highways. This paper focuses on a design of guardrails for high-speed impacts that satisfies demands exceeding those specified in the current guideline. A basic design for a guardrail capable of withstanding an impact of 20 degrees by a 20,000-kg truck running at 100 km/hr is described.

The installation of guardrails in Japan is conducted according to the Guideline of Guard Fences (*1*) and has served to prevent or alleviate accidents around the country by keeping vehicles from leaving the road. However, since the guideline was first promulgated, traffic characteristics in Japan have changed considerably. The total extension of national expressways is faster and vehicles are larger. The impact of guardrail collisions has steadily increased and is expected to increase even further.

With the development of highway networks and the construction of bypasses for ordinary roads, traffic moves faster. With the increased importance of road transportation and the enhanced performance of cars and trucks, there is a steady trend toward bigger vehicles. For these reasons, it has become necessary to reexamine the design of guardrails for high-speed impacts to develop new types that are able to withstand impacts larger than those envisioned in the design parameters for the guardrails currently in place.

In addition to revealing guardrail and vehicle impact characteristics under high-speed collisions, we propose a design for a guardrail that is able to provide sufficient strength and occupant safety in the event of an impact in excess of the design parameters for a Type S guardrail (vehicle weight = 14 000 kg; impact velocity = 80 km/hr; impact angle = 15 degrees; impact severity = 232 kJ; see Table 1), which is the strongest type of guardrail currently in use in Japan.

GENERAL DESCRIPTION

The general flow of our research is presented in Figure 1.

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Impact Condition

Impact conditions consist of the vehicle weight, the impact velocity, and the impact angle. The results of our surveys and theoretical studies and our impact conditions are presented in Table 1.

Study of Guardrail Design

As a starting point for modification in the development of a guardrail to accommodate high-speed impact, we chose to begin with a guardrail previously developed for sharp curves (Gr-SS) (*2*). This guardrail has the highest impact resistance of any of the types we developed previously, and we decided to proceed with our modifications after first verifying its high-speed impact characteristics.

Vehicle Impact Tests

To verify the vehicle guidance characteristics, strength, and other barrier performance items, barrier designs that were judged to be promising through design investigations and impact simulations were subjected to impact tests with vehicles.

Outline of Test Facilities

The test facilities used a winch to pull the vehicle into the barrier. The maximum pulling performance of the setup was as follows:

Normal truck: vehicle weight = 20 000 kg; pulling speed = 100 km/hr.

Small passenger car: vehicle weight = 2500 kg; pulling speed = 140 km/hr.

Post Foundation Ground Conditions

The condition of ground into which the barrier posts are sunk has a great effect on pillar deformation and support characteristics. For this reason, it is best that the tests are done under consistent ground conditions. As standard ground conditions for our testing, the typical highway base was adopted.

Measurement Items and Evaluation Items

Measurement items and evaluation items are presented in Table 2.

TABLE 1 Impact Condition

	Class	Vehicle type	Vehicle weight W	Impact velocity V	Impact angle θ	Impact severity IS
Impact conditions for this investigation	SS	Normal truck	20,000 (kg)	100 (km/h)	20 (°)	902 (kJ)
		Small passenger car	1,100 (kg)	140 (km/h)		92 (kJ)
Current Japanese impact standards	S	Normal truck	14,000 (kg)	80 (km/h)	15 (°)	232 (kJ)
		Small passenger car	3,500 (kg)			58 (kJ)
	A	Normal truck	14,000 (kg)	60 (km/h)		130 (kJ)
		Small passenger car	3,500 (kg)			33 (kJ)
	B	Normal truck	14,000 (kg)	40 (km/h)		58 (kJ)
		Small passenger car	3,500 (kg)			14 (kJ)
	C	Normal truck	14,000 (kg)	35 (km/h)		44 (kJ)
		Small passenger car	3,500 (kg)			11 (kJ)

$$\text{Impact severity} = \frac{W}{2g}(V \times \sin\theta)^2 \ldots (1)$$

W: vehicle weight (t)
θ: impact angle (°)
V: impact velocity (m/s)
g: acceleration of gravity (m/s²)

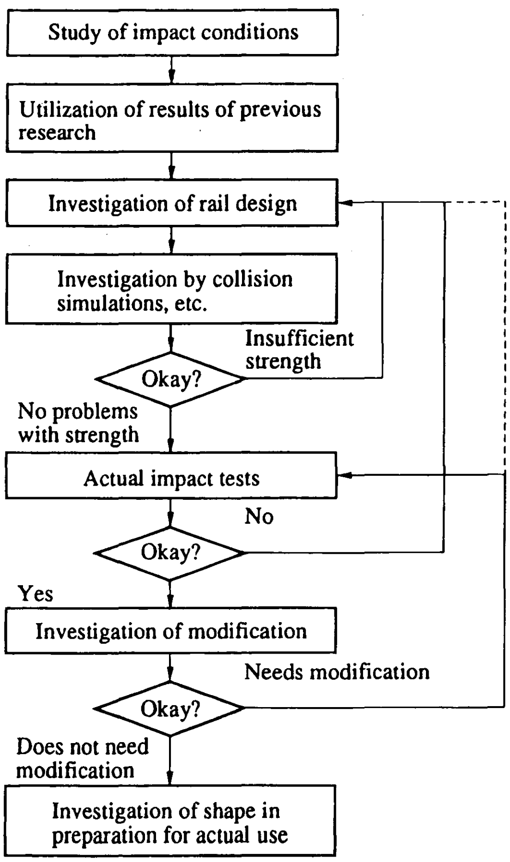


FIGURE 1 General flow of research efforts.

RESULTS

Following the procedures outlined in the previous section, we conducted a total of nine impact tests (normal trucks, six times; small passenger cars, three times) using the procedure presented in Figure 2. In the following sections, we discuss results of basic investigations into the strength and guidance characteristics of the guardrails in collisions with normal trucks. In addition, we discuss results of the investigations of occupant safety in small passenger cars in high-speed collisions. Table 3 presents a compilation of the test results.

Normal Trucks (Tests 1–6)

In the first test we examined the suitability of the guardrail for sharp curves in a high-speed collision (20 000-kg truck, 100 km/hr, 15 degrees, 516 kJ). The truck tipped onto its side on collision. Following up on this result, we modified the basic design of the guardrail and tested the effectiveness of these modifications in Tests 2 through 6. We later described some of the things we were able to confirm through this series of tests. The locations and names of various parts of a guardrail are illustrated in Figure 3.

Beam Height and Beam Strength

Because of the low height of the main beam in Test 1, the inertial force of cargo from the collision was not adequately accommodated. As a result, the truck fell on its side (Figure 4).

We modified the design by adding a cargo acceptance beam about 1300 mm above the center of gravity of the vehicle; guidance

TABLE 2 Measurement and Evaluation Items

Test evaluation	Measurement items	Evaluation items
Barrier strength	Maximum displacement Horizontal post force Beam tension	Barrier contain and redirect the vehicle. Beam-stress is within permission stress. The posts are required to be strong enough to withstand the impact force.
Vehicle behavior	Exit velocity Exit Angle Vehicle trajectory Jump height Slant angle	Vehicle stays on road and does not roll sideway or spin after collision. Exit verocity is no less than impact velocity by more than 20km/h and 25%. Exit angle is within 10degrees and 60% of impact angle.
Occupant Safety	Occupant accelerations Vehicle accelerations Vehicle trajectory	Detached elements from the barrier and the vehicle not penetrated or show potential for penetrating the occupant compartment. HIC<1,000. 50(ms) average accelerations< 25(x), 15(y).

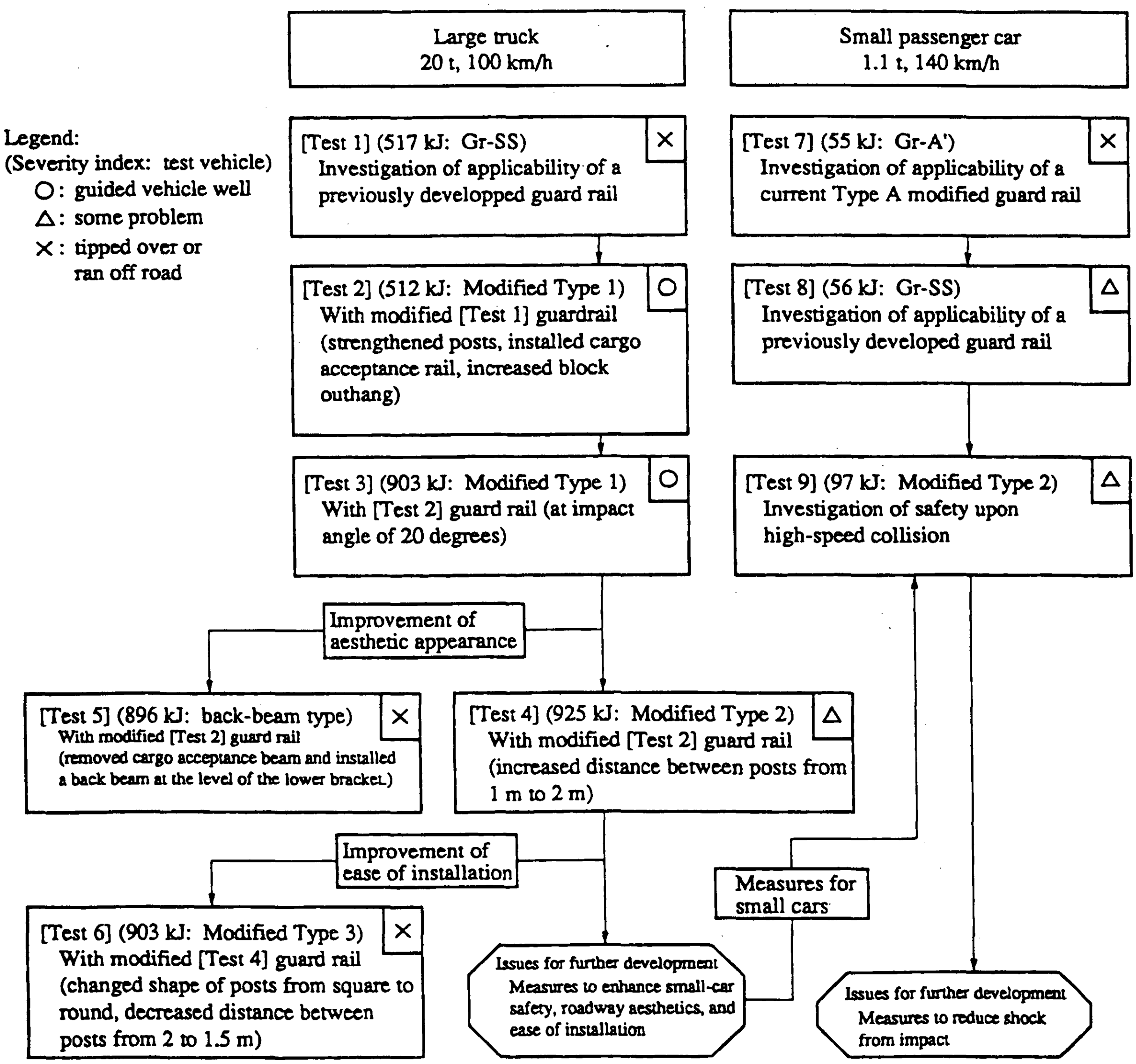
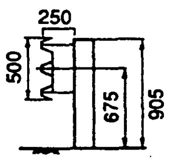
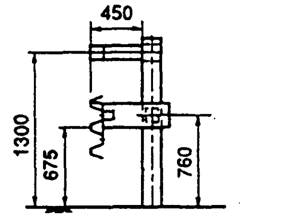
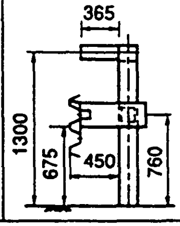
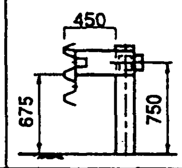
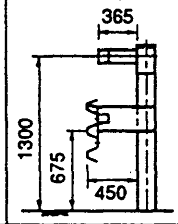
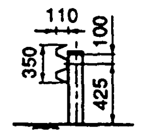
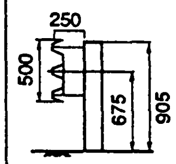
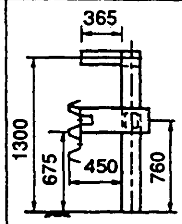


FIGURE 2 Flowchart for impact test results.

TABLE 3 Compilation of Test Results

	Test No.		Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
	Vehicle type		Large truck						Small passenger car		
	Barrier		Gr-SS	Gr-SS Modified Type 1	Gr-SS Modified Type 1	Gr-SS Modified Type 2	Gr-SS back-beam type	Gr-SS Modified Type 3	Gr-A'	Gr-SS	Gr-SS Modified Type 2
Test setup	Sectional plan										
Test setup	Post dimensions (mm)		ø139.8x4.5	□100x100x6.0				ø139.8x4.5	ø114.3x4.5	ø139.8x4.5	□100x100x6.0
Test setup	Post spacing (m)		1	1		2	1	1.5	4	1	2
Test setup	Weight (kg/m)		77.6	144.8		91.8	122.5	94.2	47.3	77.6	91.8
Collision results	Vehicle weight (t)		20.0	20.0	20.0	20.5	20.0	20.0	1.1	1.1	1.1
Collision results	Impact velocity (km/h)		100.1	100.0	100.0	100.0	99.6	100.0	138	139.5	139.5
Collision results	Impact angle (°)		15	15	20	20	20	20	15	15	20
Collision results	Impact severity	(t-m)	52.7	52.7	92.1	94.4	91.4	92.1	5.6	5.7	9.9
Collision results	Impact severity	(kJ)	517	517	903	925	896	903	55	56	97
Measurements	Exit velocity (km/h)		Tipped	88.9	76.9	79.5	Tipped	Tipped	Glided	118.5	115
Measurements	Exit angle (°)		Tipped	6.2	9.8	7	Tipped	Tipped	Glided	7	5.4
Measurements	Contact length (mm)	Main beam	17.4	11.5	12.7	19.9	13.5	25.1	11.3	5.23	8.79
Measurements	Contact length (mm)	Cargo acceptance beam	–	14.5	16.1	21.8	29.0	26.6	–	–	–
Measurements	Max. permanent displacement (mm)		1202	678	1086	1602	570	1832	680	90	177
Measurements	Ave. horizontal force on pillar (t)		6.0	8.6	8.3	16.4	9.5	9.7	5.4	4.2	6.6
Measurements	Max. tension (t)	Main beam	26.3	26.6	26.6	25.8	45.9	29.3	4.5	8.0	–
Measurements	Max. tension (t)	Cargo acceptance beam	–	14.5	12.3	24.4	10.5	37.5	–	–	–
Measurements	Acceleration at vehicle COG for first 50 ms (g)	Direction of Travel (X)	–4.4	1.8	2.0	1.6	–	–	3.3	3.2	6.7
Measurements	Acceleration at vehicle COG for first 50 ms (g)	Normal direction to Travel (Y)	3.2	4.2	2.1	1.5	–	–	7.9	–13.9	26.9
Measurements	Acceleration at vehicle COG for first 50 ms (g)	Resultant	4.9	4.3	2.6	3.5	–	–	8.4	13.9	26.9
Measurements	HIC	(driver's seat)	14.8	6.5	50.5	8.3	–	–	424.3	551.8	1311
Measurements	HIC	(front passenger's seat)	7.3	146	22.8	11.3	–	–	535.7	1530.9	902
Test evaluation	Barrier strength		Insufficient strength overall	Much structural margin	Little structural margin	Very near performance limit	Insufficient beam height	Insufficient post strength	Insufficient block outhang	Much guard rail rigidity	Much guard rail rigidity
Test evaluation	Vehicle behavior		Broke through and tipped	Normal guidance	Normal guidance	Normal guidance	Tipped on road	Broke through and tipped	Glided and tipped	Normal guidance	Normal guidance
Test evaluation	Occupant safety		×	Good	Good	Good	–	×	×	×	×
	Overall evaluation		×	○	○	○	×	×	×	Δ	Δ

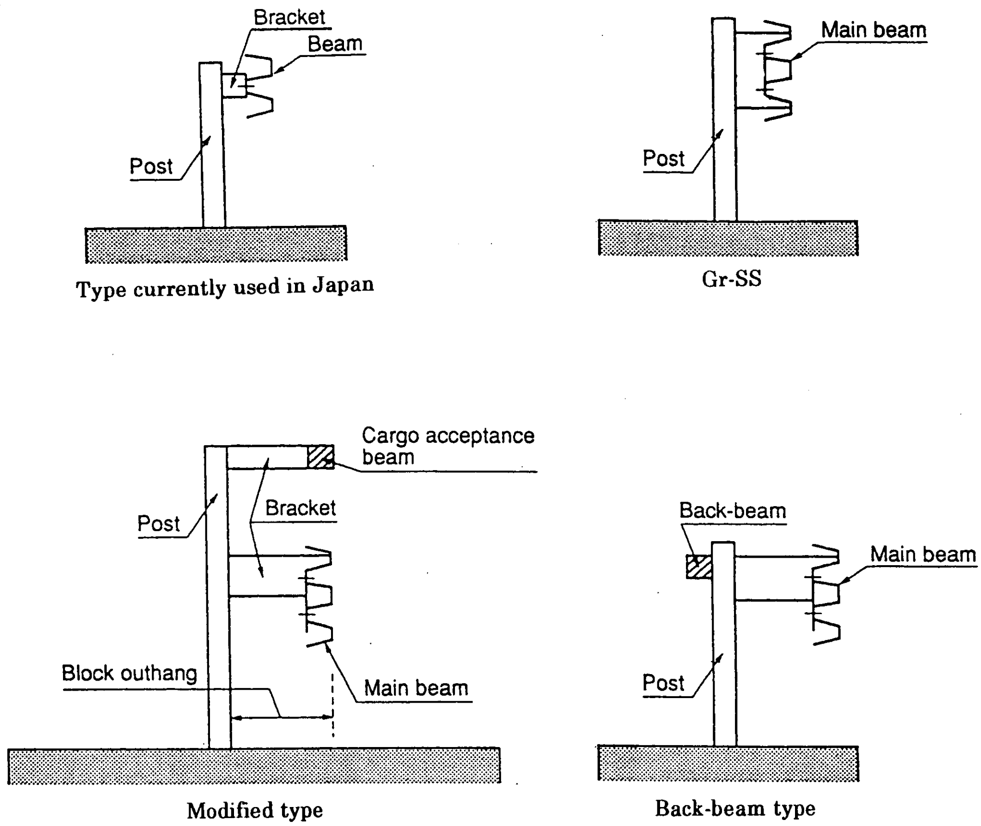


FIGURE 3 Guardrail parts.

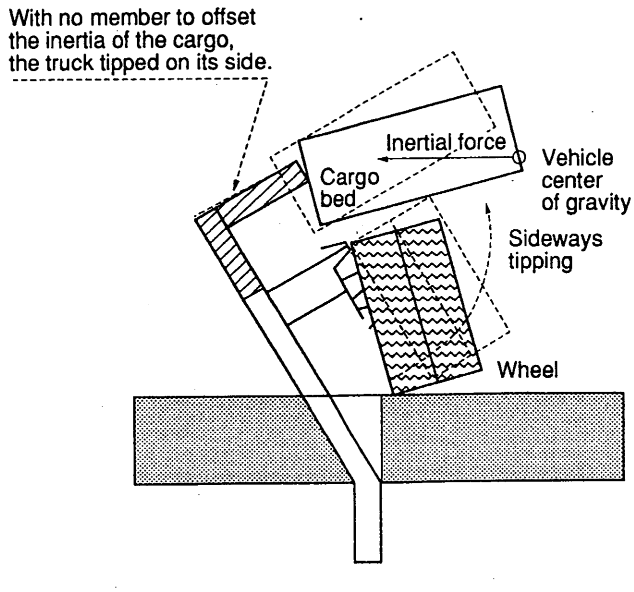


FIGURE 4 Motion of vehicle on collision.

performance was good. To confirm the effectiveness of the cargo acceptance beam, we conducted Test 5 without the cargo acceptance beam (but with a back beam; see Figure 3). In this test, the inertial force of cargo was not fully accommodated, and the vehicle tipped onto its side on the road.

We believe that for the protection of normal trucks it is necessary to install a cargo acceptance beam at a height near that of the vehicle's center of gravity. Furthermore, we confirmed through testing that a suitable location for the main beam is about the height of the vehicle tires, where the load of the collision is concentrated (Figure 5).

The main beam (SS400[3]) receives most of the impact load. It functions as a tension member on impact and must not break. In all of the tests, the resulting stress on the main beam never exceeded

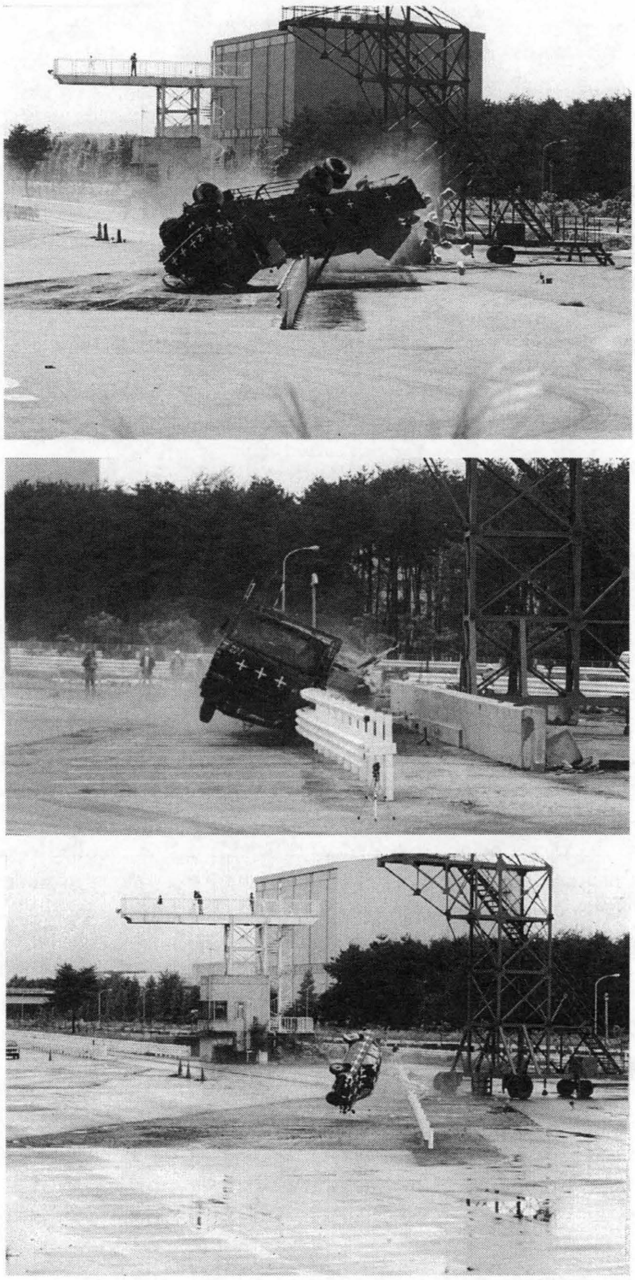


FIGURE 5 Results of impact test: (*top*) Gr-SS, (*middle*) Gr-SS Modified Type 2, (*bottom*) Gr-A′.

tolerance limits and the beam never broke. On the basis of these results, we believe suitable values for the main beam to be as follows: beam cross-sectional surface area = 31.2 cm^2, cross-sectional coefficient = 64 cm^3, and bend rigidity = 57.1 t-m^2. The cargo acceptance beam (STK400[4]) supports the load from the truck cargo and distributes that load among posts over a wide area. In Test 2, 3, and 4, in which vehicle guidance performance was good, the stress acting on the cargo acceptance beam was within limits and the beam did not break. On the basis of these results, we believe suitable values for the cargo acceptance beam to be as follows: beam cross-sectional surface area = 16 cm^2 and bend rigidity = 29 t-m^2. Our recommended shape is square: 100 · 100 · 4.5 (area = 16.7 cm^2; bend rigidity = 52 t-m^2).

Post Strength

The posts (STK400) are required to be strong enough to withstand the impact force and, on deformation, are not to have a sudden drop in supporting force caused by localized buckling or the like at or near ground level.

To make the posts easier to install, we modified them in preparation for Test 6 as presented in Table 4. As a result, however, the guardrail bent back on collision and the vehicle tipped onto its side. Consequently we believe that it is necessary when installing a guardrail intended to withstand severe impacts, to consider the relationships of post spacing, average support force per post, post shape, and other post strength-related factors.

Block Outhang

The block outhang is the distance that the main beam projects from the pole, and it is provided to keep the vehicle from colliding directly into the pole. In Test 1, the block outhang was 250 mm, which was not long enough to prevent the wheels of the truck from running over the poles and bending them down. In effect, this aggravated the problem of low beam height, and as a result, the vehicle tipped over.

From Test 2 onward, the block outhang was set at 450 mm, a distance that, by desktop calculations, we estimated would be effective in keeping the wheels from running over the poles. In the subsequent tests we found that this problem did not occur and that the longer outhang had no adverse effects on the guardrail as a whole. For these reasons, we believe that a block outhang of at least 450 mm is necessary.

The bracket that attaches the beam to the pole must continue to maintain the gap between the two even after the guardrail deforms on collision. For this reason, it must have a high rigidity.

Small Passenger Cars Tests (Tests 7 through 9)

The guardrails used in testing for normal truck collisions must be able to handle high impact energies. For this reason, their structure is such that they do not deform easily on low energy (passenger car) collisions. In Tests 7 through 9, we examined the high-speed passenger car impact behavior of three types of guardrails.

Suitability of Current Guardrails

In Test 7, we examined the ability of a currently used guardrail to handle high-speed collisions with small passenger cars. The test

TABLE 4 Revision from Modified Type 2 to Modified Type 3 Post

Revised item	Modified type 2 post	Modified type 3 post
Post	□-125 × 125 × 6 (STK400)	ø-139.8 × 4.5 (STK400)
Post support force	6 t	4 t
Post spacing	2 m	1.5 m
Support force	3 t/m	2.7 t/m

Notes: • Post support force : determined by post loading tests
• Support force : post support force/post spacing

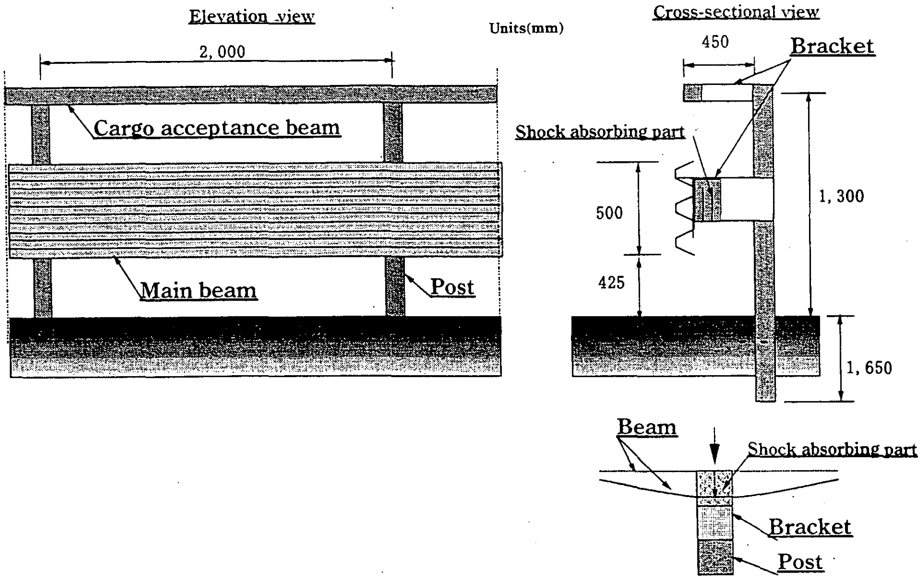


FIGURE 6 Modified Type 2.

revealed that the rail cannot adequately handle a collision at about 140 km/hr; we learned the necessity of providing sufficiently strong posts and a suitable block outhang (Figure 4).

Occupant Safety

In Test 8, we used a guardrail (Gr-SS; see Figure 3) with no cargo acceptance beam. Although it has good guidance characteristics, it imparts to vehicle occupants a head injury criteria (HIC) that exceeds the tolerance limit. The structure of the Gr-SS has a high rigidity in high-speed collisions with small passenger cars.

In Test 9, we examined the small passenger car high-speed collision behavior of the modified Type 2 guardrail, which was shown to be effective for collisions involving large trucks. In this test, tolerance limits for the acceleration at the vehicle center of gravity and for the HIC were exceeded. From this, we can say that a highly rigid rail like the modified Type 2 imparts a high impact load on vehicle occupants and still has much room for improvement in terms of safety.

Based on the results of these three tests, we conducted a separate investigation on the design of a bracket that will protect vehicle occupants. We believe that the development of this type of bracket will make it possible to assure passenger safety, even with a highly rigid guardrail like that of modified Type 2, which was shown to have good guidance characteristics for normal trucks.

Beam Height

In Tests 7 through 9, we confirmed that a beam height of about 425 mm prevents small passenger cars from "burrowing" underneath on collision.

CONCLUSION

In this series of tests with normal trucks, we found that, even with guardrail impact conditions (vehicle weight = 20 000 kg; impact velocity = 100 km/hr; impact angle = 20 degrees; impact severity = 903 kJ) considered severe by world standards, the modified Type 2 guardrail (Figures 4 and 6) has a structure that smoothly guides the vehicle on impact. Also, in three tests with small passenger cars, we examined guardrail behavior characteristics in high speed collisions with such vehicles.

Based on the structure of the modified Type 2 guardrail, which was not able to handle high-speed collisions by normal trucks adequately, we intend to study ways to further improve the performance of the guardrail structure though efforts to lessen the impact shock on passenger cars, to increase the ease of installation, to enhance its economic attractiveness, and to lighten the heavy, oppressive look along our highways.

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