NORTHWESTERN UNIVERSITY TRAFFIC INSTITUTE

TRAFFIC SAFETY STUDY

for a

MOVABLE MEDIAN BARRIER SYSTEM

on the

GOLDEN GATE BRIDGE

prepared for the

GOLDEN GATE BRIDGE, HIGHWAY AND TRANSPORTATION DISTRICT

by the

NORTHWESTERN UNIVERSITY
TRAFFIC INSTITUTE
PO BOX 1409
EVANSTON, IL 60204

October 29, 1997

P.O. Box 1409 / Evanston, IL 60204 / Noel C. Bufe, PhD., Director

CONTENTS

EXECUTIVE SUMMARY

The purpose of this study is to determine the impacts that the installation of a movable median barrier system would have on the safety and traffic operational characteristics of the Golden Gate Bridge. At this time, there are two known, commercially available movable barrier systems which have been subjected to standardized crash testing evaluation: the Quickchange Movable Barrier and the Narrow Quickchange Movable Barrier. This study is intended to evaluate these two systems for potential application of the Golden Gate Bridge.

The current accident rate on the Bridge is significantly lower than would normally be expected for this type of roadway. Although the frequency of fatal and injury accidents has decreased, the proportion of injury and fatal accidents relative to total accidents has increased during the past 10 years. A movable median barrier system would eliminate virtually all head-on collisions, but would result in some secondary accidents involving the deflected barrier and vehicles rebounding from barrier impacts. Accident experience on comparable facilities is ambiguous to some extent, and does not provide a clear-cut indication of the safety effects of a movable median barrier on the Golden Gate Bride. However, it appears that the most probable effect will be a reduced frequency of fatal and injury accidents.

In installation of a movable median barrier system would reduce the effective roadway width on the Bridge by at least one foot. Experience on comparable facilities suggests that the presence a movable median barrier system would not negatively affect the vehicle-handling capacity of the Golden Gate Bridge.

The Narrow Quickchange Barrier system has been crash tested and appears to meet all standardized performance criteria for crashworthiness. However, because of the relatively narrow lanes on the Golden Gate Bridge additional performance criteria were developed for maximum lateral deflection and rebound angle. The maximum lateral deflection observed in the crash testing of the Narrow Quickchange Barrier system was slightly more than desired.

There remain several reservations about potential application of a movable median barrier system on the Golden Gate Bridge, including concerns about limited sight distance, loss of buffer lane refuge for disabled vehicles, lateral deflections somewhat greater than desired, and reduced speed and efficiency of emergency vehicle response. In addition, there remain unresolved several important technical issues, including design and testing of an anchorage system for the San Francisco end of a barrier system, lateral positioning of the barrier system relative to the lane markings, procedures for emergency vehicle response, and development and testing of a guidance system for transfer vehicles.

A benefit-cost analysis of the potential installation of a movable median barrier system on the Golden Gate Bridge did not provide clear-cut guidance for making this decision. The outcome of such an analysis is highly sensitive to the value placed on fatal and injury accidents which may be avoided, as well as to the annual operating and maintenance costs of such a system. An expenditure of $1,647,000 to $2,567,000 is required to avoid 1 fatal accident on the Bridge. Whether such an expenditure is appropriate is a decision that must be made by the Golden Gate Bridge, Highway and Transportation District.

If the District elects to move forward with the installation of a movable median barrier system, it should consider implementing a trial installation for two to three years, perhaps leasing the barrier system if possible. A trial installation would permit an evaluation of such a system on the Golden Gate Bridge. During the trial installation period, accident frequency and severity should be closely monitored. Frequency and magnitude of barrier impacts and displacements should also be carefully recorded. Finally, alternative emergency vehicle response strategies can be tested and evaluated.

1. INTRODUCTION

The Board of Directors of the Golden Gate Bridge, Highway and Transportation District is considering the potential installation of a movable median barrier system to separate opposing directions of traffic on the Golden Gate Bridge. The Bridge is a six-lane structure that connects an eight-lane divided freeway from the north to the City of San Francisco via Doyle Drive to the south. It is operated with a movable centerline to provide four traffic lanes in the direction of peak traffic flow. Therefore, the Board has directed that any median barrier considered for application on the Bridge would have to be movable to accommodate this traffic lane allocation pattern.

At this time, there are two known, commercially available movable barrier systems which have been subjected to standardized crash testing evaluation: the Quickchange Movable Barrier and the Narrow Quickchange Movable Barrier. This study is intended to evaluate these two systems for potential application of the Golden Gate Bridge.

Previous traffic safety studies performed by the Northwestern University Traffic Institute (Ref. 1 and 3) evaluated the desirability of installing a movable median barrier system on the Golden Gate Bridge. Both of these studies concluded that the movable barrier system is a useful device with many important applications, but that it was inappropriate for use on the Golden Gate Bridge.

However, a number of important changes have occurred since these previous studies were performed. These include:

1. More than 10 years of accident experience on the Bridge has been accumulated since the Bridge roadway was widened to 62 feet.

2. Movable barrier systems have been installed on a number of permanent and temporary applications throughout the world, and useful accident data from these installations are available.

3. New technology and refinements of previous designs have eliminated several characteristics of candidate movable barrier systems and end treatments that were considered objectionable in the previous studies.

Head-on collisions have remained relatively infrequent occurrences on the Bridge, but the resulting injuries and fatalities associated with head-on collisions remain a focus of public attention. The installation of a movable median barrier system would be expected to eliminate virtually all head-on collisions. However, serious questions remain concerning potential negative impacts of a movable median barrier system, especially the possibility that other types of accidents may significantly increase.

The purpose of this study is to re-evaluate the impacts that the installation of a movable median barrier system would have on safety and traffic operations on the Golden Gate Bridge, in light of the changes that have occurred since the previous studies.

2. TRAFFIC VOLUME DATA

Traffic volumes on the Golden Gate Bridge have remained relatively constant over the last several years, although there appears to be a slight overall decline in volumes since 1990. Table 1 indicates total annual vehicle crossings based on toll collections for southbound traffic. Actual vehicles counted southbound are doubled to obtain the total two-way traffic volumes.

TABLE 1. Total Annual Vehicle Crossings

YEAR	TOTAL VEHICLE CROSSINGS
1985 (8/15-12/31)	15,229,134
1986	40,612,900
1987	42,123,328
1988	42,987,652
1989	43,259,070
1990	43,038,376
1991	41,980,318
1992	41,412,824
1993	40,870,502
1994	41,108,860
1995	40,824,256
1996 (1/1-7/31)	24,029,160

Daily and monthly traffic volumes were also analyzed, utilizing southbound toll collections for the year 1996. Monthly Average Daily Traffic volumes (ADT) are shown in Table 2. Table 3 indicates the Average Daily Traffic volumes (ADT) by day of the week. The Annual Average Weekday (Monday through Friday) Traffic volume (AAWT) for southbound traffic was calculated as 58,376 vehicles per day for 1996.

Finally, traffic counts made by automatic detectors located in each lane were analyzed for a three month period in 1996. The lane traffic counts from a single day, Thursday May 23, 1996, were selected for detailed analysis, representing a prototypical weekday. This day was selected because total southbound traffic on this day was 58,076, close to the Annual Average Weekday Traffic volume of 58,376. In addition, all lane detectors appear to have been operating properly, and no known unusual conditions occurred.

It was noted that the northbound daily traffic volume was 67,790 compared to the southbound daily traffic volume of 58,076. This 54%/46% directional distribution appears to be typical of normal weekday traffic counts. This means that the traditional approach to estimating total two-way traffic volumes on the bridge by doubling the southbound traffic through the toll plaza probably understates actual two-way traffic volumes by approximately eight percent. Similarly, accident rates calculated with this estimated two-way traffic volume are overstated by approximately eight percent.

As an input to the analysis of probability of secondary collisions due to barrier deflection in the oncoming lane and vehicle rebound into adjacent lanes, the lane-by-lane traffic counts for this prototypical day were utilized. The resulting hourly traffic volumes in the lanes immediately adjacent to such a median barrier are shown in Table 4. Some of these lane volumes were adjusted from actual traffic counts to reflect the availability of six traffic lanes at all times and to account for lane shifts that may have occurred during the middle of some hours.

TABLE 2. Monthly Average Southbound Daily Traffic Volumes

MONTH	AVERAGE DAILY TRAFFIC	PERCENT OF ANNUAL TRAFFIC
January	51,537	7.6
February	53,673	7.9
March	56,497	8.4
April	57,555	8.5
May	57,671	8.5
June	59,114	8.7
July	59,322	8.8
August	57,970	8.6
September	58,402	8.6
October	57,525	8.5
November	54,644	8.1
December	52,704	7.8

TABLE 3. Average Southbound Traffic Volumes by Day of Week

DAY	AVERAGE DAILY TRAFFIC	PERCENT OF WEEKLY TRAFFIC
Monday	56,097	14.2
Tuesday	57,357	14.5
Wednesday	58,621	14.9
Thursday	59,179	15.0
Friday	60,630	15.4
Saturday	53,089	13.5
Sunday	49,717	12.6

TABLE 4. Hourly Traffic Volumes in Lanes Immediately Adjacent to a Potential Moveable Median Barrier

HOUR BEGINNING	SOUTHBOUND LANE (vphpl)	NORTHBOUND LANE (vphpl)
0	84	242
1	46	120
2	31	90
3	33	52
4	138	53
5	240	131
6	1235	504
7	1865	1483
8	1811	1784
9	1364	1612
10	1107	1001
11	1072	830
12	904	943
13	898	1069
14	848	1499
15	994	1850
16	1709	1345
17	1846	1555
18	1829	1288
19	1261	828
20	861	1046
21	526	852
22	429	852
23	236	514

3. GOLDEN GATE BRIDGE ACCIDENT CHARACTERISTICS

General Accident Analysis

As a first step toward analyzing the potential impact of a movable median barrier system on traffic safety on the Golden Gate Bridge, the general characteristics of existing accident experience were examined. Accident statistics compiled by the Golden Gate Bridge, Highway, and Transportation District were analyzed and accident information summarized for a five year period (January 1991 through December 1995). This period represents conditions following a Bridge redecking project which widened the roadway from 60 to 62 feet.

Data analyzed in this study included all accidents which occurred during the five year period on the Bridge and its approaches between light pole #1 (north approach) and light pole #130 (south approach). Accidents which occurred in the immediate vicinity of the toll plaza were excluded from this study. A total of 230 accidents were studied in this analysis.

Table 5 indicates the number of accidents each year during the five year study period, classified by severity of accident.

TABLE 5. Severity of Accidents

YEAR	TOTAL ACCIDENTS	INJURY ACCIDENTS	FATAL ACCIDENTS	PROPERTY DAMAGE ACCIDENTS	CROSS-OVER ACCIDENTS
1991	35	18	0	17	3
1992	53	22	0	31	5
1993	46	17	0	29	6
1994	42	17	3	22	6
1995	54	28	0	26	4
TOTAL	230	102	3	125	24
PERCENT	100%	44%	1%	54%	10%
RATE (/MVM)	0.64	0.29	0.01	0.35	0.07

To provide consistency with past studies, accident rates have been calculated by doubling southbound toll plaza traffic counts to estimate daily traffic volumes. It should be noted (as previously discussed) that this likely understates actual traffic volumes because lane-by-lane traffic counts on the Bridge indicate that daily northbound traffic is somewhat higher than daily southbound traffic. As a result, reported accident rates are likely overstated by about 8%.

The total accident rate of 0.64 accidents per million vehicle-miles is significantly lower than the rate reported for the period of November 1981 through October 1983 on the Bridge (preceding the deck widening project) in a previous traffic safety study (Ref. 1). The earlier study found an accident rate of 1.25 accidents per million vehicle-miles. Injury and fatal accidents, as a percentage of total accidents, are higher (45% in the current study compared with 34% in the previous study).

The accident rates for the Golden Gate Bridge compare favorably with California statewide average accident rates compiled by the California Department of Transportation (Ref. 2). Five to six-lane undivided roadways in level, rural terrain have an average accident rate of 2.0 accidents per million vehicle-miles, and even rural five to six-lane freeways with similar traffic volumes have an average accident rate of 0.8 accidents per million vehicle-miles. Urban five to six-lane freeways have an average accident rate of 1.0 accidents per million vehicle-miles. Average accident severity on the Golden Gate Bridge is similar to statewide averages. Five to six-lane undivided roadways in level, rural terrain average 37% injury and 2% fatal accidents. Five to 6-lane rural freeways average 46% injury and 4% fatal accidents.

It should be noted that the preceding comparison of accident rates between the Golden Gate Bridge and freeway facilities is for illustrative purposes only. The Golden Gate Bridge is not a "freeway". The term "freeway" is defined by the American Association of State Highway and Transportation Officials as "a divided arterial highway for through traffic with full control of access" (Ref. 28). In its current configuration, the Golden Gate Bridge is not a divided highway.

Type of Accidents

All accidents were classified by the "first harmful event" (i.e., the first event that would result in damage or injury), as shown in Table 6.

TABLE 6. First Harmful Event

FIRST HARMFUL EVENT	PERCENT
Rear-end	70%
Side-swipe	12%
Hit Barrier	7%
Head-on	4%
Other	7%

Compared to the 1985 traffic safety study (Ref. 1), rear-end collisions now represent a larger proportion of total accidents (56% in 1985) and side-swipe, barrier, and head-on accidents are a smaller proportion (16.5%, 11% and 9% respectively in 1985).

Accidents Related to Time Variables

Accident data must be interpreted in the context of accident potential during different time periods, as measured by traffic volumes. During the period from which these accident data were drawn, the Annual Average Daily Traffic (AADT) volume on the Bridge ranged between 111,800 to 115,000 vehicles per day, with an overall AADT of 113,000 vehicles per day. However, traffic volumes (and hence accident exposure) vary by season of the year, day of the week, and time of day. Traffic volumes were slightly higher on weekdays (Monday through Friday), and Average Weekday Traffic (AWT) volume was 119,000 vehicles per day. Weekend traffic (Saturday and Sunday) was slightly lower at 104,800 vehicles per day.

There is relatively little seasonal fluctuation in weekday traffic volumes, with a range of 105,000 vehicles per day in the winter to 120,900 vehicles per day in the summer (a variation of less than 7% from the annual ADT).

Accidents per month are listed in Table 7 for the five year period of 1991 through 1995.

TABLE 7. Monthly Variations in Accidents

MONTH	TOTAL ACCIDENTS	PERCENT ACCIDENTS	PERCENT ANNUAL TRAFFIC
January	15	6.5%	7.6%
February	13	5.7%	7.9%
March	18	7.8%	8.4%
April	22	9.6%	8.5%
May	12	5.2%	8.5%
June	21	9.1%	8.7%
July	21	9.1%	8.8%
August	29	12.6%	8.6%
September	17	7.4%	8.6%
October	18	7.8%	8.5%
November	23	10.0%	8.1%
December	21	9.1%	7.8%
TOTAL	230	100%	100%

There appears to be an over-representation of accidents during the summer, peaking in August, and during late autumn, in November and December. Accident frequency relative to traffic volume is generally lower during January through May. Interestingly, May was the lowest accident frequency month in both the current data and the 1985 study (Ref. 1). Accident frequency was higher in the summer and late fall in both data sets as well.

Accidents were classified as weekday or weekend accidents. For the purposes of this analysis, the weekend was defined as 6:00 p.m. Friday through 12:00 midnight Sunday. Ninety-three of the total accidents (41%) occurred within the weekend period. Approximately 29% of total annual traffic occurs during the weekend period. Therefore the rate of accident occurrence is significantly higher during the weekend period compared to the weekday period. The weekend accident rate is 0.90 accidents per million vehicle-miles; the weekday accident rate is 0.54 accidents per million vehicle-miles. This relationship between weekend and weekday accident frequency was similar in the 1985 safety study (Ref. 1) when 45% of all accidents occurred during the weekend.

Accidents were classified by the time of day relative to ambient light conditions. Sixty-eight of the total accidents (30%) occurred at night. Approximately 29% of total annual traffic occurs during the period of 6:00 p.m. through 6:00 a.m. Therefore, the accident rate at night is approximately equal to the accident rate during daylight hours. Again, the breakdown between daylight and night accidents was similar in the 1985 safety study (Ref. 1) where 34% occurred at night.

Accident Location

The location of accidents was classified according to the light pole numbering system used in the Incident Report Forms. Accidents were also classified according to the direction of the primary vehicle, that is, the vehicle which appeared to have precipitated the collision based on the description in the Incident Report Form. The location and direction of primary vehicle are summarized in Table 8. For reference, Figure 1 shows the light pole locations on the Golden Gate Bridge and its approaches.

TABLE 8. Accident Location

LOCATION (LIGHT POLES)	PRIMARY VEHICLE NORTHBOUND	PRIMARY VEHICLE SOUTHBOUND	TOTAL ACCIDENTS
1-10	10	8	18
11-20	0	11	11
21-30	8	6	14
31-40	4	16	20
41-50	7	10	17
51-60	4	7	11
61-70	5	10	15
71-80	2	16	18
81-90	0	15	15
91-100	4	8	12
101-110	6	37	43
111-120	4	22	26
121-130	5	4	9
TOTAL	59	170	229

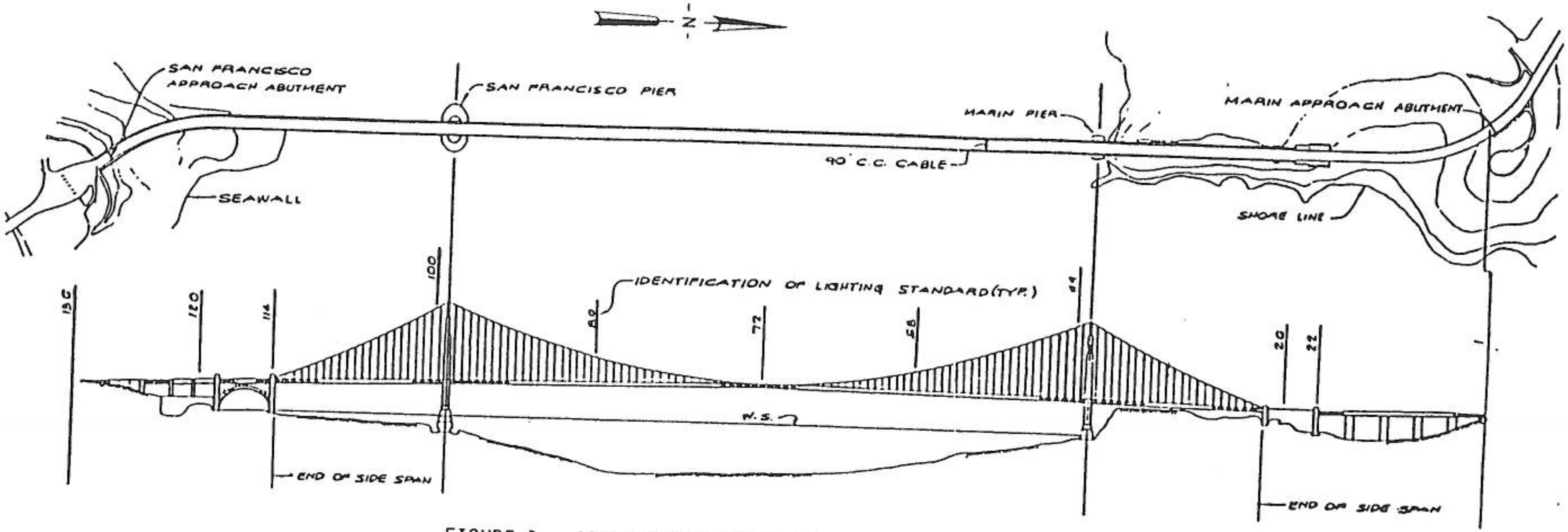


FIGURE 1. APPROXIMATE LIGHT POLE LOCATIONS

There are significantly more southbound (74%) than northbound (26%) accidents. Accidents which occurred in the toll plaza were specifically excluded from this study. There appears to be a slight clustering of northbound accidents between poles 1 to 10, and a dramatic clustering of southbound accidents between poles 101 to 120. The 101 to 120 pole location is between the San Francisco pier and the north end of the horizontal curve on the San Francisco approach, and the clustering of southbound accidents may be related to traffic which is stopped or slowing on the approach to the toll plaza. The 1 to 10 pole location is within the curve on the Marin approach and the clustering of northbound accidents may be related to traffic operations in the curve and the entrance to Vista Point. Even if the large cluster of southbound accidents between poles 101 to 120 are not included, the overall southbound accidents are significantly greater than northbound accidents. This may be related to possibly higher speeds of southbound traffic on the Bridge.

The 1985 safety study (Ref. 1) also found that southbound accidents were more frequent than northbound accidents, but the difference was not as dramatic (56% southbound accidents in 1985 vs. 74% in the current study). Also, accident clusters (both northbound and southbound) were found in different locations in the 1985 study. We are not aware of any design or operational changes that could account for these changes.

Lane Configuration

Accident occurrence was summarized according to lane configuration at the time of the accident (as recorded in the Incident Report Form). The following notation will be used in this and subsequent sections of this report: directional use of Bridge lanes will be described as 3/3 (three lanes in each direction), 4/2 (four lanes in one direction and two lanes in the other direction), 3/2/1 (three lanes in one direction, two lanes in the other direction, and one buffer lane), and 2/2/2 (two lanes in each direction and two buffer lanes). Accidents are summarized in Table 9.

TABLE 9. Accidents Related to Lane Configuration

LANE CONFIGURATION	NUMBER OF ACCIDENTS	PERCENT ACCIDENTS	PERCENT ANNUAL TRAFFIC
3/3	108	47%	43%
4/2	81	35%	41%
3/2/1	30	13%	14%
2/2/2	9	4%	3%
Other	1	-	-
TOTAL	229	100%	100%

The lowest overall accident rate occurs during periods of time when the lane configuration is 4/2, primarily during the weekday morning and evening peak periods. Thirty-five percent of total accidents occurred during this period compared with 41% of total annual traffic during the same period. Therefore, the overall accident rate during these peak periods is 0.56 accidents per million vehicle-miles. This is less than the total accident rate for all time periods of 0.64 accidents per million vehicle-miles. This comparison indicates the relatively greater safety with which the peak period, commuter traffic flow operates on the Bridge.

A somewhat disproportionately large number of accidents occur during periods when a 3/3 lane configuration is used. This configuration is in use when 47% of the accidents take place, but represents only 43% of total annual traffic volume. The accident rate during the periods when this lane configuration is in use is 0.71 accidents per million vehicle-miles, compared with the overall accident rate for all time periods of 0.64 accidents per million vehicle-miles.

In the 1985 safety study (Ref. 1), proportionately fewer of the total number of accidents occurred while the 4/2 lane configuration was in use (21%) although a larger proportion of annual traffic occurred with the 4/2 lane configuration in use (51%). Although the accident rate remains lowest for periods when the 4/2 lane configuration is in use, this favorable condition has eroded significantly since the 1985 study. The percentage of accidents occurring with the 3/2/1 and 2/2/2 lane configurations in place has decreased significantly since the 1985 study when these two configurations represented 24% and 12% respectively of total accidents.

Contributing Circumstances

One hundred fifty-eight of the 230 Incident Report Forms described traffic-related circumstances which contributed to the accident occurrence, as shown in Table 10.

TABLE 10. Traffic-Related Contributing Circumstances

CONTRIBUTING CIRCUMSTANCE	NUMBER OF REPORTS MENTIONING	PERCENT
Slow Traffic	40	17%
Stopped Traffic	100	44%
Stall or Vehicle Malfunction	18	8%
No Traffic-Related Circumstance	71	31%

The large majority of accidents with contributing circumstances related to stopped or slow traffic resulted in rear-end collisions involving two or more vehicles. It appears that circumstances which may have contributed to accident occurrence are more readily identified for rear-end collisions than for other types of collisions, or that no traffic-related circumstances exist which contribute to many of the non-rear-end collisions. Any change in the ability of motorists to see and react to stopped, slowing, or stalled vehicles on the Bridge could affect the frequency of such rear-end collisions. The proportion of accidents precipitated by slow or stopped traffic or stalled vehicles has increased from 46% of all accidents in the 1985 safety study (Ref. 1) to 69% in the current data. This appears to be consistent with the increase in rear-end accidents as a proportion of total accidents on the Bridge, as previously discussed.

Emergency Vehicle Response

The types of emergency vehicles (in addition to police vehicles) responding to accidents were tabulated from information contained in the Incident Report Forms for the five-year period in Table 11.

TABLE 11. Emergency Vehicle Response

EMERGENCY VEHICLE	FREQUENCY	PERCENT
Ambulance	68	30%
Fire	40	17%
Tow	164	72%

Some of the accidents represented in these statistics involved response by multiple emergency vehicles. Responses by fire and tow vehicles have increased over those reported in the 1985 safety study (Ref. 1) when they represented 2% and 60% respectively of all accidents.

Cross-Over Accidents

Because cross-over accidents represent a significant concern in this study, a more detailed analysis of all cross-over accidents during a 10.6 year period of January 1986 through July 1996 was undertaken. A total of 78 accidents involved one or more vehicles crossing the dividing line into oncoming traffic lanes during the 10.6-year period. These cross-over accidents were classified by severity in Table 12.

TABLE 12. Severity of Cross-Over Accidents

ACCIDENT SEVERITY	FREQUENCY	PERCENT
Property Damage Only	24	31%
Injury	46	59%
Fatality	8	10%

Over two-thirds (69%) of cross-over accidents involved injuries or fatalities, compared with 41% or all accidents on the Bridge (see earlier section on Accident Severity). This represents a higher average severity for cross-over accidents then was observed in the 1985 safety study (Ref. 1) when 49% of cross-over accidents resulted in injuries or fatalities. However, the frequency of cross-over accidents is dramatically lower compared with pre-1985 data: 7.4 cross-over accidents per year in the current data versus 22.2 cross-over accidents per year prior to the Bridge roadway widening. The frequency of injury and fatal accidents has also been reduced: 5.1 per year in the current data versus 11.0 per year before roadway widening. Nevertheless, it is noted that all 8 fatal accidents that have occurred on the Bridge since 1986 have involved cross-overs.

Although cross-over accidents have occurred throughout the length of the Golden Gate Bridge, the largest concentration occurred at the far north end, with 22 accidents (28% of the total cross-over accidents) occurring between Light Poles 1 to 20. This is the location of the curve on the Marin approach to the Bridge. The combination of the curve plus the higher speeds typical of the southbound traffic at the bottom of the Waldo grade may account for this clustering of cross-over accidents. It is possible that this accident concentration may be reduced in future years as a result of a general reduction in speeds on the Golden Gate Bridge which has been observed after recent implementation of highly publicized measures such as increased speeding fines and increased enforcement efforts.

Sixty-one (78%) of the cross-over accidents occurred during daylight hours. Sixty-one (78%) also occurred during dry pavement conditions. The number of cross-over accidents occurring by lane configuration is shown in Table 13.

TABLE 13. Cross-Over Accidents by Lane Configuration

LANE CONFIGURATION	FREQUENCY OF CROSS-OVER ACCIDENTS	PERCENT OF CROSS-OVER ACCIDENTS	PERCENT OF ANNUAL TRAFFIC VOLUME
3N/3S	37	47%	43%
4N/2S	21	27%	21%
2N/4S	10	13%	20%
3N/1B/2S	4	5%	14%
2N/2B/2S	5	6%	3%
Other	1	1%	-

Cross-over accidents are slightly more likely to occur (relative to traffic volumes) when the lane configuration is 3N/3S, 4N/2S, or 2N/2B/2S than during other lane configurations. Seventy-four percent of cross-over accidents did not involve any collision prior to any of the vehicles crossing the dividing line. This is the same percentage reported in the 1985 safety study (Ref. 1).

4. ACCIDENT CHARACTERISTICS ON COMPARABLE FACILITIES

At the time that the 1985 Traffic Safety Study (Ref. 1) was prepared by the Northwestern University Traffic Institute, there were no known installations of movable median barrier systems in existence which could provide insight into the likely impact on accidents if such a system were installed on the Golden Gate Bridge. Since that time, Quickchange Barrier systems have been installed on a number of facilities throughout the world.

Accident experience on some of these installations was investigated to provide insight into likely impacts of a movable barrier system on the Golden Gate Bridge. Unfortunately, despite repeated attempts to obtain detailed accident and operational data for these facilities, most of the information that could be obtained was rather general in nature. An analysis of available data follows.

Gennevilliers Viaduct

A Quickchange-type movable barrier system was installed on a five-lane freeway bridge near Paris, France in September 1986. Prior to installation of the movable barrier system, the bridge had a fixed median barrier with two 11.5-foot lanes in each direction and 8.2-foot outside shoulders. After movable barrier installation, there were four 9.8-foot lanes plus a 12.8-foot center reversible lane and 3.3-foot outside shoulders. The roadway carried 115,000 vehicles per day.

This facility was evaluated in a Northwestern University Traffic Institute report in 1987 (Ref. 3) which concluded that in the four months following installation of the movable barrier system the accident rate increased from 1.26 accidents per million vehicle-miles to 1.52 accidents per million vehicle-miles. Injury accidents increased from 19% to 33% of total accidents. Barrier system displacements of up to 3.9 feet were observed. No secondary impacts due to barrier displacement were identified. The use of the movable median barrier system was later discontinued due to an improvement project which widened the bridge.

Auckland Harbour Bridge

A Quickchange Movable Barrier system was installed on this bridge in Auckland, New Zealand in 1990. Although the bridge is a total of eight lanes in width, the movable barrier system is installed on a four-lane central roadway which is 42 feet wide, providing four 10-foot lanes. The bridge and approaches are 1.37 miles long with 1100-foot radius curves (5% superelevation) at both ends. Traffic volumes have increased about 20% since 1990, and current average daily traffic volume is 140,000 vehicles per day. Barrier system ends are shielded within permanent median areas at both ends of the bridge.

Available accident experience before and after installation of the movable median barrier system is summarized in Table 14 (Ref. 4, 5, and 6).

In a 46-month period (1987-1990) prior to the barrier installation, there were 24 head-on accidents on the bridge, resulting in 11 fatalities, 16 serious injuries, and 20 minor injuries. Types of accidents before and after barrier installation are compared in Table 15. Of significant interest, during the before period there was an average of 5.5 head-on accidents per year, most of which involved injuries or fatalities. After installation of the movable median barrier system, total injury and fatal accidents per year were reduced from 32.5 to 20.6, a reduction of about 10 accidents per year. This is in excess of the total number of head-on accidents that were eliminated by the movable median barrier system. In addition, the total number of annual accidents was reduced from 123.0 to 103.8, a reduction of about 19 accidents per year. This is far in excess of the total number of crossover accidents that were eliminated by the barrier system. These statistics suggest that there may be some reduction in the number and severity of accidents that do not involve vehicles that crossed the centerline as a result of the movable median barrier system installation. It is not clear whether this apparent reduction in non-crossover accidents is a secondary safety benefit of the movable median barrier system or whether it is a result of some unknown external factor. We are not aware of any obvious reason that the movable median barrier system would reduce the frequency or severity of non-crossover accidents implied by these data.

TABLE 14. Accident Data for Auckland Harbour Bridge

	BEFORE MEDIAN BARRIER (1989-1990)	AFTER MEDIAN BARRIER (1991-1995)
Years	2	5
Average Daily Traffic	117,000	129,000
Total Accidents	246	519
Accidents/Year	123.0	103.8
Accident Rate (Acc/MVM)	2.10	1.61
Injury and Fatal Accidents	65	103
Injury and Fatal Accidents/Year	32.5	20.6
Injury and Fatal Accident Rate (Acc/MVM)	0.55	0.32
Barrier Impacts	-	98*
Barrier Impacts/Year	-	19.8*
Barrier Impact Rate (Acc/MVM)	-	0.31*

*Estimated from partial data

TABLE 15. Types of Accidents on Auckland Harbour Bridge

ACCIDENTS/YEAR	BEFORE MEDIAN BARRIER (1989-1990)	AFTER MEDIAN BARRIER (1991-1995)
Head-on	5.5	0.2*
Rear-end	79.5	70.6
Lost Control	17.0	18.4
Lane Change	13.5	10.8
Other	7.5	3.8

* One head-on accident after barrier installation due to wrong-way ramp entry

Since the installation of the movable median barrier system, the accident rate on the Auckland Harbour Bridge has decreased 23% and the injury and fatal accident rate has decreased 42%. Head-on accidents have been virtually eliminated, but "lost-control" accidents have slightly increased (8%). It is likely that this increase is related to barrier impacts.

Barrier system deflections of 1.6 to 3.3 feet due to impacts have been measured. Eight known secondary collisions with the deflected barrier have occurred, all resulting only in property damage or minor injuries.

Volume counts and lane utilization studies have concluded that the barrier system has not reduced the traffic-carrying capacity of lanes adjacent to it.

Officials with Transit New Zealand, the operating agency for the Auckland Harbour Bridge, have expressed enthusiastic satisfaction with the operations and safety performance of this movable median barrier system.

San Diego-Coronado Bridge

A Quickchange Barrier System was installed on this bridge in San Diego, California in 1993. The bridge roadway is 62 feet wide, with five 12-foot lanes. The barrier system is reportedly 8100 feet (1.53 miles) long, although the bridge length is reported as 2.12 miles. The bridge includes an 1800-foot radius curve. 1995 average daily traffic volume was 65,000 vehicles per day.

Available accident experience before and after installation of the movable median barrier system is summarized in Table 16 (Ref. 7).

TABLE 16. Accident Data for San Diego-Coronado Bridge

	BEFORE MEDIAN BARRIER (1988-1992)	AFTER MEDIAN BARRIER (1993-1995)
Years	5.0	2.75
Average Daily Traffic	62,000	65,000
Total Accidents	236	98
Accidents/Year	47.2	35.6
Accident Rate (Acc/MVM)	0.98	0.71
Injury and Fatal Accidents	89	32
Injury and Fatal Accidents/Year	17.8	11.6
Injury and Fatal Accident Rate (Acc/MVM)	0.37	0.23
Barrier Impacts	-	15*
Barrier Impacts/Year	-	8.2*
Barrier Impact Rate (Acc/MVM)	-	0.16*

* In 1.83 years (July 1993-April 1995)

In a five-year period (1988-1992) prior to the barrier system installation, there were 32 cross-over accidents on the bridge, an average of 6.4 per year. Since installation of the barrier system, the accident rate on the bridge has decreased 28% and the injury and fatal accident rate has decreased 38%. The actual number of injury and fatal accidents that have occurred on the bridge has decreased from an average of 17.8 per year before installation to 11.6 per year after installation, a reduction of about 6 accidents per year. If it assumed that nearly all cross-over accidents resulted in injuries or fatalities in the before period, then the reduction in total injury and fatal accidents since installation of the movable median barrier system is essentially equal to the crossover injury and fatal accidents. In over words, there does not appear to have been any increase in severity of non-crossover accidents after installation of the movable median barrier system. In addition, the total number of annual accidents on the bridge has decreased from 47.2 to 35.6, a reduction of about 11 accidents per year. Again, this is in excess of the actual number of crossover accident that were eliminated by the movable median barrier system.

Recorded barrier system deflections due to impacts average 2.04 feet, with a maximum deflection of 6 feet. There do not appear to be any records of the actual number of barrier system impacts, nor any secondary impacts with the deflected barrier system.

Tappan Zee Bridge

A Quickchange Barrier system was installed on this bridge in New York in May 1993. The bridge roadway is seven lanes wide and is operated in a 4/3 lane configuration at all times. All lane widths are approximately 11 feet, with no shoulders. The movable median barrier system is 18,000 feet (3.41 miles) long. The movable median barrier system replaced a permanent median barrier. 1996 average daily traffic volume was 121,600 vehicles per day, of which 6% was commercial vehicles.

Available accident experience following installation of the movable median barrier system is summarized in Table 17 (Ref. 8).

TABLE 17. Accident Data for Tappan Zee Bridge

Years (1994-1996)	3.0
Average Daily Traffic	117,500
Total Accidents	2186
Accident Rate (Acc/MVM)	14.9
Injury and Fatal Accidents	379
Injury and Fatal Accident Rate (/MVM)	2.59

These accident rates are extremely high compared to other bridges with and without movable median barrier systems. In part, the high accident rate may result from including accidents related to the bridge toll plaza in the reported statistics. It is also noted that approximately one-half of the three-year accident total occurred during only one year (1994). It is possible that an unusual condition existed during 1994 such as construction activity. However, even without the 1994 data, the accident experience in the remaining two years is still much higher than other facilities. No accident data from before the median barrier system installation are available.

Barrier impacts are reported to occur approximately once per week. No information is available on secondary accidents related to these barrier impacts. Reported barrier displacement due to impacts is typically in the range of one to four feet.

Caltrans Median Barrier Study

A study published by the California Department of Transportation (Ref. 9) analyzed accident data on freeway and non-freeway facilities before and after installation of permanent median barriers. A general conclusion was that total accidents tended to increase 20 to 30 percent after barrier installation on freeways and 50 percent or more on non-freeway facilities.

For median widths of less than 20 feet, the study found that 26% of barrier impacts resulted in secondary rebound impacts with other vehicles. Intuitively, this seems to be an extraordinarily high proportion of secondary impacts, and may result from an underreporting of less severe barrier impacts, those not resulting in significant damage to the impacting vehicle.

Two of the facilities analyzed in this study had median widths of 8 feet or less. One of these facilities experienced a 4% reduction in overall accident rate, but the other facility experienced a 163% increase in overall accident rate after median barrier installation (however, this increase involved a very small number of actual accidents). Fatal and injury accident rates on the two facilities changed by -12% and +78% respectively (again, a very small number of actual accidents).

Implications for Accident Experience on the Golden Gate Bridge

The accident experience on the four bridges with movable median barrier systems was highly variable, as summarized in Table 18. It should be recognized that some of this variability may result from different criteria for accident reporting among different operating agencies. It is certainly possible that some of the operating agencies providing accident data for this analysis may have less complete reporting of accidents (especially less severe accidents) than occurs on the Golden Gate Bridge.

Of the other bridges studied, the Auckland Harbour Bridge and the San Diego-Coronado Bridge are probably the facilities that are most closely comparable to the Golden Gate Bridge. These two facilities reported overall accident rate reductions of 19 to 28% after movable median barrier system installation and injury and fatal accident rate reductions of 38 to 42%. As previously noted, the observed total accident frequency reductions after installation of movable median barrier systems on these bridges actually exceeded the number of crossover accidents that were eliminated by the barrier systems. No increases in non-crossover injury and fatal accident frequency were observed on either bridge, in fact a decrease in non-crossover injury and fatal accidents occurred on the Auckland Harbour Bridge. It is not intuitively obvious why such decreases in non-crossover accidents would occur after installation of a movable median barrier system; in fact data utilized in our previous traffic safety study (Ref. 1) suggested that such non-crossover accidents (especially rear-end collisions) would significantly increase in both frequency and severity. Nevertheless, the current data from the Auckland Harbour Bridge and the San Diego-Coronado Bridge indicate the likelihood of secondary safety benefits from the movable median barrier system in reducing non-crossover accidents. It must be recognized that this contradictory data increases the uncertainty in estimating the safety implications of installing a movable median barrier system on the Golden Gate Bridge.

Accident experience on the Gennevilliers Viaduct, the Caltrans Median Barrier Study (Ref. 9), and the comparable facilities evaluated in the 1985 safety study (Ref. 1) suggest that there remains a significant concern that overall accidents as well as injury accidents could increase on the Golden Gate Bridge if a movable median barrier system were installed. However, the most directly applicable accident experience (Auckland Harbour Bridge and San Diego-Coronado Bridge) suggest that overall accidents as well as injury and fatal accidents would be reduced if a movable median barrier system were installed on the Golden Gate Bridge. It should be noted that neither of these bridges utilized buffer lanes prior to installation of the movable median barrier system. The present use of buffer lanes on the Golden Gate Bridge appears to provide a significant safety benefit by allowing disabled vehicles a potential refuge area less vulnerable to rear-end collisions. Because these buffer lanes would be likely be discontinued if a movable median barrier system were installed on the Golden Gate Bridge, accident experience may not be quite the same as on the other facilities. It should also be noted, however, that the installation of a movable median barrier system on the Golden Gate Bridge does not preclude the continued use of plastic tubes to create buffer lanes during off-peak periods. This is further discussed in Section 11, "Lane Width and Barrier Positioning".

Nevertheless, it appears that the most likely outcome of installation of a movable median barrier on the Golden Gate Bridge would be a small reduction in property damage accidents (0 to 30%), an elimination of most fatal accidents, and a 20% to 40% reduction in injury accidents, based on the experience on the comparable bridges.

TABLE 18. Summary of Accident Experience on Comparable Facilities

FACILITY	GENNEVIL. VIADUCT	AUCKLAND HARBOUR	SAN DIEGO-CORONADO	TAPPAN ZEE	CALTRANS STUDY
			Overall Accident Rate (/MVM)		
Before	1.26	2.10	0.98	-	-
After	1.52	1.61	0.71	14.9	-
% Change	+21%	-19%	-28%	-	+20 to 50%
			Injury and Fatal Accident Rate (/MVM)		
Before	0.24	0.55	0.37	-	-
After	0.50	0.32	0.23	2.59	-
% Change	+108%	-42%	-38%	-	-12 to +78%
Barrier Impact Accident Rate	-	0.31	0.16	-	-

5. RISK ANALYSIS OF DEFLECTION OF BARRIER SYSTEM INTO ONCOMING TRAFFIC

The possibility that a median barrier system could be deflected into an opposing traffic lane by a vehicle impact is a significant safety concern in the analysis of the proposed installation on the Golden Gate Bridge. For this analysis, it has been assumed that such a barrier system would be positioned on lane lines at all times of the day and all days of the week, and that at no time would it be positioned in the middle of a lane.

Because such a barrier system would be positioned immediately adjacent to the edges of moving traffic lanes and lane widths are relatively narrow, any deflection as the result of a barrier impact may result in secondary collisions either as a result of oncoming vehicles striking the deflected barrier system, or as a result of such vehicles attempting to make evasive lane change maneuvers and colliding with other nearby vehicles.

The possibility of barrier system deflections due to vehicle impacts is very real. Experience with the Quickchange barrier system on other bridges such as the San Diego-Coronado Bridge, the Auckland Harbour Bridge, and the Gennevilliers Viaduct has indicated deflections of up to 6 feet, with deflections of up to 3 feet being relatively common. It is recognized that the Quickchange Barrier system has been recently redesigned to reduce such deflections. In addition, it is recognized that other alternative barrier systems may have different deflection characteristics.

It should also be recognized that in actual operation on the Golden Gate Bridge, such barrier deflections would be relatively rare and random events. The intrusion of the movable median barrier system into the lane of oncoming traffic would certainly be unexpected by drivers in the lane adjacent to the barrier. However, because of the rare and random nature of such intrusions, it would not be possible to provide any effective warning to such drivers utilizing static warning signs. Even if a system could be devised to detect the presence of a barrier system intrusion into the oncoming lane, any warnings activated after the intrusion were detected would only serve to warn drivers upstream of the intrusion. It is improbable that any detection and warning system could effectively warn drivers in the immediate vicinity of the intrusion as it occurs.

Only sketchy data are available concerning secondary collisions resulting from such barrier system deflections in current installations. There were 8 known such collisions in a 6-year period on the Auckland Harbour Bridge. All involved property damage only or minor injuries. However, it appears that there have been an unknown number of additional such collisions which are not recorded or classified such that they can be identified as secondary collisions.

In order to analyze the likelihood of secondary collisions on the Golden Gate Bridge related to a barrier system deflection, a risk prediction model was developed, using many of the concepts described by Bryden and Bruno (Ref. 10) in their analysis of the movable barrier system on the Tappan Zee Bridge. This model is generic in the sense that it calculates the probability of a secondary collision based on the amount of barrier system deflection, regardless of the specific barrier system configuration. The resulting model does not attempt to predict the frequency of initial barrier impacts, but rather predicts whether any initial impact will result in a secondary collision between the deflected barrier and oncoming traffic. The results of the analysis are useful in establishing performance criteria for maximum tolerable barrier system deflection.

Model Development

Important variables that must be considered in such an analysis of the probability of secondary barrier collisions include:

1. Extent of lateral deflection of barrier system
2. Extent of length of barrier system that is deflected

3. Density and speed of opposing traffic in the lane adjacent to the barrier

4. Distance required for opposing vehicle operators to react to a barrier system deflection and take appropriate evasive action

For any given amount of barrier system lateral deflection, D_L, the model will determine the probability, P_I, that a secondary barrier collision will occur after an initial barrier impact has occurred.

Then,

$$P_I = P_{LAT} \times P_{LONG}$$

where P_{LAT} = probability that an opposing vehicle is within the lateral deflection zone of the impacted barrier, and

P_{LONG} = probability that an opposing vehicle is within the longitudinal interference zone of the impacted barrier.

The probability that an opposing vehicle is within the lateral deflection zone of the impacted barrier system depends on the amount of deflection and the lateral placement of the vehicle within its lane.

The probability that an opposing vehicle is within the longitudinal interference zone of the impacted barrier depends on the density of opposing traffic flow in the lane adjacent to the barrier. This density, of course, varies hour to hour during the day and varies by direction of traffic flow within a given hour. The current (1996) hourly lane distribution of traffic flow on the Golden Gate Bridge for a prototypical weekday was utilized for this analysis.

The probability of a secondary barrier collision was calculated separately for each hour of the typical weekday. A weighted average of these hourly probabilities was then calculated for the day as a whole, as follows. It was assumed that the probability that an initial barrier impact will occur is proportional to the density of traffic flow in the lane adjacent to the initial impact side of the barrier. Therefore, the probabilities of secondary collisions for each hour were weighted by the volume of traffic during that hour in the lane adjacent to the initial impact side of the barrier. The resulting calculated probabilities represent the likelihood that a barrier impact at any time during a typical day would result in a secondary collision.

In order to find P_{LAT} the following assumptions were made:

1. the lane adjacent to the barrier system is 10 feet wide

2. the lateral position of vehicles within this lane are evenly distributed across the lane, but no vehicle is closer than 1 foot from the barrier system

3. vehicles are an average of 5.5 feet wide.

Therefore, the left side of vehicles within the adjacent lane vary between 1 foot and 4.5 feet from the barrier system in its normal position, and the probability that a lateral deflection of the barrier system will be greater than or equal to the offset of the vehicle from the barrier is:

$$P_{LAT} = (D_L/42) - 0.29$$

where D_L is the lateral deflection of the barrier system in inches.

An opposing vehicle which is within the lateral deflection zone of the impacted barrier system will have a secondary collision if it is also within the longitudinal interference zone of the impacted barrier system. The longitudinal interference zone includes the longitudinal deflected length of the barrier system, D_C, plus the distance that the opposing vehicle travels while the driver perceives the deflected barrier, reacts, and implements an evasive action such as braking to a stop or changing lanes D_R.

Using data from crash testing of the original Quickchange Barrier system reported by Bryden and Bruno (Ref. 10), the deflected length of the barrier system (in inches) is:

$$D_C = 6.67 \times D_L - (560/D_L) + 257.3$$

To calculate the distance that an opposing vehicle would travel while the driver perceives, reacts, and implements an evasive action, the following assumptions were made:

1. opposing vehicles are traveling at 45 mph
2. driver perception/reaction time is 2 seconds (this represents an unexpected condition for which the driver may have to evaluate several alternative responses)
3. the distance to brake to a stop from 45 mph under wet weather conditions is 135 feet
4. the distance to change lanes is 198 feet at 45 mph (3 seconds travel time)
5. the smaller of the two previous response distances (i.e., braking to a stop) is used for this calculation.

Therefore, driver response distance, D_R (in inches), is:

$$D_R = 1620 + 35.3 \times S$$

where S = traffic speed (mph)

When $S = 45$ mph, then D_R is 3204 inches.

The probability that there is no opposing vehicle in the lane adjacent to the barrier within a distance equal to $D_L + D_R$ depends on the distribution of gap sizes in the opposing traffic flow. A statistical distribution known as a "Erlang distribution" effectively models gaps in such traffic flow. The Erlang distribution recognizes that gaps in traffic flow are random in nature, but that extremely small gaps have a very low probability (Ref. 11). Using this distribution,

$$P_{LONG} = 1 - e^{-V_L t}(1 + V_L t)$$

where V_L = opposing traffic flow rate (vehicles per second per lane)

t = gap size in seconds [$= (D_L + D_R)/(17.64 \times S)$]

S = opposing traffic speed (mph)

and

$$P_I = P_{LAT} \times P_{LONG}$$

Interpretation of Model Results

A spreadsheet computer program was used to perform these calculations and to determine the weighted average probabilities of secondary collisions with a deflected barrier system for lateral deflections of 12 to 48 inches. Table 19 presents the results of this analysis.

TABLE 19. Probability of Secondary Collisions with Deflected Barrier System (Weighted Average Throughout Day)

Lateral Barrier Deflection (inches)	Probability of Secondary Barrier Collision
12	0
18	0.06
24	0.12
30	0.18
36	0.24
42	0.30
48	0.36

This analysis indicates that, for example, on occasions when an initial barrier impact results in a lateral deflection of the barrier system of 36 inches a secondary collision will occur on the opposite side of the barrier system 24 percent of the time. It should be remembered, however, that this probability represents the weighted probability of a secondary collision based on initial impacts that may occur at any time during the day. Table 20 indicates probability of secondary collisions during the morning and evening weekday peak periods. If the same 36 inch deflection occurred during the morning or evening peak periods (when opposing traffic flow rates are high) the probability of a secondary collision would be 36 percent.

TABLE 20. Probability of Secondary Collisions with Deflected Barrier System (Morning and Evening Peak Periods)

Lateral Barrier Deflection (inches)	Probability of Secondary Barrier Collision
12	0
18	0.09
24	0.18
30	0.27
36	0.36
42	0.46
48	0.55

It is difficult to draw any absolute conclusions from this analysis concerning acceptable performance criteria for barrier system deflections. There are scant data available related to two important aspects that affect the development of such performance criteria:

1. little data on the severity of such secondary barrier collisions

2. little data on the number of current encroachments into oncoming lanes and/or buffer lanes on the Golden Gate Bridge. Such encroachments do not necessarily result in collisions at the present time, but would result in barrier impacts and potential secondary barrier collisions if a barrier system were in place.

In the absence of an analytical interpretation of these results, a more subjective evaluation may be all that is possible. Traditionally, transportation engineers have utilized an 85 percent performance level in setting many design criteria. As examples, speed limits are often set at a level which is not exceeded by 85 percent of drivers, and assumed driver eye height used for design is intended to include 85 percent of driver/vehicle combinations on the road. This level of performance is seen as a reasonable compromise between providing a design criterion that is generous enough to cover the large majority of day-to-day conditions, yet is not so generous as to be economically infeasible.

Utilizing such an 85 percent level of performance in this context would suggest that the maximum tolerable barrier deflection (under testing protocols established by Reference 12) should be 24 to 30 inches. If a 30-inch maximum deflection performance criterion were adopted, then 82 percent of all barrier impacts would be expected to not result in secondary barrier collisions. If a 24-inch maximum deflection performance criterion were adopted, then 82 percent of peak period barrier impacts would be expected to not result in secondary barrier collisions.

6. RISK ANALYSIS OF REBOUND COLLISIONS WITH ADJACENT TRAFFIC

Vehicles that impact a median barrier system may be redirected by the barrier impact into adjacent lanes of traffic. Because lane widths on the Golden Gate Bridge are relatively narrow, any redirection as the result of a barrier impact may result in secondary collisions either as a result of the barrier impact vehicle striking a vehicle in an adjacent lane, or as a result of such vehicles attempting to make evasive lane change maneuvers and colliding with other nearby vehicles.

Only sketchy data are available concerning secondary collisions resulting from such barrier system impact rebounds in current installations. In a 6-year period following installation of a movable barrier system on the Auckland Harbour Bridge, accidents classified as "lost control" increased very slightly compared to the two years before the barrier installation (18.4 accidents per year after installation versus 17.0 per year before installation). Some of these accidents may be related to barrier system impact rebounds. However, there appears to be a significant potential for such accidents to occur if the exit angle of vehicles striking the barrier system is large and if traffic flow in adjacent lanes is dense.

In order to analyze the likelihood of secondary collisions on the Golden Gate Bridge related to barrier system impact rebounds, a risk prediction model was developed, using many of the concepts described by Bryden and Bruno (Ref. 10) in their analysis of the movable barrier system on the Tappan Zee Bridge. This model is generic in the sense that it calculates the probability of a secondary collision based on the barrier system exit angle, regardless of the specific barrier system configuration. The resulting model does not attempt to predict the frequency of initial barrier impacts, but rather predicts whether any initial impact will result in a secondary collision between the barrier impact vehicle and adjacent same-direction traffic. The results of the analysis are useful in establishing performance criteria for the maximum tolerable barrier system exit angle.

Model Development

Important variables that must be considered in such an analysis of the probability of secondary barrier impact rebound collisions include:

1. Exit angle for a vehicle rebounding from a barrier system impact
2. The longitudinal distance that a rebounding vehicle will travel before the operator can come to a stop
3. Density and speed of traffic in the lanes adjacent to the barrier
4. Distance required for adjacent vehicle operators to react to a vehicle rebounding from a barrier system impact and take appropriate evasive action.

For this analysis, it has been assumed that the vehicle which initially impacts the barrier system will begin braking from a speed of 45 mph as soon as it separates from the barrier system. The distance to brake to a stop from 45 mph in wet weather was calculated as 135 feet. It was further assumed that the probability of a secondary collision with a vehicle in the first lane adjacent to the barrier system is negligible. A vehicle trailing the vehicle which impacts the barrier system should be able to brake to a stop to avoid such a secondary collision.

The rebounding vehicle will collide with a vehicle in another lane if that vehicle is within the "longitudinal interference zone". The probability, $P_{R,2}$, that a rebounding vehicle will collide with an adjacent vehicle in the second lane away from the barrier system after an initial barrier impact has occurred is equal to the probability that there will be a vehicle present in that lane within the longitudinal interference zone. If the rebounding vehicle travels far enough to also encroach into the third lane away from the barrier system, the probability, $P_{R,3}$, of a secondary impact is equal to the probability that there will be a vehicle present in the third lane within the longitudinal interference zone multiplied by the probability that a secondary impact did not already occur in the second lane. The probability, $P_{R,4}$, of a secondary impact with a vehicle in the fourth lane away from the barrier system can be calculated in a similar fashion.

It must also be considered that if the lateral encroachment of the rebounding vehicle is sufficiently large, the vehicle will impact the curb barrier at the outside edge of the bridge roadway. Table 21 indicates the amount of lateral encroachment by the rebounding vehicle as it brakes to a stop, based on a range of exit angles (a 5.5-foot vehicle width is assumed).

TABLE 21. Lateral Encroachment by Rebounding Vehicle

Exit Angle	Lateral Encroachment (feet)	Rebounding Vehicle Contacts Curb Barrier if Roadway Width Is:
6°	19.6	-
8°	24.3	Less than 3 lanes
10°	28.9	Less than 3 lanes
12°	33.6	Less than 4 lanes
14°	38.1	Less than 4 lanes
16°	42.7	All configurations
18°	47.2	All configurations
20°	51.7	All configurations

The probability that an adjacent vehicle in the second, third, or fourth lane is within the longitudinal interference zone depends on the density of traffic flow in these lanes. This density, of course, varies hour to hour during the day and varies by direction of traffic flow within a given hour. The current (1996) hourly lane distribution of traffic flow on the Golden Gate Bridge for a prototypical weekday was utilized for this analysis.

The probability of a secondary rebound collision was calculated separately for each hour of the typical weekday and for a range of exit angles. A weighted average of these hourly probabilities was then calculated for the day as a whole, as follows. It was assumed that the probability that an initial barrier impact will occur is proportional to the density of traffic flow in the lane adjacent to the barrier. Therefore, the probabilities of secondary collisions for each hour were weighted by the volume of traffic during that hour in the lane adjacent to the barrier. The resulting calculated probabilities represent the likelihood that a barrier impact at any time during a typical day would result in a secondary rebound collision.

The size of the longitudinal interference zone, D_L, is equal to one vehicle length plus the distance an overtaking vehicle in the adjacent lane would travel while its driver is reacting to the rebounding (and assumed braking) vehicle. A driver perception/ reaction time of 2 seconds is assumed. This represents an unexpected condition for which the driver may have to evaluate several alternative responses. It is not necessary to account for braking distance of the overtaking vehicle in calculating the longitudinal interference zone because it is assumed that the overtaking vehicle can decelerate at the same rate as the rebounding vehicle. The resulting D_L is 152 feet (2 seconds at 45 mph equals 132 feet plus one vehicle length of 20 feet).

The probability that there is no vehicle in the second lane from the barrier within a distance equal to D_L depends on the distribution of gap sizes in the traffic flow in that lane. A statistical distribution known as a "Erlang distribution" effectively models gaps in such traffic flow. The Erlang distribution recognizes that gaps in traffic flow are random in nature, but that extremely small gaps have a very low probability (Ref. 11). Using this distribution,

$$P_{R,2} = 1 - e^{-VL2xt}(1 + V_{L2}t)$$

where

V_{L2} = traffic flow rate in the second lane (vehicles per second per lane)

t = gap size in seconds [= $D_L/(1.47 \times S)$]

S = traffic speed (mph)

and

$$P_{R,3} = [1 - e^{-VL3xt}(1 + V_{L3}t)] \times [1 - P_{R,2}]$$

If the rebounding vehicle does not encroach all the way across a lane before coming to a stop, these probabilities are reduced by the probability, P_{LAT}, that the vehicle in the adjacent lane is positioned within the lane such that an impact would occur with the rebounding vehicle. In order to find P_{LAT}, it is assumed:

1. the adjacent lane is 10 feet wide
2. the lateral position of vehicles within this lane are evenly distributed across the lane
3. vehicles are an average width of 5.5 feet.

Therefore, the left side of vehicles within the adjacent lanes vary between 0 feet and 4.5 feet from the edge of lane, and the probability that an encroachment by a rebounding vehicle will be greater than or equal to the offset to the vehicle is:

$$P_{LAT} = E_L/4.5$$

where E_L is the amount of lateral encroachment of the rebounding vehicle into the adjacent lane.

Interpretation of Model Results

A spreadsheet computer program was used to perform these calculations and to determine the weighted average probabilities of secondary rebound collisions resulting from exit angles ranging from 6 to 20 degrees. Tables 22 and 23 present the results of this analysis.

TABLE 22. Probability of Secondary Collisions with Vehicles in Adjacent Lanes (Weighted Average Throughout Day)

Rebound Exit Angle	Probability of Secondary Rebound Collision
6°	18.6%
8°	27.6%
10°	28.0%
12°	31.0%
14° or more	31.7%

TABLE 23. Probability of Secondary Collisions with Vehicles in Adjacent Lanes (Morning and Evening Peak Periods)

Rebound Exit Angle	Probability of Secondary Rebound Collision
6°	30.6%
8°	43.0%
10°	48.1%
12°	54.7%
14° or more	57.4%

It is difficult to draw any absolute conclusions from this analysis concerning acceptable performance criteria for barrier impact exit angles. In the absence of an analytical interpretation of these results, a more subjective evaluation may be all that is possible. Traditionally, transportation engineers have utilized an 85 percent performance level in setting many design criteria. As examples, speed limits are often set at a level which is not exceeded by 85 percent of drivers, and assumed driver eye height used for design is intended to include 85 percent of driver/vehicle combinations on the road. This level of performance is seen as a reasonable compromise between providing a design criterion that is generous enough to cover the large majority of day-to-day conditions, yet is not so generous as to be economically infeasible.

However, application of an 85 percent performance level for barrier system exit angles would suggest a maximum exit angle of less than 6°. This low of an exit angle does not appear to be a reasonable expectation. NCHRP 350 (Ref. 12) performance criteria indicate that "after collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes." Because of the lack of shoulders and narrow traffic lanes on the Golden Gate Bridge, this also does not appear to be a reasonable expectation.

Another NCHRP 350 criterion indicates that "the exit angle from the barrier system preferably should be less than 60 percent of the test impact angle, measured at the time of vehicle loss of contact with the barrier system." This suggests a maximum exit angle criterion of 12° to 15°. Exit angles in this range would result in a secondary rebound collision approximately 31% of the times that barrier impacts occur. Also, as previously noted, exit angles of 12° or more are likely to result the rebounding vehicle also impacting the curb barrier even if it does not collide with other vehicles in adjacent lanes.

The following conclusions with regard to barrier impact exit angles appear to be reasonable:

1. Although ideally, the exit angle should be less than 6°, this is not a realistic expectation for evaluation of candidate barrier systems.
2. Exit angles within the range of 6° to 12° appear to provide acceptable performance and should be reasonably attainable.
3. Exit angles of greater than 12° would be undesirable for candidate barrier systems to be considered for application of the Golden Gate Bridge.

7. STATE-OF-THE-ART PRACTICE IN MEDIAN BARRIER APPLICATION

The California Department of Transportation Traffic Manual (Ref. 24) indicates that, when utilized, "median barriers should:

1. Prevent an out-of-control vehicle from crossing the median and colliding with opposing traffic.
2. Minimize the potential for the deflection back into the traffic stream of a vehicle colliding with the barrier.
3. Decelerate the errant vehicle within tolerable limits.

While median barriers are capable of preventing nearly all of the cross-median accidents, their installation will result in fixed object accidents that might not otherwise occur." A California Department of Transportation study concluded that on freeway facilities, total accidents would likely increase 20 to 30 percent after median barrier installation and as much as 50 percent on non-freeway facilities (Ref. 9).

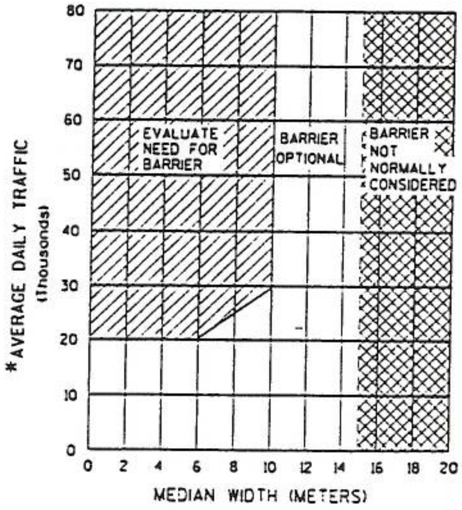
It is a fundamental principle of barrier application that "a median barrier should be installed only if striking the barrier is less severe than the consequences that would result if no barrier existed....It should be noted that after a warranted median barrier is installed, accident severity may decrease, but accident frequency may increase since the space available for return-to-the-road maneuvers is reduced" (Ref. 25).

The American Association of State Highway and Transportation Officials (Ref. 25) has suggested the warrants shown in Figure 2 for median barriers on high-speed, controlled-access roadways. This warrant is based on what is described as "a limited analysis of median crossover accidents and research studies," and should not overrule site-specific data. According to this warrant, conditions on the Golden Gate Bridge fall within the range entitled "Evaluate Need for Barrier." However, it should be noted that this warrant was developed based on the characteristics of permanent barrier installations, and does not directly consider the characteristics nor the potential desirability of a movable median barrier system. Further, this warrant does not mandate barrier installation for any roadway condition.

The California Department of Transportation Traffic Manual contains warrants for median barrier installation for freeway facilities only. It indicates that "barriers should be provided on freeways whenever these warrants are met and an accident history is developing unless there are unique circumstances to justify omitting the barrier" (Ref. 24). This freeway median barrier warrant is shown in Figure 3. Freeway conditions comparable to the Golden Gate Bridge would fall within the range in this figure that indicates a median barrier is warranted. The California Department of Transportation manual further indicates that regardless of freeway median width and daily traffic volume, "barriers should be considered if there has been a high rate of out-of-control cross-median accidents involving opposing vehicles. A rate, based on at least three accidents in five years, of 0.31 cross-median accidents per kilometer (0.50 accidents per mile) per year of any severity or 0.07 fatal cross-median accidents per kilometer (0.12 fatal accidents per mile) per year involving opposing vehicles justifies further analysis to determine the advisability of a barrier" (Ref. 24). In the 10.6-year period of January 1986 through July 1996, the Golden Gate Bridge has experienced 4.3 cross-over accidents per mile per year and 0.44 fatal cross-over accidents per mile per year, thus exceeding the preceding freeway accident experience warrant. As previously discussed, such barrier warrants were developed for permanent barrier installations, and do not explicitly consider the characteristics nor the desirability of a movable median barrier system.

It must be emphasized that the foregoing discussion of California Department of Transportation criteria for median barrier installation is specifically limited to freeway facilities, and that the Golden Gate Bridge is not a freeway, as discussed earlier in this report. Any reference to criteria for freeway facilities is for illustrative purposes only. The Traffic Manual indicates that "median barriers can be an appropriate solution to cross-median accidents on expressways and conventional highways. The volume/median width and accident warrants apply to freeways only, but they may be used as a guide for non-freeways. Normally other solutions are preferred, but at locations where the roadway resembles or behaves like a freeway, median barriers should be considered....Careful consideration of the...accident history, alignment, grade, and sight distance as well as traffic volumes and median width must be given for non-freeway installations....Also, barrier accident severity should be considered when evaluating median barrier installations. At locations with operating speeds below 72 km/h (45 mph), cross-median accident severity is greatly reduced. For these locations, the increased numbers of accidents may not be offset by reduction in accident severity" (Ref. 24).

A comparison of accidents on California freeway and non-freeway facilities before and after median barrier installation (Ref. 9) concluded that after barriers were installed, fatal accident rates decreased but injury accident rates and total accident rates increased.



* *Based on a 5-year projection*

FIGURE 2. American Association of State Highway and Transportation Officials Median Barrier Warrant

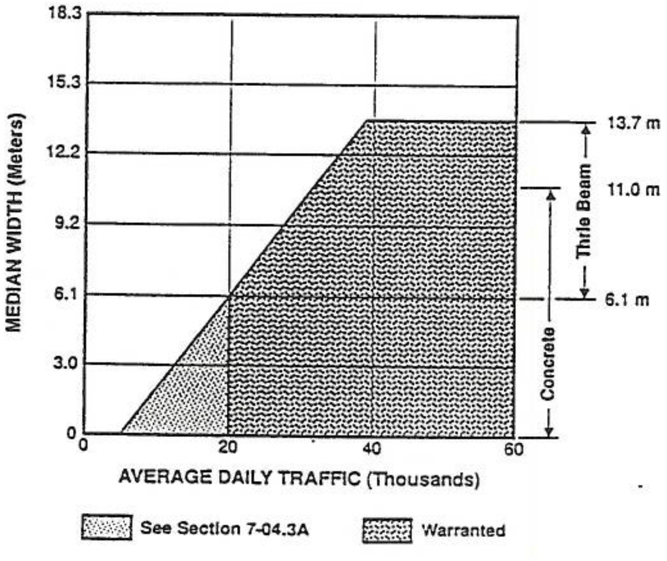


FIGURE 3. California Department of Transportation Freeway Median Barrier Warrant

8. BARRIER PERFORMANCE CRITERIA AND CRASH TESTING

Many traffic barrier systems and crash cushions have been developed by state agencies, universities, and private firms to address road safety concerns. New systems are continually emerging to address safety problems, and existing devices and practices are continually improved in response to an increased understanding of safety performance, a changing vehicle fleet, emergence of new materials and concepts, and other factors. Full-scale impact testing has been and continues to be the most common method of evaluating the safety performance of such devices.

In order to provide for uniformity in the procedures and criteria used to evaluate barriers and crash cushions, a set of guidelines have been developed and published in NCHRP Report 350 Recommended Procedures for the Safety Performance Evaluation of Highway Features (Ref. 12). This publication will be referred to as NCHRP 350. It identifies a standardized set of six "test levels" based on vehicle type, weight, speed, and approach angle. Test level 3 is considered the basic test level, and is the most widely used and generally applicable set of test procedures. Its use is appropriate for many high-speed arterial highways. Test levels 1 and 2 are generally applicable to lower volume and/or lower speed highways and to work zones. Test levels 4, 5, and 6 involve testing of various types of trucks, and may be applicable where there are high volumes of trucks on the highway.

Performance criteria are provided in terms of degree of hazard to vehicle occupants, structural adequacy of the safety feature, hazard to others in the vicinity, and post-impact behavior of the test vehicle. The test procedures and performance criteria contained in NCHRP 350 are generally accepted and consistently applied in the evaluation of barrier systems and crash cushions throughout the United States. Additional factors that should be considered (but are not specifically addressed by NCHRP 350) include aesthetics, costs (initial, operating, and maintenance), and durability.

The following discussion identifies test procedures and performance criteria that are applicable to the impact testing of candidate movable barrier systems and/or crash cushions which may be considered for use on the Golden Gate Bridge.

Movable Barrier Systems - Test Procedures

NCHRP 350 Test Level 3 requires impact testing of a small car with a nominal weight 820 kg (1800 lbs) at a speed of 100 km/h (62 mph) and an approach angle of 20° and a pickup truck with a nominal weight of 2000 kg (4400 lbs) at a speed of 100 km/h and an approach angle of 25°. A third test using a small car with a nominal weight of 700 kg (1540 lbs) at a speed of 100 km/h and an approach angle of 20° is desirable but is considered optional because this vehicle type represents only a very small portion of the vehicle fleet.

The standard impact conditions for Test Level 3 appear to be appropriate for testing of any candidate barrier systems considered for use on the Golden Gate Bridge. Although the posted speed limit is 45 mph, speed studies have consistently indicated prevailing speeds in excess of 50 mph, considerably higher than the Level 1 and 2 speeds of 70 km/h (43 mph). The impact angles of 20° and 25° specified for Level 3 testing are also appropriate. With the lanes in a 4/2 configuration, it is possible for a 60 mph vehicle to impact such a barrier system at an angle of 28° on the tangent sections of alignment under dry pavement conditions. Even higher angles of impact are possible in the sections of curved alignment. Finally, the use of the 820 kg small car and 2000 kg pickup truck as test vehicles appears to be appropriate. As previously noted, the smaller 700 kg (1540 lbs.) car is rare (lighter than a Geo Metro, for example). Test Levels 4 through 6 using larger trucks are also not appropriate since trucks and buses represent only about 2 to 3 percent of vehicle traffic on the Golden Gate Bridge.

Movable Barrier Systems - Performance Criteria

NCHRP 350 specifies the following performance criteria for Test Level 3:

1. The barrier system should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the barrier is acceptable.

2. Detached elements, fragments, or other debris from the barrier system should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic or pedestrians. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.

3. The vehicle should remain upright during and after collision although moderate roll, pitching and yawing are acceptable.

4. After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.

5. The exit angle from the barrier system preferably should be less than 60 percent of the test impact angle, measured at the time of vehicle loss of contact with the barrier system.

6. For the small car tests, longitudinal and lateral occupant impact velocities should not exceed 9 m/s (29 ft/sec) (preferred) or 12 m/s (39 ft/sec) (maximum) and longitudinal and lateral occupant ridedown accelerations should not exceed 15 G's (preferred) or 20 G's (maximum). For the pickup truck test, longitudinal occupant impact velocity should not exceed 12 m/s (39 ft/sec) and the longitudinal occupant ridedown acceleration should not exceed 20 G's.

Two of these performance criteria are of special concern for potential application to testing of candidate barrier systems that may be considered for use on the Golden Gate Bridge.

The NCHRP 350 criteria indicate that "controlled lateral deflection of the barrier is acceptable." Such lateral deflection of a barrier system is of critical concern on the Golden Gate Bridge because any deflection would encroach into a relatively narrow opposing traffic lane. This may result in secondary collisions either as a result of oncoming vehicles striking the deflected barrier system, or as a result of such vehicles attempting to make evasive lane change or braking maneuvers. As previously discussed, the maximum acceptable deflection for the Level 3 testing conditions should be 24 to 30 inches. A maximum deflection of 30 inches would limit the probability of a secondary collision to no more than 0.18 overall. A desirable maximum deflection of 24 inches would limit the probability of a secondary collision to no more than 0.12 overall and no more than 0.18 during the morning and evening peak periods of a typical weekday.

A second area of critical concern relates to the exit angle and trajectory of the test vehicle after impact with the barrier system. The NCHRP 350 performance criteria indicate that "after collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes." Another criteria indicates that "the exit angle from the barrier system preferably should be less than 60 percent of the test impact angle, measured at the time of vehicle loss of contact with the barrier system." Because of the relatively narrow lanes on the Golden Gate Bridge and the lack of any clearance between a median barrier system and the edge of the adjacent lane, it does not appear to be a reasonable expectation that such a post-impact trajectory could be contained within the lane adjacent to the barrier system. As previously discussed, a maximum exit angle of 6° to 12° appears to be a desirable performance criteria for application on the Golden Gate Bridge. This is somewhat less than the normal NCHRP 350 criteria of "less than 60 percent of the test impact angle" which would be 12° and 15° respectively for the small car and pickup truck tests. However, a 12° maximum exit angle appears to be a reasonable criteria for application to the Golden Gate Bridge.

Evaluation of Quickchange Movable Barrier and Narrow Quickchange Movable Barrier Systems

There are two known, commercially available movable barrier systems that have undergone appropriate crash testing. The Quickchange Movable Barrier system was originally developed in the 1980's and was crash tested by the California Department of Transportation in 1985 through 1988, using pre-NCHRP 350 test procedures (Ref. 23). This barrier system has been installed in a large number of temporary and permanent locations throughout the world. The Narrow Quickchange Movable Barrier system was developed in the 1990's and has been crash tested using the NCHRP 350 test procedures (Ref. 22).

Crash test results for four tests of the Quickchange Movable Barrier system are shown in Table 24. Results of two tests of the Narrow Quickchange Movable Barrier system are shown in Table 25. Both barrier systems appear to perform adequately in terms of structural strength and vehicle stability. Both systems also appear to satisfy the NCHRP 350 performance criteria for longitudinal and lateral ridedown acceleration and longitudinal and lateral occupant impact velocity. The Narrow Quickchange Movable Barrier system performed significantly better than the standard Quickchange Movable Barrier system in terms of exit angle. As previously noted, an exit angle of no more than 12° is an acceptable criteria for application on the Golden Gate Bridge. The Narrow Quickchange Movable Barrier satisfies this criteria for both the small passenger car and the pickup truck test vehicles. The standard Quickchange Movable Barrier system resulted in exit angles in excess of this 12° criteria for both large and small vehicles.

As previously discussed, a maximum barrier system lateral deflection of no more than 30 inches is an acceptable criteria for application on the Golden Gate Bridge. Both the Narrow and standard Quickchange Movable Barrier systems meet this criteria for the small test vehicle. However, neither system meets this criteria for a test vehicle in the range of 4400 lbs, with barrier deflections of 34.5 inches for the Narrow Quickchange Movable Barrier system and 34 to 45 inches for the standard Quickchange Movable Barrier system. A 34-inch lateral deflection would increase the probability of a secondary collision with the deflected barrier to approximately 0.24 if used on the Golden Gate Bridge. In other words, 24% of barrier impacts with a 34-inch deflection would be expected to result in a secondary barrier collision. Because this risk is associated only with initial barrier impacts at high speed by relatively heavy passenger cars or pickup trucks (60 mph/4400 lbs.), this may be considered marginally acceptable for application on the Golden Gate Bridge. The large majority of barrier impacts should result in less deflection. However, a barrier deflection of as much as 45 inches, as occurred in one crash test of the standard Quickchange Movable Barrier system, appears to be unacceptable for application on the Golden Gate Bridge. That magnitude of deflection would increase the probability of a secondary barrier impact to 0.36 (0.55 during peak traffic periods).

In summary, the Narrow Quickchange Movable Barrier system appears to satisfy all of the desired performance criteria for application on the Golden Gate Bridge except for maximum lateral deflection which is somewhat more than the desired criterion of 30 inches. Because relatively few barrier impacts would be expected to exceed this 30-inch criterion in actual practice, the Narrow Quickchange Movable Barrier system may be considered marginally acceptable in this regard. If a movable median barrier system were to be installed on the Golden Gate Bridge, the Narrow Quickchange Movable Barrier system would be preferred over the standard Quickchange Movable Barrier system. No other movable barrier systems are known to meet desired criteria. However, if any other systems become available which satisfy appropriate performance criteria, they also should be considered for potential application.

TABLE 24. Crash Test Results for Quickchange Movable Barrier System (Ref. 23)

Test	443	444	445	446
Vehicle Weight (lbs)	4370	2000	4300	1890
Impact Angle	24°	15.5°	16°	20.5°
Impact Speed (mph)	59.3	57.7	59.4	58.6
Longitudinal Ridedown Acceleration (G's)	-5.6	≤15	-3.9	≤15
Lateral Ridedown Acceleration (G's)	7.6	≤15	10.6	≤15
Longitudinal Occupant Impact Velocity (ft/sec)	27.0	15.1	14.3	16.9
Lateral Occupant Impact Velocity (ft/sec)	18.0	NA	14.0	NA
Exit Angle	14.7°	10.2°	16.5°	19.5°
Barrier System Lateral Deflection (inches)	45	21	34	27

TABLE 25. Crash Test Results for Narrow Quickchange Movable Barrier System (Ref. 22)

Test	001	002
Vehicle Weight (lbs)	1936	4500
Impact Angle	21°	24.5°
Impact Speed (mph)	66.5	61.0
Longitudinal Ridedown Acceleration (G's)	-11.6	-6.1
Lateral Ridedown Acceleration (G's)	18.3	15.3
Longitudinal Occupant Impact Velocity (ft/sec)	13.1	16.8
Lateral Occupant Impact Velocity (ft/sec)	24.6	22.0
Exit Angle	10°	9.5°
Barrier System Lateral Deflection (inches)	18.3	34.5

Crash Cushions - Test Procedure

NCHRP 350 specifies three alternative test levels for barrier terminals and crash cushions. These three test levels use the same size vehicles as Test Level 3 for longitudinal barrier systems (previously discussed), but are conducted at impact speeds of 50, 70, and 100 km/h (31, 43, and 62 mph) respectively for Test Levels 1, 2, and 3. Further, different angles of impact and locations of impact points are specified depending on whether the terminal or crash cushion is considered "redirective" or "nonredirective".

Candidate crash cushions considered for use on the Golden Gate Bridge to safely terminate any movable barrier system should logically meet different test levels depending on where they would be located.

A crash cushion used at the south end of a movable barrier system, if located relatively close to the toll plaza, should meet Test Level 2 criteria (70 km/h impact speed), consistent with typical speeds of northbound vehicles as they pass through the toll plaza area. Because the end of such a barrier system (and hence the location of the crash cushion) would likely be some distance north of the toll plaza with no barrier separation between northbound and southbound traffic in the immediate toll plaza area, it does not appear to be necessary that such a crash cushion be non-gating nor redirective. However, any lateral deflection of the crash cushion or end of the barrier system into the oncoming southbound lanes would be undesirable and should be minimized.

NCHRP 350 Test Level 2 for non-redirective crash cushions requires a minimum of five impact tests, as follows:

1. 820 kg (1800 lbs) small car impacting the nose of the crash cushion at 70 km/h (43 mph) approaching parallel to the roadway with impact offset to the left or right of the vehicle centerline.
2. 2000 kg (4400 lbs) pickup truck impacting the nose of the crash cushion at 70 km/h (43 mph) approaching parallel to the roadway with impact at the vehicle centerline.
3. 820 kg (1800 lbs) small car impacting the nose of the crash cushion at 70 km/h (43 mph) and at an angle of 15° to the roadway.
4. 2000 kg (4400 lbs) pickup truck impacting the nose of the crash cushion at 70 km/h (43 mph) and at an angle of 15° to the roadway.
5. 2000 kg (4400 lbs) pickup truck impacting the side of the crash cushion at 70 km/h (43 mph) and at an angle of 20° to the roadway.

Two additional optional tests using a 700 kg small car are also listed in NCHRP 350, but do not appear appropriate for candidate crash cushions considered for use on the Golden Gate Bridge, as previously discussed.

A crash cushion used at the north end of a movable barrier system should meet Test Level 3 criteria (100 km/h impact speed), consistent with typical speeds of southbound vehicles as they approach the bridge on a freeway section and on a downhill grade. Depending on the location of such a crash cushion, it may have to be non-gating and redirective.

NCHRP 350 Test Level 3 for non-gating, redirective crash cushions requires a minimum of eight impact tests, as follows:

1. 820 kg (1800 lbs) small car impacting the nose of the crash cushion at 100 km/h (62 mph) approaching parallel to the roadway with impact offset to the left or right of the vehicle centerline.
2. 2000 kg (4400 lbs) pickup truck impacting the nose of the crash cushion at 100 km/h (62 mph) approaching parallel to the roadway with impact at the vehicle centerline.

3. 820 kg (1800 lbs) small car impacting the nose of the crash cushion at 100 km/h (62 mph) and at an angle of 15° to the roadway.

4. 2000 kg (4400 lbs) pickup truck impacting the nose of the crash cushion at 100 km/h (62 mph) and at an angle of 15° to the roadway.

5. 820 kg (1800 lbs) small car impacting the side of the crash cushion near the nose at 100 km/h (62 mph) and at an angle of 15° to the roadway.

6. 2000 kg (4400 lbs) pickup truck impacting the side of the crash cushion near the nose at 100 km/h (62 mph) and at an angle of 20° to the roadway.

7. 2000 kg (4400 lbs) pickup truck impacting the side of the crash cushion near its connection to the longitudinal barrier system at 100 km/h (62 mph) and at an angle of 20° to the roadway.

8. 2000 kg (4400 lbs) pickup truck impacting the midpoint of the side of opposing traffic flow of the crash cushion at 100 km/h (62 mph) and at an angle of 20° to the roadway.

Three additional optional tests using a 700 kg small car are also listed in NCHRP 350, but do not appear appropriate for candidate crash cushions considered for use on the Golden Gate Bridge, as previously discussed.

Crash Cushions - Performance Criteria

NCHRP 350 specifies the following performance criteria for Test Level 3:

1. Acceptable crash cushion performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.

2. Detached elements, fragments, or other debris from the crash cushion should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic or pedestrians. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.

3. The vehicle should remain upright during and after collision although moderate roll, pitching and yawing are acceptable.

4. After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.

5. For most of the tests, longitudinal and lateral occupant impact velocities should not exceed 9 m/s (preferred) or 12 m/s (maximum) and longitudinal and lateral occupant ridedown accelerations should not exceed 15 G's (preferred) or 20 G's (maximum). For some of the pickup truck tests, longitudinal occupant impact velocity should not exceed 12 m/s and the longitudinal occupant ridedown acceleration should not exceed 20 G's.

6. For most of the tests, vehicle trajectory behind the crash cushion is acceptable.

When applying these performance criteria to the evaluation of candidate crash cushions for potential application on the Golden Gate Bridge, it would appear that Criteria 4 and 6 are incompatible with each other. Any after-impact vehicle trajectory behind the crash cushion would result in the vehicle intruding into the opposing traffic lane. These criteria should be interpreted in the context of the unique conditions on the Golden Gate Bridge including relatively narrow lanes and no offset between lane edges and any movable barrier system. It must further be recognized that, at least at the south end of such a median barrier system, the primary purpose of a crash cushion is to reduce the severity of impacts with the end of the barrier, not to prevent intrusion into the opposing lanes. It therefore may be tolerable to permit a limited intrusion of the deflected crash cushion and the impacting vehicle into the opposing traffic lane at the south end of a movable barrier system. However, it would be extremely undesirable to permit any significant lateral displacement of the crash cushion and/or the movable barrier system itself into opposing traffic lanes. A maximum lateral displacement of the impacted crash cushion and/or the end of the movable barrier system of one lane width (10 feet) appears to be a desirable performance criteria.

Finally, the NCHRP 350 performance criteria do not directly address issues of crash cushion installation, maintenance, and replacement. These are clearly important issues for any potential application in connection with a movable barrier system on the Golden Gate Bridge. Any candidate crash cushion should be compatible with a movable barrier system in terms of providing a structurally adequate connection to the barrier system. It desirably should be capable of being transferred with the movable barrier system without detaching it from the system. If this is not feasible, then the crash cushion should be capable of being easily and quickly detached, moved, and reattached with a minimum of power tools and/or lifting devices for normal barrier system movements as well as when damaged by impacts. This work should be capable of being performed with a minimum of personnel and vehicles and should occupy no more than one traffic lane. Finally, it should be sufficiently durable to withstand numerous transfers without damage or deterioration to the cushion or the connecting mechanism.

Evaluation of N-E-A-T Crash Cushion

There is one known, commercially available crash cushion currently available which appears to satisfy most of the performance criteria previously described for candidate crash cushions for potential application at the south end of the Golden Gate Bridge. There are no known crash cushions currently available that satisfy the performance criteria previously described for application at the north end of the Bridge.

The currently available crash cushion that potentially could be used at the south end of the Golden Gate Bridge is designated the N-E-A-T System (Non-Redirective, Energy-Absorbing Terminal) manufactured by Energy Absorption Systems, Inc. This crash cushion was developed to be compatible with a standard safety-shape concrete barrier and the QuickChange Barrier. It likely could be adapted to be compatible with other candidate barrier systems.

According to the manufacturer, the N-E-A-T System is relatively light-weight (approximately 300 lbs), is compact (10 feet by 22.5 inches), requires no special tools or heavy equipment for installation, has integrated caster wheels to assist in movement and resetting the system, can be installed in less than 15 minutes, results in minimal post-impact debris, and meets NCHRP 350 Test Level 2 criteria for non-redirective crash cushions (Ref. 17).

Crash testing of this crash cushion was conducted in 1994, and the product passed all five of the NCHRP Test Level 2 impact tests using the 820 kg small car and the 2000 kg pickup truck (Ref. 18). However, it is noted that in four of the five impact tests, the barrier system to which the crash cushion was attached was restrained to prevent lateral deflection. Although this restraint imposed a more critical condition on the performance of the crash cushion itself, it does not represent a full evaluation of the impact performance of the combined crash cushion and barrier system on the Golden Gate Bridge if the barrier system is not similarly restrained to prevent lateral deflection. The only impact test conducted without lateral restraint of the barrier system was the small car (820 kg) impacting the nose of the crash cushion at 70 km/h (43 mph) approaching parallel to the roadway with impact offset to the left of the vehicle centerline. This impact resulted in the crash cushion and end of the barrier system being deflected into the opposing traffic lane by 10.1 feet. It is likely that an angle impact by a larger vehicle would result in significantly more lateral deflection if the crash cushion and/or barrier system were not restrained. If the N-E-A-T System is to be considered for potential application in conjunction with a movable barrier system on the Golden Gate Bridge, provision should be made for restraining the end of the barrier system to prevent unacceptable deflections in the opposing traffic lane.

9. EVALUATION OF BARRIER END TREATMENTS

The location and treatment of the ends of any movable barrier system considered for use on the Golden Gate Bridge will have an important affect on the expected safety performance of the barrier. There are two significant considerations which must be satisfactorily addressed and resolved before a barrier system could be considered as feasible. First, the location of the end of the barrier system must be compatible with lane allocations at the toll plaza at the San Francisco approach and the freeway connection at the Marin approach. Second, the end treatments must be designed or located so as to provide adequate safety for traffic flow adjacent to the barrier. Because the considerations and potential treatments are somewhat different at the two ends of the bridge, they will be discussed separately.

San Francisco Approach

A total of thirteen lanes are currently available through the toll plaza. The allocation of toll plaza lanes to northbound and southbound traffic varies depending on the time of day and lane configuration on the bridge. It is assumed that the current allocation of lane usage through the toll plaza will be retained for the immediate future, although the lane configuration on the Bridge would likely change if a movable barrier system were installed, as indicated in Table 26. The end treatment of any barrier system would be required to accommodate this allocation of lanes. The end treatment of any barrier system would also be required to accommodate the movement of southbound wide load vehicles through the toll plaza. Finally, any barrier system should also provide sufficient flexibility to adapt to future changes in lane availability and usage through the toll plaza.

TABLE 26. Assumed Lane Allocation Through the Toll Plaza
and on the Bridge

Time Period	Bridge Lanes		Toll Plaza Lanes	
	Northbound	Southbound	Northbound	Southbound
Weekday Mornings	2	4	2	11
Midday	3	3	4	9
Weekday Evenings	4	2	5	8
Night	3	3	4	9
Sunday Evening	2	4	2	11
Weekends	3	3	4	9

Several alternative end treatments could be considered. One alternative would be a continuation of the barrier system up to the immediate proximity of the toll booth islands. Thus, the exposed end section of the barrier would be shielded from vehicles traveling northbound through the toll plaza by the somewhat wider toll islands. However, in order to implement this alternative, it would be necessary at some times to laterally shift the south end of the barrier system two lanes at the toll islands while shifting the remainder of the barrier system only one lane (for example, morning peak to midday configurations). This differential shift must be made in a smooth taper approximately 400 feet long. It may be possible to accomplish such a differential shift of a barrier system such as the Quickchange Barrier by "crabbing" the transfer vehicle as it approaches or departs the toll islands.

However, even if such a differential shift were feasible, the extension of a continuous barrier up to the toll islands would interfere with the current method of transferring southbound wide load vehicles to the far east lane through the toll plaza. As many as 20 to 30 southbound wide load vehicles must make this maneuver each year. This problem cannot be avoided unless one of the west toll booth lanes were widened by encroaching into the sidewalk area in front of the Golden Gate Bridge, Highway and Transportation District administration building or by combining two existing toll booth lanes into one wide lane, effectively eliminating one of the toll booth lanes. Widening into the sidewalk area does not appear to be structurally feasible. Eliminating a toll booth lane also does not appear to be feasible because no excess capacity currently exists at the toll plaza. Therefore, this alternative treatment does not appear to be feasible at the present time.

An analysis of vehicle turning paths indicates that a barrier system would have to be terminated at least 150 feet north of the toll islands to permit an easy transfer of wide load vehicles across the plaza. The exposed end of the barrier system would then require safety treatment because it would no longer be shadowed by the islands. The roadway section between the end of the barrier system and the toll islands could be divided using flexible tubes, traffic cones, or a low movable curb similar to the one which was used upstream of the movable median barrier installation on the A-15 bridge over the Seine River in Gennevilliers, France (Ref. 3). However, the movable curb would interfere with the transfer of southbound wide loads, similar to the first alternative. Any of these divisional techniques would leave the exposed end of the barrier system vulnerable to potential impacts from northbound traffic.

A possible safety treatment for the end of the barrier system is the "N-E-A-T System", a proprietary energy absorbing crash cushion specifically designed for use with portable concrete barriers (or comparable devices). This device is relatively light weight (approximately 300 pounds), is compact (10 feet by 22.5 inches), is mounted on casters for manual repositioning, and can be installed or repaired relatively quickly with simple hand tools. It provides adequate decelerations for vehicles weighing up to 4500 pounds traveling at speeds up to 45 mph. Post-impact debris is minimal due to the self-contained cartridge construction, resulting in relatively fast cleanup and replacement.

However, if the end of the barrier system was not anchored to the roadway surface, the N-E-A-T crash cushion and the end of the barrier system may be expected to deflect into the adjacent oncoming traffic lane when impacted at an angle. Because of its exposed position immediately adjacent to the northbound traffic lanes, the crash cushion would likely be impacted relatively frequently. Therefore, although this alternative appears to be a feasible method of terminating a movable barrier system on the Golden Gate Bridge, a system of anchoring the end of the barrier system would have to be developed. Such an anchorage would have to be strong enough to withstand impact forces, sufficiently flexible to cope with slight variations in the longitudinal and lateral location of the barrier system end, and quick and simple to connect and disconnect. This does not appear to be an insurmountable design problem, and it is likely that the N-E-A-T crash cushion or comparable device could be manually repositioned with each barrier system movement while workers are shielded by a truck blocking one lane, similar to current practice for repositioning flexible tubes in the toll plaza area.

Terminating a barrier system farther north than the vicinity of the toll plaza does not appear to be practical or reasonable. A terminal at any point farther north would share the same concerns about the safety treatment of the barrier end as the second alternative, and would deny the intended benefit of the barrier in reducing crossover accidents in a curved section where crossover accidents are likely to be more frequent than in tangent sections of the bridge. As a result, this alternative was not considered further.

Marin Approach

On the Marin approach, the Golden Gate Bridge connects with an eight-lane freeway. There is one clearly superior treatment at this location, as follows. As illustrated in Figure 4, the barrier system could be extended a short distance up the northbound freeway roadway, just past the end of the existing median guardrail. In all lane configurations, the north end of the barrier system would be shielded from southbound traffic by the freeway median guardrail and would therefore not need a crash cushion end treatment. As an added benefit, the end of the freeway median guardrail would also be shielded from northbound traffic by the barrier system and the existing crash cushion on the end of the median guardrail would no longer be needed.

For barrier systems that utilize a transfer vehicle, such as the Quickchange Barrier, this vehicle could be stored on the freeway pavement and would also be shielded from north and southbound traffic by the barrier system and the freeway median guardrail. This is also illustrated in Figure 4.

Implementing this treatment would require that a short length of the freeway median shoulder be graded and paved to allow storage of the end of the barrier system on the shoulder during periods of time that four northbound lanes are provided on the Bridge.

During periods when there are two or three southbound lanes provided on the bridge, the current method of closing one or two southbound freeway lanes in advance of the Bridge using changeable message signs and flexible tubes or cones would have to be retained.

This alternative end treatment appears to be highly desirable if a movable median barrier system were to be installed on the Golden Gate Bridge. Any other alternative end treatment that involved terminating the barrier system south of the end of the freeway approach does not appear to be practical or reasonable. A terminal at any point farther south would require a safety treatment of the barrier end. However, there are no known, available crash cushions which are portable enough to be moved with the barrier system transfers and provide adequate protection for the speeds typical of southbound freeway traffic approaching the Bridge.

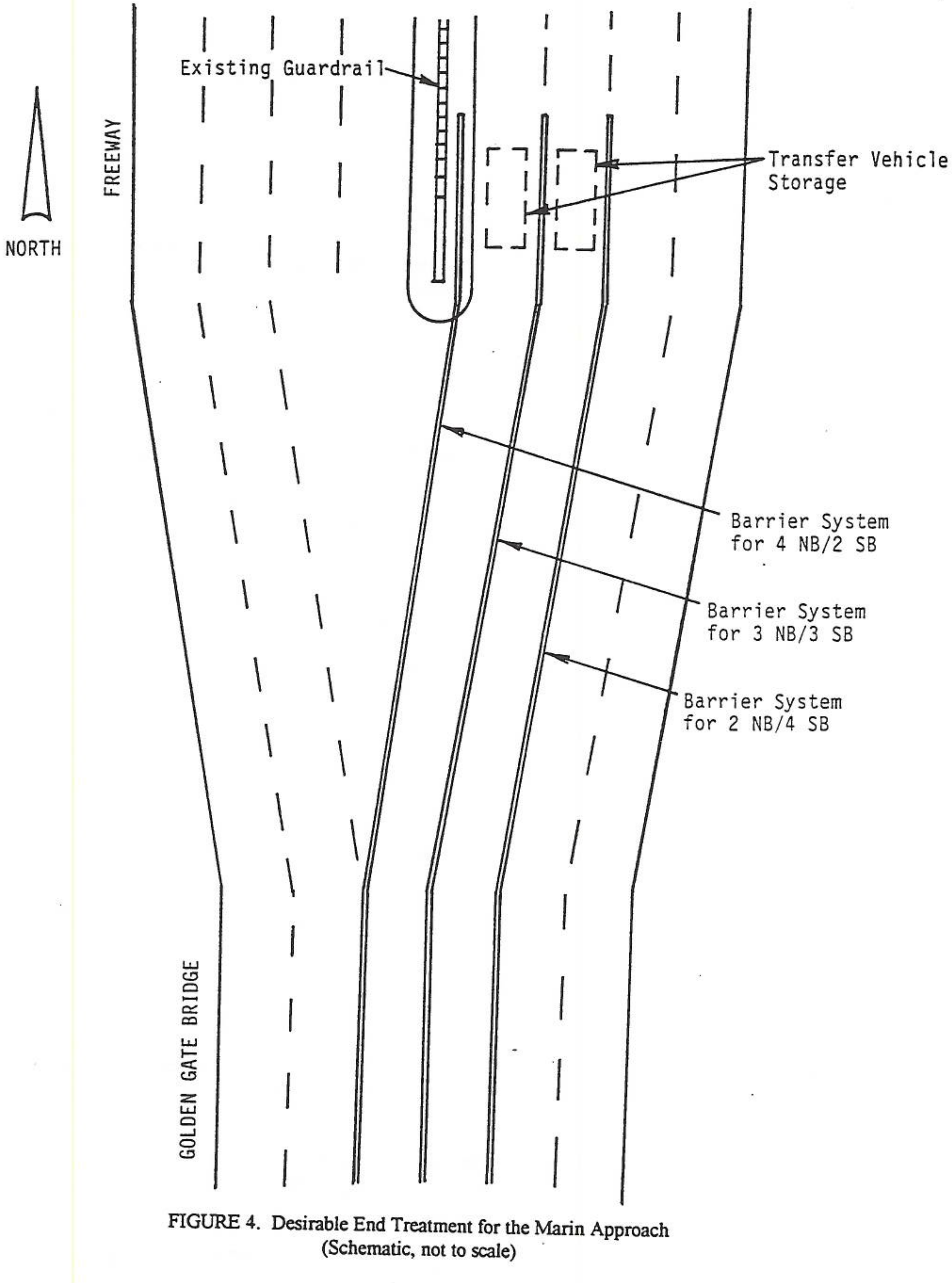


FIGURE 4. Desirable End Treatment for the Marin Approach
(Schematic, not to scale)