SIMULATED OPTIMAL PERFORMANCE DESIGN FOR CONCRETE MEDIAN BARRIER

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Abstract: The current concrete median barrier of NJ type and its variation have problems of vehicle overturn and rollover due to its low height. This study evaluated various concrete median barrier designs by varying the height, top and bottom width, and slope. The MESH program was used for modeling the 14-ton trucks. The simulated collision program of PAM-CRASH was used for design evaluation. It was found that the height is the most significant factor affecting the vehicle overturn and rollover. The vehicle's deceleration rate after impact is mostly affected by the angle of the first slope. The detailed shape and dimension of the best performance concrete median barrier was developed and proposed for further crash evaluation.

Key Words : Concrete Median Barrier, Pam-Crash, Clash Test, Crash Simulation, Vehicle Impact

1. INTRODUCTION

The concrete median barriers have been utilized to provide safe protection of vehicles from the opposing direction. Its primary function includes guiding a vehicle after crashing a barrier and to prevent the critical accidents possibly caused by the opposing traffic. Such type of accident costs critical damages in both people and property.

In the Korean freeway system, it has been experienced that the concrete median barrier does not effectively hold vehicles after crashing. The statistic shows that total of 535 accidents were involved in the crashes with the median barrier on the Korean freeways during the recent 5 years. In 36.6% of such accidents, the crashing vehicles were fully and partially passed to the other side of barrier. Table 1 summarizes the accidents experienced. The accident groups categorized in the item 1,2 and 3 are the ones that the barrier did not hold crashing vehicles in their side of the barrier. The crashing vehicles appeared in the other side of barrier by rolling over, jumping over and stopping at the top of the barrier. The 196 (36.6%) accidents were categorized in those groups. Figure 1 shows the cases of rolling over and stopping at the top of the barrier experienced in Korea. It was also observed from the statistic that the subsequent accident caused by the debris from the previous accident contributes 50.2% (269 cases) of the total accidents.

Table 1. Accident Characteristics Associated Concrete Median Barrier

Category	Accident Type (Total 535)	
1	Cross Over Barrier	136
2	Stopping at the top of Barrier	40
3	Crash Barrier and Rollover	20
4	Crash Barrier and collide other Vehicle	3
5	Crash Barrier and stopped	51
6	2nd Accident by Broken Pieces	269
7	Pushed Barrier	16

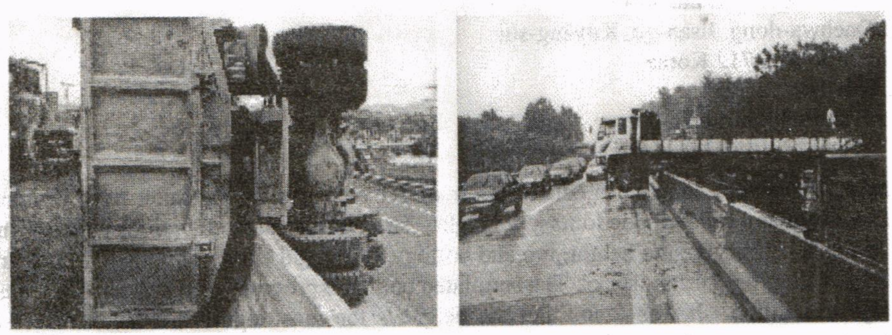


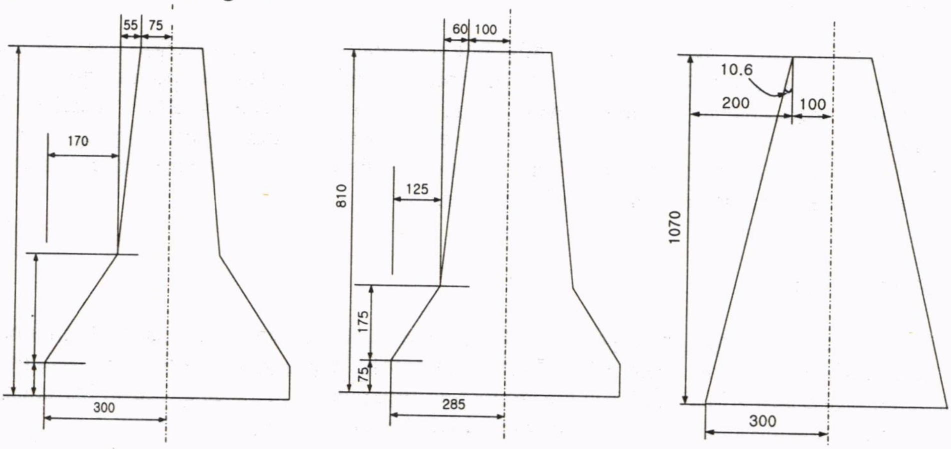
Figure 1. Cases of Barrier Crash Accident

The objective of this study is to propose a new design of the concrete-median barrier that overcomes the problems experienced with the existing barrier. The new design should not only satisfy the functional requirement as a median barrier but also reduce the degree of damage by minimizing the impact power to the crashing vehicles. The PAM-CRASH program, a car-crash-simulation program, was used to analyze the performance of the design alternatives of the barrier. The MESH program was employed to model a design truck used in the test.

2. BACKGROUND

Several types of the concrete median barriers are installed in Korea. The major types of barriers used in Korea were developed in the United States through the real-crash-experiment tests.

Those types of concrete barriers can be categorized into three groups. They include the New Jersey barrier, the Configuration F barrier and the Constant Slope barrier. Figure 2 presents the design standard of those three types of barrier. Brief description on each type of barrier is provided in the following list.



Configuration F Barrier   Constant Slope Barrier

Figure 2. Design Standard of Median Barriers

The New Jersey barrier

The New Jersey barrier was developed in New Jersey, U.S., and its first installation was made in the U.S. in 1955. Its height was initially set to 460 millimeters (mm) but has been increased to 610 and 810 mm due to the safety problems experienced. The up-to-date height of New Jersey Barrier was set to 810 mm in 1959. Through the crash test performed in California in 1967, it was proved that the functionalities of the New Jersey barrier met the safety requirements as a median barrier with the designed condition used in the test. The New Jersey barrier is proposed to be used on highways where its median width is less than 10 meters (m).

The Configuration F barrier

The Southwest Research Institute developed the Configuration F barrier in 1977 to resolve the safety problem experienced with the New Jersey barrier with small-size vehicles. The Configuration F barrier was featured with its shorter height of slope placed in-between the upper and lower parts of the barrier than the one of the New Jersey barrier (see Figure 2). It has been experienced that the Configuration F Barrier reduces the number of vehicles flipped after crashes. However, it provides slightly higher impact to vehicles. The usage of the Configuration F barrier in the U.S. highway system has been grown because of its overall superiority as a median barrier. Since 1990, Configuration F Barrier has dominantly been installed in the Korean freeway facilities.

The Constant-slope barrier

The constant-slope barrier is featured with the constant slope (80°) in-between the top and bottom parts of the barrier. The Texas Transportation Institute (TTI) developed the Constant-slope barrier in 1990 to minimize the rollover of the crashing vehicles after crashes. However, this type of barrier transmits higher impact energy to people in the vehicle crashing than the other types do and does not guide the vehicles to stable paths after crash. Continuous research has been being conducted to mitigate the shock impact influencing drivers and passengers and to stabilize vehicles after crash.

In the Korean freeway system, the Configuration F barrier is mostly used. It has been experienced in Korea that the type of barrier does not fully satisfy the major functionality required as a median barrier – holding the crashing vehicles in the crashed side of barrier. The problems experienced with the Configuration F barrier include rolling over, jumping over and stopping at the top of the barrier. It reveals that the Configuration F barrier does not meet the functionalities required in Korea as a median barrier.

3. METHODOLOGY

The simulation method was employed to evaluate the design alternatives due to the limitation of the field-crash experiment. The PAM-CRASH and MESH programs were employed in the simulation process. PAM-CRASH is the simulation program that is specialized in car-crashing test. MESH is the modeling tool that constructs three-dimensional objects.

Eight design variables were set to design the concrete median barrier. The variables include (1) the height of barrier, (2) top and (3) bottom widths of barrier, (4) the height of the base, (5,6) two angles of slopes and (7,8) two radiuses of curves. Those variables are presented with the illustration in Figure 3. The half of a concrete median barrier was used to determine the design parameters since the barrier should be symmetric in its shape. The values of variables were varied as shown on Table 2 to produce the design alternatives based on the standard condition set for the test.

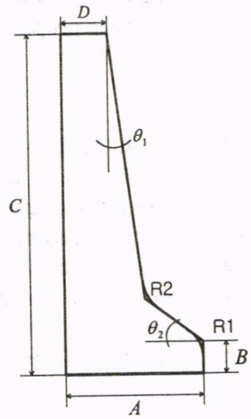


Table 2. Design Factors and Levels

Factor	No. of Level	Level			Factor	No. of Level	Level		
		1	2	3			1	2	3
R2	2	100	90		D	3	100	85	75
A	3	305	295	285	θ_1	3	7	6	5
B	3	85	80	75	θ_2	3	65	55	45
C	3	1270	1140	1000	R1	3	290	280	270

Figure 3. Eight Design Variables of Median Barrier

3.1 Concrete Median Barrier Design Procedure

The barrier following the standard condition was controlled to be the shape of the Configuration F barrier. Figure 4 shows the shape of the standard barrier used in the test. The bottom width and the height of the barrier were set to 61 and 127 centimeter (cm), respectively. The bottom width was set to satisfy the 150mm of the minimum requirement of the top width. The height was designed to prevent the rollover of crashing vehicles. The height was computed based on the average-moment equation at the point 'O' on the barrier, as shown in Figure 5. Figure 5 provides diagram used to draw the equation.

$$H = \frac{CGa - B/2}{\mu + Ga} \qquad (1)$$

In the equation, the height of concrete median barrier that prevents vehicle's rollover is a function of (1) acceleration rate, (2) the height of vehicle centroid, (3) the width of vehicle and (4) the pavement friction factor. It should be noted that the center of gravity (COG) of the design vehicle is higher than the height of the barrier; however the moment of restoration mitigates the moment of rollover. On the other hand, the TTI provided a guideline to design the barrier height. The TTI guideline is provided in Table 3. The barrier height considered in the standard condition satisfies the guideline proposed by TTI.

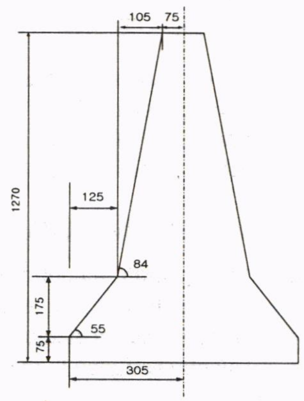


Figure 4. Shape of the Standard Barrier Used in the Test

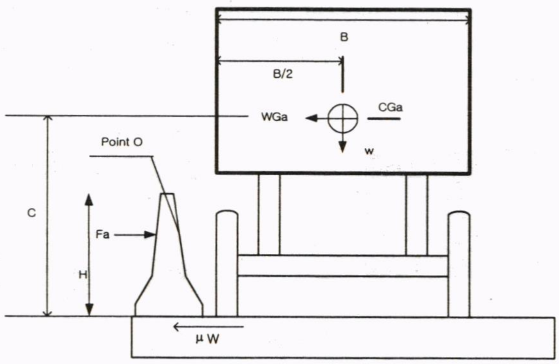


Figure 5. Diagram of Valid Height Equation

Table 3. Guideline to Design the Barrier Height by TTI

	Speed	Angle	Height Guideline
Passenger car & Light Truck	60mph (100km/h)	25°	27"~32" (69~81cm)
Bus (9~18ton)	60mph (100km/h)	15°	38"~42" (97~107cm)
Van Truck (18~36ton)	50mph (80km/h)	15°	50"~54" (127~137cm)
Tank Truck (36ton)			78"~90" (198~228cm)

The eight design variables were varied based on the standard design condition set for the study. The Taguchi method was used to define the best design among the alternatives based on the simulation results. The Taguchi method is a methodology that defines the best combination of performance characteristics of elements with the small number of computations. The test procedure used in this study can be summarized as following. First, the design alternatives were set by varying the value of each design variable from the standard condition. Then, the performance of the design alternatives was estimated through the simulation study, and the results were compared with the Taguchi method. Due to the correlation that may exist among the variables, another set of alternatives was set based on the best design selected in the previous test. Again, the best was selected through the Taguchi method.

The Taguchi method utilizes the Analysis of Variance (ANOVA) test based on the characteristic value determined by the equation. The character of the performance of proposed design is determined based on three factors: Von Mises (VM) stress, acceleration at the COG of the truck and the size of contact area between truck and barrier. The equation used in the test is provided below:

$$\text{SN ratio} = -10 \log[a(\text{max. VM stress})^2 + b(\text{max. Vol.})^2 + c(\text{max. COG Accl.})^2]$$

Three weight parameters were used in the equation to control the effect from the three factors to the characteristics of proposed design. The factor a, b and c were set to 0.3, 0.3 and 0.4, respectively. The highest weight was given to the acceleration at the COG of vehicle due to the safety problem, while the rest was equivalently assigned to the other weights.

3.2 Truck and Barrier Modeling

For the simulation study, a 14-ton truck and the concrete median barrier were modeled with the MESH program. Seven different component modules were set to model the test truck. They include cab, door, frame, tire, assembly, carrying box and miscellaneous parts. The modeled truck used in the test is presented in Figure 6.

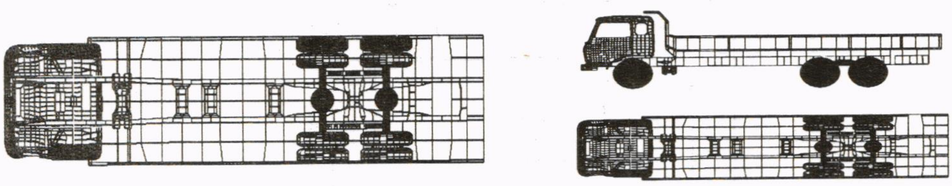


Figure 6. Modeled Truck

The cap part was densely meshed since the shape is expected to be changed aggressively after a crash. For the door part, one side that attaches to the barrier at crash was designed with small shall, while the other side was designed with beam to minimize the modeling work. The frame and carrying parts was designed with large mesh since the damage from crash on those would be insignificant. The tire part was designed by considering inner air pressure. The left-side tires expected to contact the barrier were designed with small mesh, while the other was done with large mesh to minimize modeling work. The assembly part was set for the engine and transmission, and those were modeled as solid components. The miscellaneous part representing the shock absorber and axles are designed with bar elements. Table 4 provides the information about the elements considered in the truck modeling, and Table 5 provides the number of components and materials used in the modeling.

Table 4. Elements and Specifications of Modeling Truck

Kind of Element (No.)	Soild Elements	612
	Shell Elements	24073
	Beam Elements	24
	Bar Elements	2
Number of Points		23578
Weight Specification	Truck Weight (kg)	8933
	Max. Load Weight (kg)	5069
	Total Weight (kg)	1400

Table 5. Material Types and Number of Components of Modeling Truck and Barrier

No.	Material Type	No. of Components
99	Null Material for Solid Elements	3
1	Elastic-Plastic for Solid Elements	10
100	Null Material for Shell Elements	39
101	Elastic for Shell Elements	17
102	Elastic-Plastic for Shell Elements	50
200	Null Material for Beam and Bar Elements	2
201	Elastic for Beam and Bar Elements	3
Barrier	Elastic-Plastic for Solid Elements	1

The alternatives of designs of concrete median barrier were modeled through the MESH program. Figure 7 shows the median barrier modeled for the simulation test.

Figure 7. Median Barrier Model

3.3 Simulation Test

The first set of simulation tests was conducted to analyze the performance of the 18 sets of design variables. The simulation test uses the designed condition specified in the Korean highway safety facility design guideline presented in Table 6.

Table 6. Design Standard of Concrete Median Barrier

Classification	Implemented Road	Design Condition				
		Impact Value (Kj)	Collision Speed (Km/h)	Mass Of Vehicle (t)	Collision Angle (°)	Degree of Acceleration to the Vehicle (g)
Am	Freeway Main National Road	130	60	14	15	Under 4g
Bm	Others	60	40			

The impact shock is the moment energy of a vehicle crashing at a right angle to the median barrier. It can be computed through the following equation. Figure 8 provides a diagram drawn for the computation of impact shock.

$$SI = \frac{1}{2} \bullet m \bullet (\frac{V}{3.6} \bullet \sin\theta)^2 \qquad (2)$$

SI : Impact Value(KJ)
m : Mass of the Vehicle (ton)
V : Collision speed (km/h)
θ : Collision Angle (°)

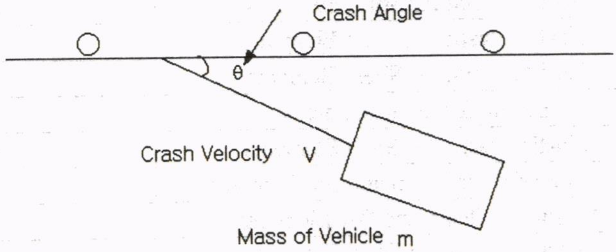


Figure 8. Diagram of Impact Value

The simulation study was made based on the condition specified in the Korean highway safety design guideline. The condition includes the 14-ton truck, 15° of approaching angle, 60 m/h of approaching speed. The simulation was made with the unit time of 1.45×10^{-5} second, and the results were obtained by the unit of 1 million second (ms).

The points of engine and the COG of truck were tracked during the simulation to visualize the trajectory of the vehicle crashing. Figure 9 shows simulation screen shots displayed during the test at 0, 200, 500 and 800 ms, respectively.

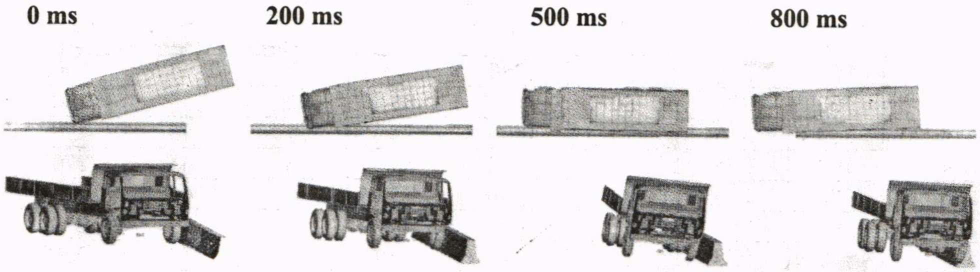
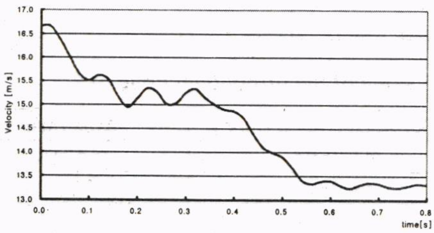


Figure 9. Simulation Screen Shots of Pam-Crash

Figure 10 and Figure 11 shows the variation of average speed and acceleration from the PAM-CRASH program. Figure 11 shows that the acceleration reaches to its maximum near 400 ms, which is the time that rear tires crash to the barrier. This is unrealistic. The PAM-CRASH program provided the unexpected shape of graph due to the material used in truck modeling. The truck was modeled with heavy steel, which features high repulsive power, so the acceleration reaches to the maximum when the rear tires hit the barrier. Thus, the initial acceleration observed at the time when crash occurs was considered as the maximum acceleration in this study.



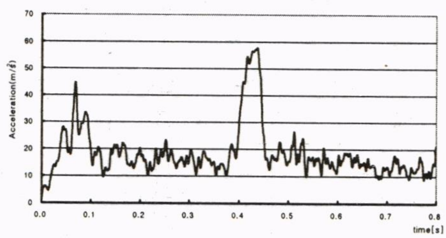


Figure 10. Truck Velocity Graph (L_{18}) Figure11. Truck COG Acceleration Graph (L_{18})

An orthogonal array table (L_{18}), presented in Table 7, was prepared for the Taguchi test that determines the best among the alternatives. The simulation runs with the design alternatives were made, and the results are summarized in Table 8. The values of each characteristic factor presented in Table 8 were normalized by dividing them by their average value. The normalized data are then plotted and presented in Figure 12. Figure 12 visualizes the best design values through the charts. The best values of design variables proposed by Taguchi method without considering the correlation effect of variables are $R2_2(90)$, $A_3(285)$, $B_2(80)$, $C_2(1140)$, $D_1(100)$, $\theta 1_2(6)$, $\theta 2_3(45)$ and $R1_1(290)$.

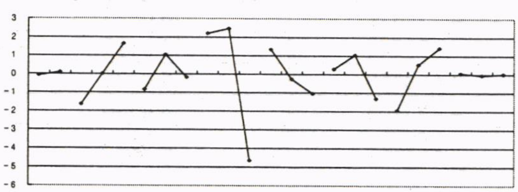


Figure 12. Graph of Factor Effect

Table 7. Orthogonal Array Table of $L_{18}(2^1 \times 3^7)$

No.	R_2	A	B	C	D	Theta1	Theta2	R_1
1	100	305	85	1270	100	7	65	290
2	100	305	80	1140	85	6	55	280
3	100	305	75	1000	75	5	45	270
4	100	295	85	1270	85	6	45	270
5	100	295	80	1140	75	5	65	290
6	100	295	75	1000	100	7	55	280
7	100	285	85	1140	100	5	55	270
8	100	285	80	1000	85	7	45	290
9	100	285	75	1270	75	6	65	280
10	90	305	85	1000	75	6	55	290
11	90	305	.80	1270	100	5	45	280
12	90	305	75	1140	85	7	65	270
13	90	295	85	1140	75	7	45	280
14	90	295	80	1000	100	6	65	270
15	90	295	75	1270	85	5	55	290
16	90	285	85	1000	85	5	65	280
17	90	285	80	1270	75	7	55	270
18	90	285	75	1140	100	6	45	290

Table 8. Maximum and Characteristic value of the orthogonal table of L_{18}

No.	VM Stress [Pa]	COG Acceleration [m/s^2]	Area [m^2]
1	3.775568	41.3594	0.4718
2	4.514434	38.0878	0.3588..
3	8.258017	35.9984	0.2854
4	3.726901	39.8947	0.4090
5	5.900868	41.3548	0.3474
6	7.017464	39.7122	0.3096
7	3.877320	38.5016	0.3510
8	5.399447	40.2365	0.3162
9	3.843352	38.2979	0.3920
10	7.611220	39.3779	0.3080
11	3.915734	34.2751	0.4238
12	4.936339	41.4656	0.3894
13	4.567314	36.2513	0.3560
14	5.550330	41.6231	0.3470
15	4.353832	36.0825	0.3914
16	7.878744	42.8519	0.3154
17	3.648459	38.0425	0.4056
18	4.453163	38.4640	0.2994
maximum	8.258017	42.8519	0.4718

Based on the best set of variables selected, another orthogonal array table (L_{27}) was set to test the possible combination of the variables that may be correlated to each other. Two variables were excluded in the second test: R1 and R2. The L_{27} orthogonal table presented for the second test is presented in Table 9. The simulation runs with the design alternatives were made, and the results are summarized in Table 10. The values of each characteristic factor presented in Table 10 were normalized by dividing them by their average value. The normalized data are then plotted and presented in Figure 13. Figure 13 visualizes the best design values through the charts. The best values of design variables proposed by Taguchi method are A_2, B_2, C_2, D_3, Θ_{11} and Θ_{22}.

Table 9. Orthogonal array table of $L_{27}(3^{13})$

No. of	1	2	3	4	5	6	7	8	9	10	11	12	13
Exp.	B	C	B*C	B*C	θ_1	B*θ_1	B*θ_1	C*θ_1	A	D	C*θ_1	Θ_2	E
1	85	1270	1	1	7	1	1	1	305	100	1	65	1
2	85	1270	1	1	6	2	2	2	295	85	2	55	2
3	85	1270	1	1	5	3	3	3	285	75	3	45	3
4	85	1140	2	2	7	1	1	2	292	85	3	45	3
5	85	1140	2	2	6	2	2	3	285	75	1	65	1
6	85	1140	2	2	5	3	3	1	305	100	2	55	2
7	85	1000	3	3	7	1	1	3	285	75	2	55	2
8	85	1000	3	3	6	2	2	1	305	100	3	45	3
9	85	1000	3	3	5	3	3	2	295	85	1	65	1
10	80	1270	2	3	7	2	3	1	295	75	1	55	3
11	80	1270	2	3	6	3	1	2	285	100	2	45	1
12	80	1270	2	3	5	1	2	3	305	85	3	65	2
13	80	1140	3	1	7	2	3	2	285	100	3	65	2
14	80	1140	3	1	6	3	1	3	305	85	1	55	3
15	80	1140	3	1	5	1	2	1	295	75	2	45	1
16	80	1000	1	2	7	2	3	3	305	85	2	45	1
17	80	1000	1	2	6	3	1	1	295	75	3	65	2
18	80	1000	1	2	5	1	2	2	305	100	1	55	3
19	75	1270	3	2	7	3	2	1	295	85	1	45	2
20	75	1270	3	2	6	1	3	2	285	75	2	65	3
21	75	1270	3	2	5	2	1	3	285	100	3	55	1
22	75	1140	1	3	7	3	2	2	305	75	3	55	1
23	75	1140	1	3	6	1	3	3	295	100	1	45	2
24	75	1140	1	3	5	2	1	1	285	85	2	65	3
25	75	1000	2	1	7	3	2	3	295	100	2	65	3
26	75	1000	2	1	6	1	3	1	285	85	3	55	1
27	75	1000	2	1	5	2	1	2	305	75	1	45	2

Through the Taguchi method, the total number of computations required to determine the best combination was reduced to 35 (18+17). It is significant when compared to 4374 computations required to search whole feasible combinations through the cross-array ($2^1 \times 3^7$) method.

Table 10. Maximum and Characteristic value of the orthogonal table of L_{27}

No. of experiment	Max. Von Mises stress[MPa]	Max volume[m^3]	Max. COG acceleration[m/s^2]	SN ratio
1	3.0091	7.548	41.7004	1.571
2	3.4228	6.595	39.2403	2.281
3	5.0370	5.814	39.4678	2.320
4	3.2670	6.004	41.9958	2.244
5	5.1038	5.619	39.6913	2.364
6	4.0718	6.111	37.1809	2.671
7	6.4186	4.891	38.1124	2.515
8	5.1698	5.406	39.6365	2.449
9	7.4484	5.136	41.8102	1.676
10	3.4491	6.498	39.2445	2.326
11	4.1253	7.010	42.8808	1.544
12	5.1923	6.571	40.3288	1.838
13	3.4247	6.472	37.0000	2.622
14	4.2773	5.882	38.7584	2.543
15	5.6764	5.187	36.9458	2.758
16	6.4717	5.181	38.9358	2.282
17	6.7981	5.063	43.4376	1.695
18	8.1770	5.157	40.7465	1.566
19	2.9974	6.813	38.2392	2.351
20	4.9262	6.487	42.5137	1.680
21	4.0685	6.758	36.2087	2.447
22	4.7510	5.801	38.3322	2.534
23	5.0835	6.175	36.6313	2.483
24	6.6330	5.654	42.2866	1.659
25	5.5590	5.662	43.3536	1.791
26	9.2918	4.934	42.0062	1.151
27	9.8867	4.572	38.8658	1.365
maximum	9.8867	7.548	43.4376	

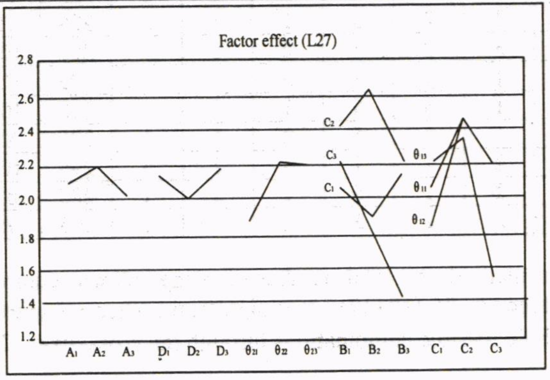


Figure 13. Graph of Factor Effect (L_{27})

The results from the crash simulation with the best set of design parameters were illustrated in Figure 14 and Figure 15. Figure 14 indicates that the best design caused 24% reduction of the truck speed after crash. Figure 15 illustrates that the maximum acceleration is at 38.7 m/s^2. The range of errors of the estimated characteristic from the L_{27} orthogonal array table and from the crash simulation test are 3.14±0.42 and 2.80, respectively. This shows that the test results are acceptable at the designed significant level. It should be noted that the acceleration of configuration F barrier is higher than 4G, but the one from the best set of design variables is less than 4G, which is specified in the Korean highway safety design guideline .

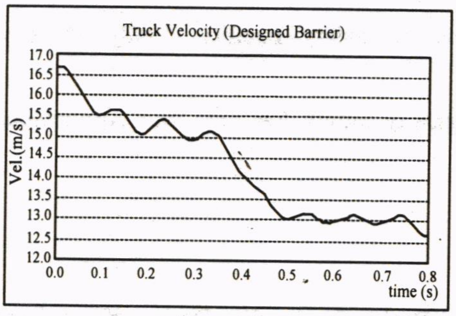


Figure 14. Truck Velocity Graph (L_{27})

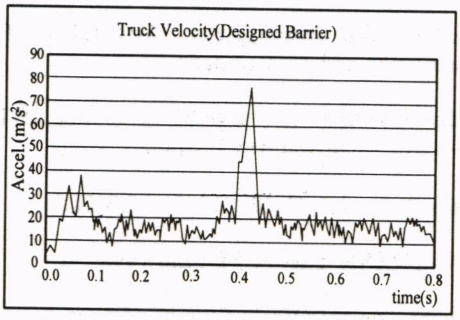


Figure15. Truck COG Acceleration Graph(L_{27})

4. CONCLUSION

The Configuration F Barrier widely used in the Korean freeway system has experienced the rollover, jumping over, and stop at the top of the barrier. A new design of concrete median barrier was studied through the PAM-CRASH program, a vehicle-crash simulation program, to propose a new design of concrete median barrier. A new design was developed and presented in Figure 16. It was found that the best set of design variables for a concrete median barrier in Korea are R2(90), A(295), B(80), C(1140), D(75), θ1(7°) and θ2(55°) and R1(280).

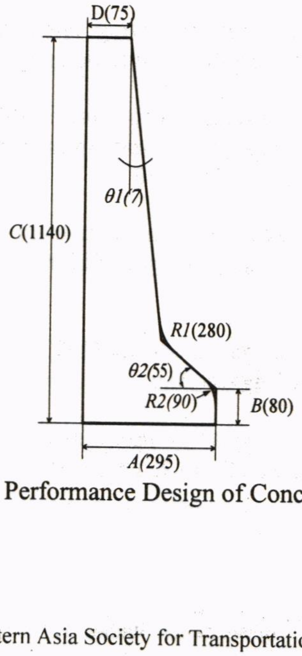


Figure 16. Optimal Performance Design of Concrete Median Barrier

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