VOL. 28, NO. 8

JUNE 1955

Public Roads

A JOURNAL OF HIGHWAY RESEARCH

PUBLISHED BY
THE BUREAU OF
PUBLIC ROADS,
U. S. DEPARTMENT
OF COMMERCE,
WASHINGTON

Driver reaction to objects placed on highway shoulders

Public Roads

A JOURNAL OF HIGHWAY RESEARCH

Vol. 28, No. 8 *June 1955*

Published Bimonthly

Edgar A. Stromberg, *Editor*

BUREAU OF PUBLIC ROADS

Washington 25, D. C.

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The printing of this publication has been approved by the Direc of the Bureau of the Budget, March 17, 1955.

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Driver Behavior as Affected by Objects on Highway Shoulders

BY THE HIGHWAY TRANSPORT RESEARCH BRANCH
BUREAU OF PUBLIC ROADS

Reported by ASRIEL TARAGIN
Highway Engineer

Shoulders along a highway expedite traffic and contribute to driving comfort and safety. This study was undertaken to determine how driver behavior is influenced by parked vehicles or other objects placed on shoulders at various distances from the outer edge of traffic lanes. The objects selected were a passenger car, a truck, and a barricade. Each was placed at the pavement edge, 3 feet from the edge, and 6 feet from the edge. Passenger and commercial vehicle speeds and lateral positions were recorded on two-lane highways carrying light to moderate traffic volumes and on a four-lane divided highway carrying up to 3,400 vehicles per hour in one direction.

For all vehicle types it was found that speeds were not affected significantly by objects on the shoulder. Such objects affected the lateral position of only those vehicles traveling in the adjacent lane. Objects placed at the pavement edge had the greatest effect and lateral shifts decreased sharply when objects were set 3 and 6 feet from the edge. The narrower the pavement, the further the traffic shifted left, away from the object on the shoulder. On a two-lane 16-foot highway, the shift was 3.3 feet, while on a 24-foot surface the shift was 1.8 feet. The various objects—car, truck, and barricade—caused about the same degree of shifting. On narrow two-lane roads, some vehicles shifted over the centerline when the object was placed at the pavement edge.

SHOULDERS along a highway are needed for several reasons. They add to the comfort of the drivers and increase safety. Wide shoulders provide a storage space outside the traffic lanes for disabled vehicles and for short-time parking of vehicles as may be desired by drivers. They also serve as a space to avoid an accident in case of emergency.

It is generally believed that vehicles standing along the traveled way of a highway either by choice of the drivers or due to mechanical failure influence the behavior of vehicles on the highway. It is the purpose of this article to report the results of studies made to determine the extent to which traffic is influenced by parked vehicles or other objects on the shoulders at various distances from the edges of the traffic lanes.

Vehicle speeds and placements were recorded on two-lane highways carrying light to moderate traffic and on a four-lane divided highway carrying volumes as high as 3,400 vehicles per hour in one direction.

Study Procedure

A description of the sites selected for study for two-lane operations is given in table 1. These sites were studied in cooperation with the Oregon State Highway Department and were on level tangent sections with no restrictive sight distances in either direction of travel. A yellow dashed centerline separated the two traffic lanes, and the pavements were flanked by well-maintained gravel shoulders. The 16-foot concrete pavement at site 1 was flanked by 2-foot bituminous shoulders beyond which were the 5-foot gravel shoulders.

The study of four-lane operations was conducted during September 1953, on a level tangent at the north end of the Shirley Memorial Highway, a freeway connecting the Pentagon Network and Woodbridge, Va. The section studied has two 12-foot lanes in each direction of portland cement concrete with shoulders 10 feet wide. A 30-foot grass median separates the vehicles traveling in the opposing directions. The posted speed limit at this location is 50 miles per hour for passenger cars and 45 miles per hour for trucks.

The speeds and transverse positions of vehicles were first recorded at all locations under normal conditions, that is, with the shoulders clear of any object. Similar data were then recorded with the objects placed on the shoulder at various distances from the pavement edge. The data for normal conditions were used as a base to determine the effect on driver behavior of each of the several objects placed on the shoulder. These data cannot be used, however, to compare driver behavior on various surface widths, because design elements and traffic conditions were not the same at the different locations included in this study. The results of another study based on extensive data for comparable locations show the effect of roadway width on driver behavior.[1]

Conclusions

From studies of driver behavior with and without objects on the shoulders of two-lane and four-lane divided highways it may be concluded that:

1. Vehicle speeds were not affected significantly by objects on the shoulder during light to moderate traffic volumes. This observation confirms earlier studies of speeds on narrow pavements and at narrow bridges and other obstructions.
2. Objects parked on one shoulder affected the lateral position of only those vehicles traveling in the lane adjacent to the occupied shoulder. The effect was greatest when the object on the shoulder was at the pavement edge, and diminished rapidly with an increase in the distance of the object from the edge of the pavement.
3. The narrower the pavement, the greater was the shift of traffic to the left or away from the object on the shoulder. On a two-lane highway with a 16-foot surface, the shift was 3.3 feet, and on one with a 24-foot surface the shift was 1.8 feet.
4. A car, truck, or barricade on the shoulder had about the same effect on the lateral positions of vehicles on two-lane highways. On the four-lane highway a truck had about the same effect as a car, but a barricade caused a lateral movement about one-half as great as a car or truck.

Objects on One Shoulder

The objects placed on the shoulder included a passenger car, a highway maintenance truck, and a barricade. Studies were conducted with each of these objects at the pavement edge, 3 feet from the edge, and 6 feet from the edge. Data were recorded during a period of 3 hours for each condition at each location. Driver behavior data were thus obtained for nine different conditions in addition to the normal condition at each study location. The type and position of the objects placed on the shoulder are shown on the cover page. The three lines across the pavement in the foreground of the photographs are the speed and placement detectors which were connected to recording instruments that were well hidden from the drivers.

The hourly traffic volume in both directions on the two-lane roads during each of the studies is shown in table 2. The table shows

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[1] *Effect of roadway width on vehicle operation*, by A. Taragin, PUBLIC ROADS, vol. 24, No. 6, Oct.-Nov.-Dec. 1945.

that traffic volumes were moderate at all locations and not widely different for each shoulder condition at any one location; thus the effect of traffic volume or density was eliminated from consideration in this study.

Data were analyzed separately for passenger cars and commercial vehicles traveling in each of the two traffic lanes. For the two-lane studies, the data were also analyzed separately for free-moving vehicles, meeting vehicles, and all other vehicles. Free-moving vehicles are those that were not influenced by other traffic on the highway, whereas meeting vehicles are those that might be influenced by opposing traffic. Vehicles overtaking and passing other vehicles on the two-lane roads have been omitted from the analysis because they were too small in number during the study periods to be considered.

Normal Speeds

Average passenger car speeds during norma daytime conditions at the different location on the two-lane roads varied from 42.9 to 48. miles per hour as shown in table 3. Unde similar conditions, the average speeds of commercial vehicles (dual-tired only) varied fron 37.6 to 43.2 miles per hour as shown in table 4 At individual locations, however, commercia vehicles traveled, on an average, 3.9 to 8.

Table 1.—Description of the two-lane highways studied in Oregon

Site No.	Route and location	Width of pavement[1]	Width of shoulders		Number of vehicles observed	
			Bituminous	Gravel	Day	Night
		Feet	*Feet*	*Feet*		
1	U. S. 99E, 7 miles S. of Salem	16	2	5	6, 600	-----
2	U. S. 99W, S. of Tigard	20	-------	7	10, 246	2, 997
3	U. S. 99, 6 miles N. of Eugene	22	-------	9	9, 144	1, 985
4	U. S. 99E, 1 mile S. of Brooks	26	-------	5	10, 694	-----

[1] Sites numbered 1-3 have portland cement concrete surfaces; site 4 has bituminous surface.

Table 2.—Hourly traffic volume observed during study periods on two-lane highways

Position of object on shoulder	Daytime				Nighttime	
	16-foot pavement	20-foot pavement	22-foot pavement	26-foot pavement	20-foot pavement	22-foot pavement
	V. p. h.	*V. p. h.*	*V. p. h.*	*V. p. h.*	*V. p. h.*	*V. p. h.*
Shoulder clear	179	233	192	282	152	-------
Car at edge of pavement	201	349	220	323	214	-------
Car 3 feet from edge of pavement	176	364	169	263	116	107
Car 6 feet from edge of pavement	196	258	213	469	107	151
Truck at edge of pavement	164	269	214	310	-------	-------
Truck 3 feet from edge of pavement	216	325	232	287	-------	-------
Truck 6 feet from edge of pavement	211	268	229	344	-------	-------
Barricade at edge of pavement	247	344	280	321	146	189
Barricade 3 feet from edge of pavement	211	307	257	394	167	99
Barricade 6 feet from edge of pavement	228	483	288	364	115	88

Table 3.—Average speeds of passenger cars observed during study periods on two-lane highways

Position of object on shoulder	Daytime								Nighttime			
	16-foot pavement		20-foot pavement		22-foot pavement		26-foot pavement		20-foot pavement		22-foot pavement	
	Near[1]	Far[2]	Near	Far	Near	Far	Near	Far	Near	Far	Near	Far
	M. p. h.	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*
Shoulder clear	47. 1	42. 9	45. 2	43. 8	48. 7	48. 9	45. 9	46. 1	43. 1	41. 1	------	------
Car at edge of pavement	45. 0	43. 9	42. 6	44. 2	47. 0	48. 0	45. 6	45. 2	40. 8	41. 6	------	------
Car 3 feet from edge of pavement	45. 8	43. 2	42. 5	42. 9	49. 9	48. 5	45. 8	44. 9	43. 5	41. 8	46. 3	48. 0
Car 6 feet from edge of pavement	46. 5	44. 4	41. 8	43. 0	49. 2	47. 6	42. 9	42. 1	43. 7	45. 0	44. 9	43. 9
Truck at edge of pavement	40. 9	43. 7	42. 4	41. 8	48. 0	48. 6	44. 4	44. 4	------	------	------	------
Truck 3 feet from edge of pavement	45. 9	43. 9	42. 4	43. 4	48. 4	48. 7	45. 8	46. 0	------	------	------	------
Truck 6 feet from edge of pavement	45. 3	43. 2	43. 4	44. 3	49. 2	49. 1	44. 6	44. 3	------	------	------	------
Barricade at edge of pavement	42. 6	42. 4	40. 6	43. 4	47. 1	47. 0	42. 0	43. 2	41. 7	44. 6	40. 6	42. 2
Barricade 3 feet from edge of pavement	44. 4	43. 3	40. 7	42. 1	48. 0	44. 2	44. 0	42. 0	39. 2	39. 9	42. 6	43. 9
Barricade 6 feet from edge of pavement	44. 3	42. 9	39. 6	42. 2	47. 8	45. 2	44. 6	44. 9	40. 7	40. 6	44. 7	44. 8

[1] Vehicles traveling in lane adjacent to occupied shoulder.
[2] Vehicles traveling in lane adjacent to clear shoulder.

Table 4.—Average speeds of commercial vehicles observed during study periods on two-lane highways

Position of object on shoulder	Daytime								Nighttime			
	16-foot pavement		20-foot pavement		22-foot pavement		26-foot pavement		20-foot pavement		22-foot pavement	
	Near[1]	Far[2]	Near	Far	Near	Far	Near	Far	Near	Far	Near	Far
	M. p. h.	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*
Shoulder clear	43. 2	38. 1	38. 5	37. 6	40. 8	42. 4	37. 6	39. 1	35. 6	36. 2	------	--------
Car at edge of pavement	40. 8	37. 5	37. 6	37. 2	38. 6	42. 9	41. 7	39. 0	35. 2	34. 6	------	------
Car 3 feet from edge of pavement	42. 3	39. 7	36. 9	38. 5	42. 9	41. 2	37. 6	37. 4	36. 4	37. 6	44. 2	37. 8
Car 6 feet from edge of pavement	42. 4	38. 7	34. 4	38. 5	40. 3	42. 0	37. 8	37. 4	37. 0	37. 7	40. 3	41. 0
Truck at edge of pavement	38. 4	37. 3	36. 9	36. 5	40. 5	41. 6	39. 6	40. 8	------	------	------	------
Truck 3 feet from edge of pavement	41. 8	41. 5	36. 9	37. 0	42. 3	43. 3	37. 4	38. 5	------	------	------	------
Truck 6 feet from edge of pavement	40. 4	35. 1	37. 8	39. 5	42. 0	41. 9	38. 1	38. 3	------	------	------	------
Barricade at edge of pavement	40. 8	38. 0	34. 1	36. 8	43. 4	39. 6	37. 6	37. 6	35. 5	40. 3	37. 6	37. 7
Barricade 3 feet from edge of pavement	42. 3	39. 0	35. 4	39. 1	40. 7	41. 9	38. 0	36. 8	31. 2	37. 2	38. 5	37. 5
Barricade 6 feet from edge of pavement	44. 0	40. 6	40. 4	40. 3	41. 0	42. 5	40. 7	34. 5	33. 8	34. 2	36. 9	38. 9

[1] Vehicles traveling in lane adjacent to occupied shoulder.
[2] Vehicles traveling in lane adjacent to clear shoulder.

miles per hour slower than passenger cars. In addition to the speeds for normal conditions, tables 3 and 4 show average speeds while each of the objects was on the shoulder at various distances from the pavement edge.

On the four-lane divided highway during normal conditions, and at volumes below 2,000 vehicles per hour in one direction, passenger cars averaged about 50 miles per hour in the left lane and 43 miles per hour in the right lane. Commercial vehicles under similar conditions traveled about 2 miles per hour slower than passenger cars. The average speed on the four-lane highway when carrying volumes above 2,000 vehicles per hour was far more dependent on other conditions, which could not be held constant, than on the shoulder condition. For this reason, therefore, analysis of the effect of an object on the shoulder on vehicle speeds on the four-lane road was confined to volumes below 2,000 vehicles per hour.

Effect on Speeds

A parked vehicle or a barricade on the shoulder of the two-lane highways included in this study had a general tendency to reduce vehicle speeds. The reduction, however, was not consistently greater for one of the objects than for another. Also, the reduction was

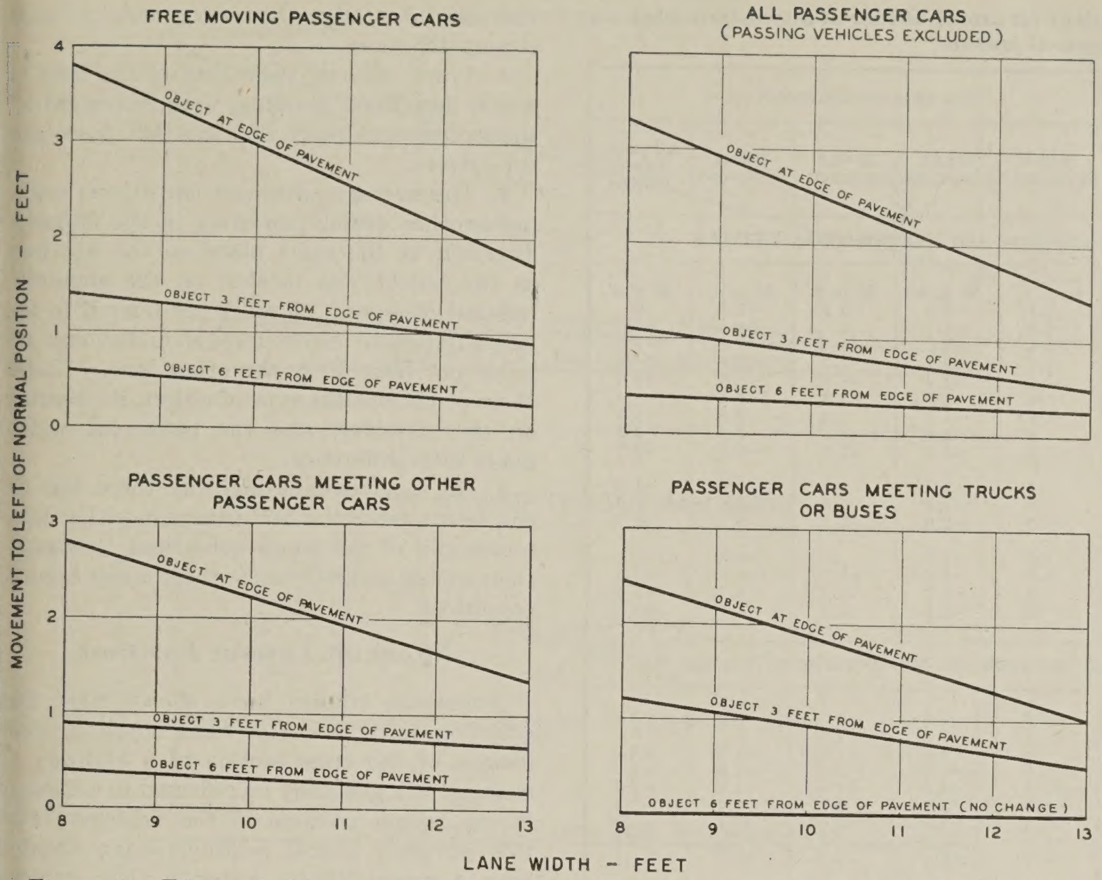

Figure 1.—Effect of objects on the lateral position of passenger cars traveling in lane adjacent to occupied shoulder.

Table 5.—Change in average speeds due to an object on one shoulder of a two-lane highway compared with normal speeds

Type of object on shoulder	Distance of object from pavement edge	Change in average speeds for—				
		16-foot pavement [1]	20-foot pavement	22-foot pavement	26-foot pavement	All pavement widths
PASSENGER CARS TRAVELING IN LANE ADJACENT TO CLEAR SHOULDER						
	Feet	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*
Car	0	1.0	0.4	−0.9	−0.9	−0.1
	3	.3	−.9	−.4	−1.2	−.6
	6	1.5	−.8	−1.3	−4.0	−1.2
Truck	0	.8	−2.0	−.3	−1.7	−.8
	3	1.0	−.4	−.2	−.1	.1
	6	.3	.5	.2	−1.8	−.2
Barricade	0	−.5	−.4	−1.9	−2.9	−1.4
	3	.4	−1.7	−4.7	−4.1	−2.5
	6	0	−1.6	−3.7	−1.2	−1.6
Average, by type of object:						
Car	-----	.9	−.4	−.9	−2.0	−.6
Truck	-----	.7	−.6	−.1	−1.2	−.3
Barricade	-----	0	−1.2	−3.4	−2.7	−1.8
Average, by distance of object:						
0 feet	-----	.4	−.7	−1.0	−1.8	−.8
3 feet	-----	.6	−1.0	−1.8	−1.8	−1.0
6 feet	-----	.6	−.6	−1.6	−2.3	−1.0
Average, all conditions	-----	.5	−.8	−1.5	−2.0	−.9
COMMERCIAL VEHICLES TRAVELING IN LANE ADJACENT TO CLEAR SHOULDER						
Car	0	−0.6	−0.4	0.5	−0.1	−0.2
	3	1.6	.9	−1.2	−1.7	−.1
	6	.6	.9	−.4	−1.7	−.2
Truck	0	−.8	−1.1	−.8	1.7	−.3
	3	2.6	−.6	.9	−.6	.6
	6	−3.0	−1.9	−.5	−.8	−1.6
Barricade	0	−.1	−.8	−2.8	−1.5	−1.3
	3	.9	1.5	−.5	−2.3	−.1
	6	2.5	2.7	.1	−4.6	.2
Average, by type of object:						
Car	-----	.5	.5	−.4	−1.2	−.2
Truck	-----	−.4	−1.2	−.1	.1	−.4
Barricade	-----	1.1	1.1	−1.1	−2.8	−.4
Average, by distance of object:						
0 feet	-----	−.5	−.8	−1.0	0	−.6
3 feet	-----	1.7	.6	−.3	−1.5	.1
6 feet	-----	0	.6	−.3	−2.4	−.5
Average, all conditions	-----	.4	.1	−.5	−1.3	−.3

[1] 16 feet of portland cement concrete with 2-foot bituminous shoulders.

Table 6.—Change in average speeds due to an object on one shoulder of a two-lane highway compared with normal speeds

Type of object on shoulder	Distance of object from pavement edge	Change in average speeds for—				
		16-foot pavement [1]	20-foot pavement	22-foot pavement	26-foot pavement	All pavement widths
PASSENGER CARS TRAVELING IN LANE ADJACENT TO OCCUPIED SHOULDER						
	Feet	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*
Car	0	−2.1	−2.6	−1.7	−0.3	−1.7
	3	−1.3	−2.7	1.2	−.1	−.7
	6	−.6	−3.4	.5	−3.0	−1.6
Truck	0	−6.2	−2.8	−.7	−1.5	−2.8
	3	−1.2	−2.8	−.3	−.1	−1.1
	6	−1.8	−1.8	.5	−1.3	−1.1
Barricade	0	−4.5	−4.6	−1.6	−3.9	−3.6
	3	−2.7	−4.5	−.7	−1.9	−2.4
	6	−2.8	−5.6	−.9	−1.3	−2.6
Average by type of object:						
Car	-----	−1.3	−2.9	0	−1.1	−1.3
Truck	-----	−3.1	−2.5	−.2	−1.0	−1.7
Barricade	-----	−3.3	−4.9	−1.1	−2.4	−2.9
Average, by distance of object:						
0 feet	-----	−4.3	−3.3	−1.3	−1.9	−2.7
3 feet	-----	−1.7	−3.3	.1	−.7	−1.4
6 feet	-----	−1.7	−3.6	0	−1.9	−1.8
Average, all conditions	-----	−2.6	−3.4	−.4	−1.5	−2.0
COMMERCIAL VEHICLES TRAVELING IN LANE ADJACENT TO OCCUPIED SHOULDER						
Car	0	−2.4	−0.9	−2.2	4.1	−0.4
	3	−.9	−1.6	2.1	0	−.1
	6	−.8	−4.1	−.5	.2	−1.3
Truck	0	−4.8	−1.6	−.3	2.0	−1.2
	3	−1.4	−1.6	1.5	−.2	−.4
	6	−2.8	−.7	1.2	.5	−.4
Barricade	0	−2.8	−4.4	2.6	0	−1.2
	3	−.9	−3.1	−.1	.4	−.9
	6	.8	1.9	.2	3.1	1.5
Average, by type of object:						
Car	-----	−1.4	−2.2	−.2	1.4	−.6
Truck	-----	−3.0	−1.3	.8	.8	−.7
Barricade	-----	−1.0	−1.9	.9	1.2	−.2
Average, by distance of object:						
0 feet	-----	−3.3	−2.3	0	2.0	−.9
3 feet	-----	−1.1	−2.1	1.2	.1	−.5
6 feet	-----	−.9	−1.0	.3	1.3	−.1
Average, all conditions	-----	−1.8	−1.8	.5	1.1	−.5

[1] 16 feet of portland cement concrete with 2-foot bituminous shoulders.

Table 7.—Change in average speeds due to an object on one shoulder of a two-lane highway compared with normal speeds

Type of object on shoulder	Distance of object from pavement edge	Change in average speeds for—				
		16-foot pavement[1]	20-foot pavement	22-foot pavement	26-foot pavement	All pavement widths
Passenger Cars in Lane Adjacent to Clear Shoulder and Meeting Other Vehicles						
	Feet	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*
Car	0	2.1	−0.3	−0.2	−1.5	0
	3	−2.3	−1.1	0	−4.4	−2.0
	6	1.4	−2.0	.5	−5.9	−1.5
Truck	0	1.7	−2.7	1.3	−3.6	−.8
	3	−.1	−1.9	−.5	−1.6	−1.0
	6	.4	−1.0	3.2	−4.3	−.4
Barricade	0	−.9	−1.5	.4	−5.5	−1.9
	3	.4	−4.3	−4.6	−5.7	−3.6
	6	−1.1	−2.0	−2.5	−5.3	−2.7
Average, by type of object:						
Car	-------	.4	−1.1	.1	−3.9	−1.2
Truck	-------	.7	−1.9	1.3	−3.2	−.7
Barricade	-------	−.5	−2.6	−2.2	−5.5	−2.7
Average, by distance of object:						
0 feet	-------	1.0	−1.5	.5	−3.5	−.9
3 feet	-------	−.7	−2.4	−1.7	−3.9	−2.2
6 feet	-------	.2	−1.7	−.4	−5.2	−1.5
Average, all conditions	-------	.2	−1.9	−.3	−4.2	−1.5
Passenger Cars in Lane Adjacent to Occupied Shoulder and Meeting Other Vehicles						
Car	0	−5.6	−2.6	−3.3	−2.0	−3.4
	3	.1	−1.5	1.5	0	0
	6	.6	−3.0	−1.9	−4.3	−2.2
Truck	0	−5.5	−1.5	−2.0	−1.9	−2.7
	3	−1.8	−3.5	−1.6	−1.4	−2.1
	6	−1.3	−3.7	−3.2	−1.1	−2.3
Barricade	0	−6.8	−2.9	−2.0	−5.1	−4.2
	3	−2.5	−3.2	−2.5	−1.4	−2.4
	6	−.1	−3.0	−2.0	−1.8	−1.7
Average, by type of object:						
Car	-------	−1.6	−2.4	−1.2	−2.1	−1.9
Truck	-------	−2.9	−2.9	−2.3	−1.5	−2.4
Barricade	-------	−3.1	−3.0	−2.2	−2.8	−2.8
Average, by distance of object:						
0 feet	-------	−6.0	−2.3	−2.4	−3.0	−3.4
3 feet	-------	−1.4	−2.7	−.9	−.9	−1.5
6 feet	-------	−.3	−3.2	−2.4	−2.4	−2.1
Average, all conditions	-------	−2.5	−2.8	−1.7	−2.1	−2.3

[1] 16 feet of portland cement concrete with 2-foot bituminous shoulders.

not consistently greater when the object on the shoulder was placed at the edge of the pavement than when located 3 or 6 feet from the edge, although there was some tendency in this direction.

The results are not surprising because a number of other studies have shown that speeds are not reduced as much as one would expect by unusual conditions. A study of speeds at short, narrow, two-lane bridges,[2] for example, showed that drivers did not reduce their speeds appreciably as they approached the bridges although the drivers did make a considerable change in the lateral position of their vehicles—shying away from the bridge railings or parapet walls. The changes in speed caused by placing the three types of objects on the shoulder at various distances from the pavement edge are shown in tables 5–8. The following statements are based on a study of the data shown by these tables:

1. There is only a slight tendency for passenger car drivers to reduce their speeds when traveling in the lane adjacent to the unoccupied shoulder. On an average, the reduction in speed was less than 1 mile per hour. The surface width, type of object, or its location on the other shoulder made little difference.

2. The average passenger car driver traveling in the lane adjacent to the occupied shoulder reduced his speed an average of 3 miles per hour on two-lane pavements 16 and 20 feet wide, and an average of 1 mile per hour on pavements 22 and 26 feet wide. There was a somewhat greater tendency under these conditions for the drivers to reduce their speeds with a barricade on the shoulder than with a truck or passenger car parked on the shoulder. The distance of the object from the pavement edge, however, made no consistent difference.

3. Truck drivers, regardless of the lane in which they were traveling, were influenced by the shoulder condition even less than passenger car drivers.

4. The average passenger car driver, meeting another vehicle traveling in the opposite direction at the same place on the highway as the object was located on the shoulder, reduced his speed 2.3 miles per hour if in the lane adjacent to the occupied shoulder, and 1.5 miles per hour if in the other lane. Under these conditions the type of object, its location on the shoulder, and the pavement width made little difference.

5. On the four-lane highway there was no consistent tendency for drivers in either lane under any of the study conditions to change their speeds with respect to those under normal conditions.

Effect on Lateral Position

Numerous studies have shown that the effect on driver behavior when any geometric feature of the cross section of a highway is changed will generally be reflected in a change in the lateral position of the vehicles. For this purpose, lateral positions have usually been a more definite criterion than vehicle speeds or any other characteristic of driver behavior that can be measured.

Two-lane highways

Neither the parked car, truck, nor barricade had any effect on the lateral position of vehicles traveling in a traffic lane not adjacent to the shoulder on which these objects were located. The differences between the lateral positions of the vehicles in this lane under normal conditions and when the objects were located on the shoulder are shown in table 9. In nearly all cases the values in this table, representing the change in lateral positions, are 0.3 of a foot or less, the precision to which the lateral positions were measured. There is no consistent tendency for the change in

Table 8.—Change in average speeds due to an object on the shoulder of a four-lane divided highway compared with normal speeds [1]

Position of object on shoulder	Change in average speeds in—			
	Left lane		Right lane	
	Passenger cars	Commercial vehicles	Passenger cars	Commercial vehicles
	M. p. h.	*M. p. h.*	*M. p. h.*	*M. p. h.*
Car at pavement edge	0.1	1.9	−0.7	0
Car 3 feet from pavement edge	.4	−.9	−1.1	−.4
Car 6 feet from pavement edge	.7	1.3	−1.1	−1.3
Truck at pavement edge	−.5	1.5	−.4	−1.3
Truck 3 feet from pavement edge	−.6	.7	3.0	3.0
Truck 6 feet from pavement edge	−3.5	−2.7	.6	1.0
Barricade at pavement edge	−.9	−1.1	0	−.8
Barricade 3 feet from pavement edge	−1.0	−1.1	1.6.	.5
Barricade 6 feet from pavement edge	−2.0	−3.4	.4	1.2
Average, by type of object:				
Car	.4	.8	−1.0	−.6
Truck	−1.5	−.2	1.1	.9
Barricade	−1.3	−1.9	.7	.3
Average, by distance of object:				
0 feet	−.4	.8	−.4	−.7
3 feet	−.4	−.4	1.2	1.0
6 feet	−1.6	−1.6	0	.3
Average, all conditions	−.8	−.4	.2	.2

[1] Traffic volume less than 2,000 vehicles per hour in the two lanes.

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[2] *Influence of bridge widths on transverse positions of vehicles*, by W. P. Walker, proceedings of the Highway Research Board, 1941, vol. 21, p. 361.

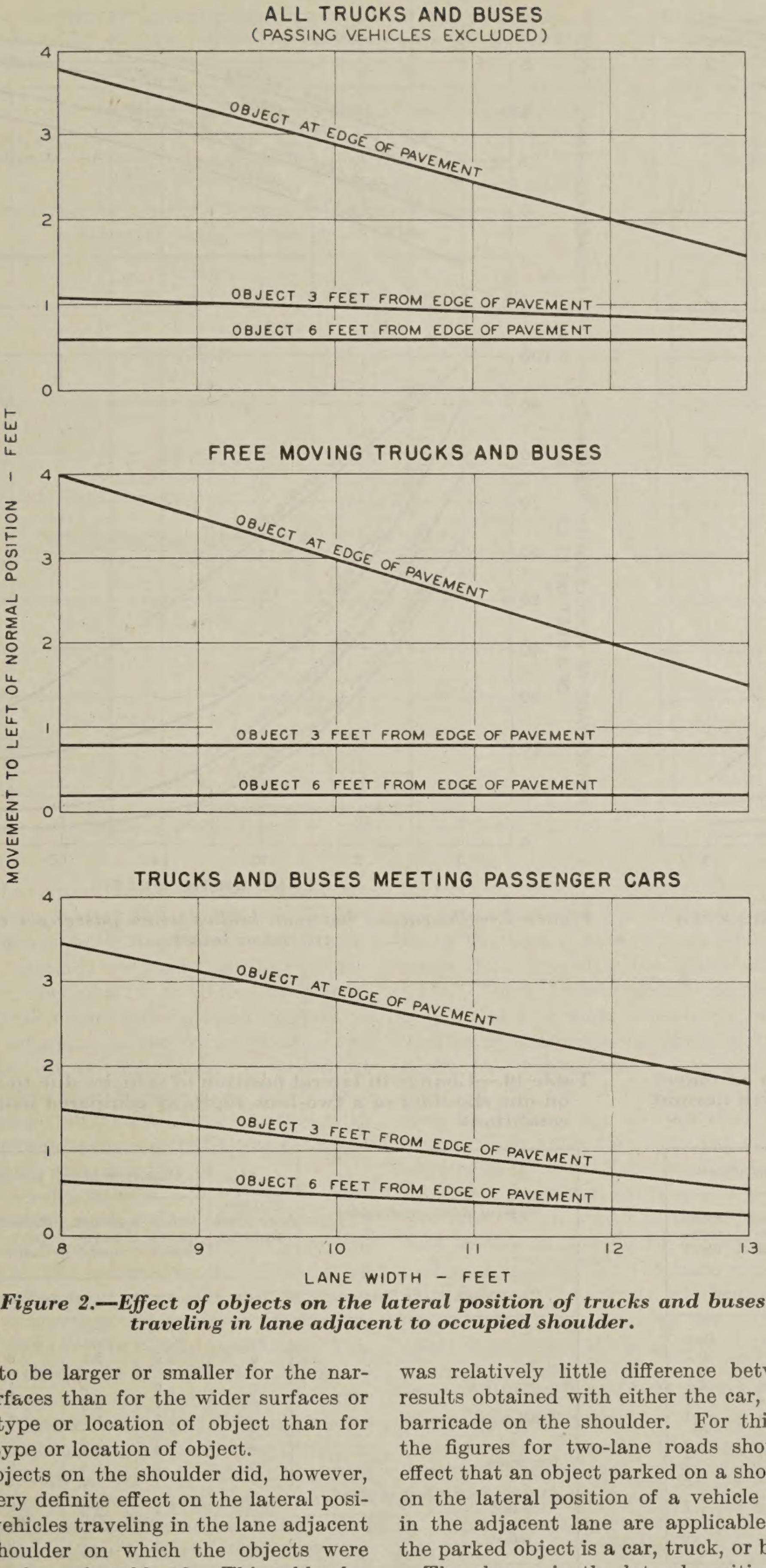

Figure 2.—Effect of objects on the lateral position of trucks and buses traveling in lane adjacent to occupied shoulder.

position to be larger or smaller for the narrower surfaces than for the wider surfaces or for one type or location of object than for another type or location of object.

The objects on the shoulder did, however, have a very definite effect on the lateral positions of vehicles traveling in the lane adjacent to the shoulder on which the objects were placed, as shown in table 10. This table also shows that the changes in the lateral positions because of an object on the shoulder were greater for the narrow surfaces than for the wider ones, and that they were greater when the objects on the shoulder were closer to the pavement edge.

The type of object, however, had no consistent effect on the results. An analysis of the clearances between vehicles when meeting on the two-lane highways also showed that there was relatively little difference between the results obtained with either the car, truck, or barricade on the shoulder. For this reason, the figures for two-lane roads showing the effect that an object parked on a shoulder has on the lateral position of a vehicle traveling in the adjacent lane are applicable whether the parked object is a car, truck, or barricade.

The change in the lateral position of passenger cars caused by a vehicle or barricade being parked on the shoulder adjacent to the traffic lane in which the passenger car was traveling is shown in figure 1. Similar information is shown for commercial vehicles in figure 2. The change in the lateral positions in these and all subsequent figures is shown in terms of the movement to the left of the position that the vehicle occupied under normal conditions. In other words, it is the distance that the average vehicle, of a certain group of vehicles, shifted its position toward the centerline of the highway and away from the occupied shoulder.

The drivers of free-moving passenger cars or drivers not influenced by the presence of other traffic on the highway made the greatest shift toward the centerline and away from their normal position because of objects placed on the right shoulder. On the other hand, drivers of passenger cars meeting a truck or bus at a point adjacent to the vehicle or barricade placed on the shoulder made the smallest change from their normal paths. Under this latter condition, however, the movement to the left was 1 foot when the object was placed at the edge of a 13-foot lane and 2.5 feet when the object was at the edge of an 8-foot lane. The only drivers not changing their lateral positions were those who met commercial vehicles when the objects on the shoulder were 6 feet from the pavement edge.

The objects on the shoulders generally caused trucks to veer farther than passenger cars from their normal paths (figs. 1–2). There were some exceptions, however, such as the effect on free-moving vehicles when the objects were either 3 or 6 feet from the pavement. Under these conditions, the passenger cars veered away from the objects more than trucks.

Clearance Between Vehicles

Two-lane roads carrying two-directional traffic should be of sufficient width to provide adequate clearance between the bodies of meeting vehicles. The results of previous studies have shown that 3 feet is the minimum desirable lateral clearance for this condition and that clearances of less than 3 feet occur infrequently on two-lane roads with 12-foot traffic lanes and adequate shoulders. This study shows, however, that when an object such as a car, truck, or barricade was placed on one shoulder at the edge of a two-lane road with a 24-foot surface, 30 percent of the passenger cars had a clearance of 3 feet or less when meeting other passenger cars (fig. 3). On surfaces with 11-foot traffic lanes the corresponding figure was 46 percent. Surfaces with 8-foot traffic lanes are obviously too narrow for modern vehicles and speeds, since 56 percent of the meetings of passenger cars took place with clearances of 3 feet or less although the average clearance exceeded 3 feet under normal conditions when the shoulders were clear. Placing a car, truck, or barricade on one of the shoulders increased the percentage from 56 to 94 and decreased the average clearance between vehicles from 3.2 to 1.3 feet (fig. 3).

Figure 4, which is similar to figure 3, shows clearances between bodies of passenger cars and trucks as they met. In figure 4 the average clearances are less and the percentage of vehicles with clearances of 3 feet or less are greater than in figure 3. This is to be expected because trucks are wider than passenger cars.

Crossing of Centerline

The average position of both passenger cars and trucks under normal conditions is to the

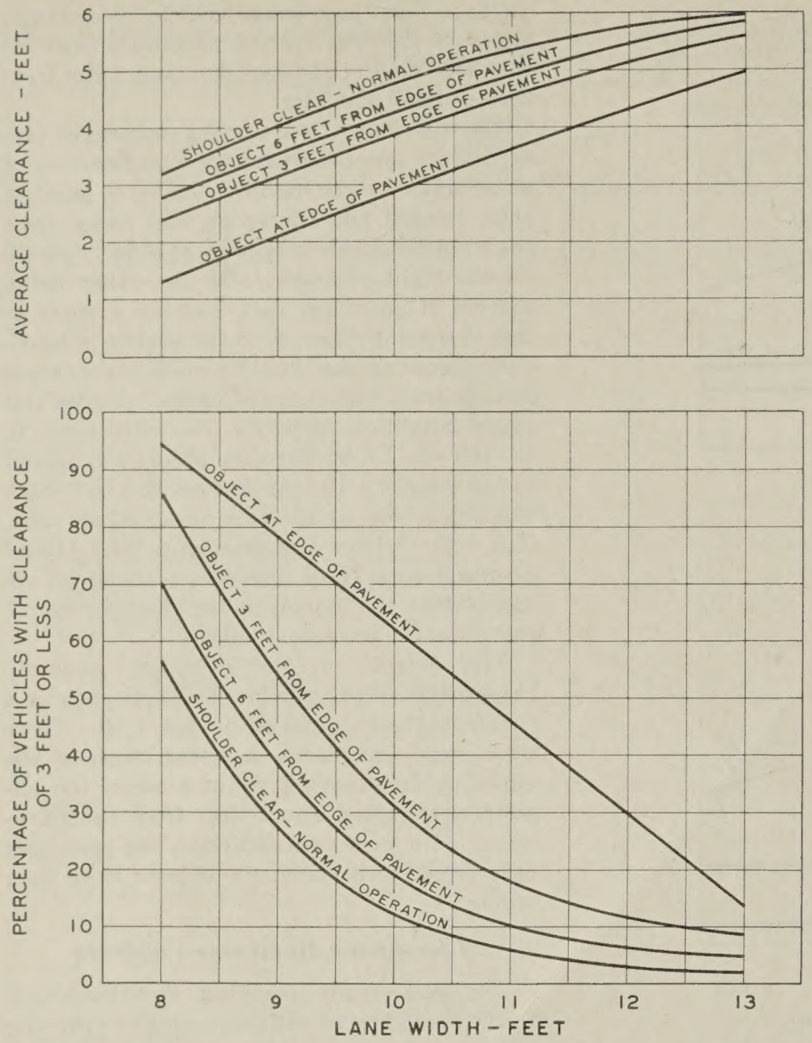

Figure 3.—Clearances between bodies of passenger cars when meeting.

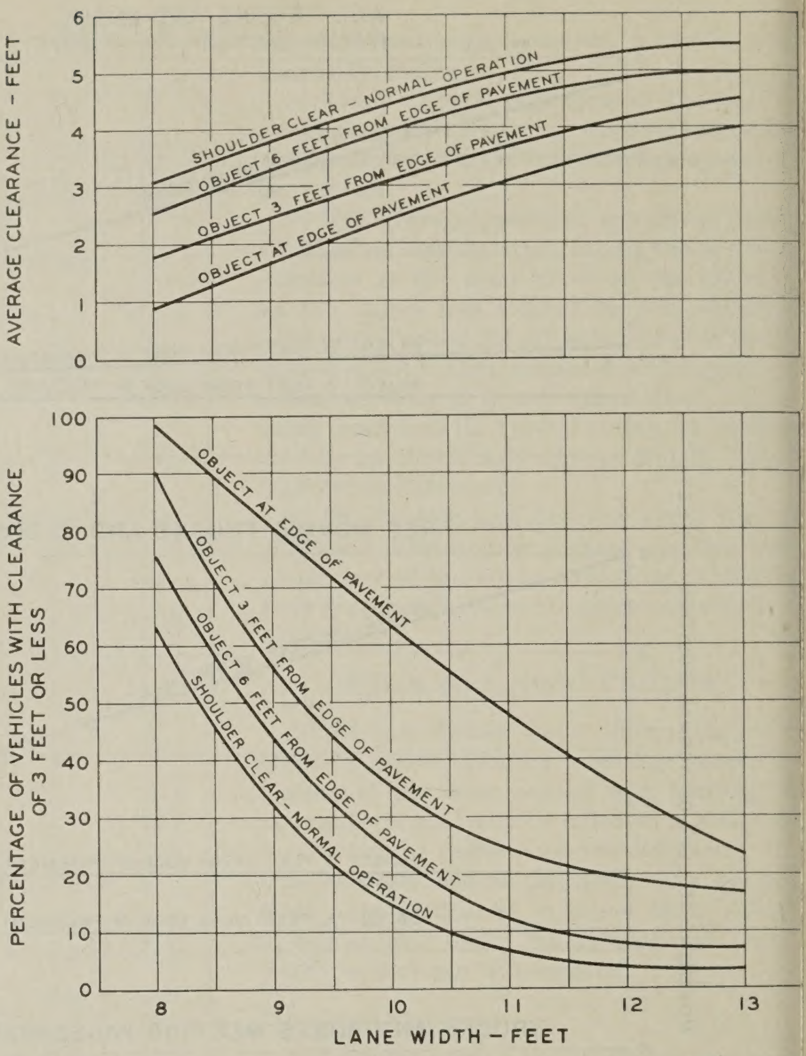

Figure 4.—Clearances between bodies when passenger cars mee trucks or buses.

Table 9.—Change in lateral position of vehicles due to an object on one shoulder of a two-lane highway compared with normal conditions

Type of object on shoulder	Distance of object from pavement edge	Change in lateral position for—			
		16-foot pavement	20-foot pavement	22-foot pavement	26-foot pavement
PASSENGER CARS TRAVELING IN LANE ADJACENT TO CLEAR SHOULDER					
	Feet	*Feet*	*Feet*	*Feet*	*Feet*
Car	0	0.1	−0.3	−0.1	−0.2
	3	.1	−.5	−.1	0
	6	.1	−.6	−.1	0
Truck	0	.2	−.2	.4	.1
	3	.1	−.3	.1	−.1
	6	.2	−.3	.1	0
Barricade	0	.1	−.2	.2	.3
	3	−.2	−.3	.1	.3
	6	−.1	−.4	.1	.2
Average, by distance of object:					
0 feet	-------	.1	−.2	−.2	−.1
3 feet	-------	0	−.4	0	.1
6 feet	-------	.1	−.4	0	.1
COMMERCIAL VEHICLES TRAVELING IN LANE ADJACENT TO CLEAR SHOULDER					
Car	0	0.6	0.2	−0.3	−0.1
	3	.3	−.1	−.2	−.2
	6	.4	−.2	−.3	−.1
Truck	0	.4	0	.2	.3
	3	.1	−.1	−.1	0
	6	.1	−.2	0	.1
Barricade	0	.4	−.1	.1	.4
	3	0	−.4	−.2	0
	6	−.1	−.2	−.1	.1
Average, by distance of object:					
0 feet	-------	.5	0	0	.3
3 feet	-------	.1	−.2	−.2	−.1
6 feet	-------	.1	−.2	−.1	0

Table 10.—Change in lateral position of vehicles due to an objec on one shoulder of a two-lane highway compared with norma conditions

Type of object on shoulder	Distance of object from pavement edge	Change in lateral position for—			
		16-foot pavement	20-foot pavement	22-foot pavement	26-foot pavement
PASSENGER CARS TRAVELING IN LANE ADJACENT TO OCCUPIED SHOULDER					
	Feet	*Feet*	*Feet*	*Feet*	*Feet*
Car	0	3.0	2.1	2.6	1.0
	3	1.3	.4	1.0	.5
	6	.6	.3	.5	.3
Truck	0	3.7	2.6	2.8	1.7
	3	1.3	1.1	1.5	.8
	6	.6	.1	.7	.5
Barricade	0	3.4	2.1	2.0	1.6
	3	.9	.4	.9	.6
	6	.1	.2	.2	0
Average, by distance of object:					
0 feet	-------	3.4	2.3	2.5	1.4
3 feet	-------	1.2	.6	1.1	.6
6 feet	-------	.4	.2	.5	.3
COMMERCIAL VEHICLES TRAVELING IN LANE ADJACENT TO OCCUPIED SHOULDER					
Car	0	3.4	2.4	2.6	1.2
	3	.8	.7	1.0	.7
	6	.4	.3	.5	.3
Truck	0	3.9	3.0	3.0	1.9
	3	1.4	1.2	1.6	.9
	6	.6	.1	.7	.8
Barricade	0	3.8	2.2	2.3	1.8
	3	1.1	.5	.9	.8
	6	.5	.3	.7	.4
Average, by distance of object:					
0 feet	-------	3.7	2.5	2.6	1.6
3 feet	-------	1.1	.8	1.2	.8
6 feet	-------	.5	.2	.6	.5

Table 11.—Change in lateral position of vehicles due to an object on one shoulder of a four-lane highway compared with normal conditions

Type of object on shoulder	Distance of object from pavement edge	Change in lateral position for traffic volumes of—						
		1,000 v. p. h.	1,500 v. p. h.	2,000 v. p. h.	2,500 v. p. h.	3,000 v. p. h.	3,500 v. p. h.	All volumes
PASSENGER CARS TRAVELING IN LEFT LANE								
	Feet	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
Car	0	0.1	0.1	0.1	0.1	0	0	0.1
	3	0	0	.1	.1	−0.1	−0.2	−.1
	6	.2	.1	.1	.1	0	0	.1
Truck	0	.1	.1	.1	0	0	0	.1
	3	.1	.1	.1	.1	.1	.1	.1
	6	−.1	−.1	−.1	−.1	−.2	−.2	−.1
Barricade	0	.2	.1	0	0	−.1	−.2	0
	3	−.1	−.1	−.1	−.1	−.1	−.2	−.1
	6	0	0	−.1	−.1	−.1	−.1	−.1
Average, by distance of object:								
0 feet	-----	.2	.1	.1	0	0	−.1	0
3 feet	-----	0	0	0	0	−.1	−.1	0
6 feet	-----	0	0	0	0	−.1	−.1	0
COMMERCIAL VEHICLES TRAVELING IN LEFT LANE [1]								
Car	0	---	−0.2	0.4	---	---	---	0.1
	3	---	0	.5	---	---	---	.2
	6	---	.3	.4	---	---	---	.3
Truck	0	---	.2	−.1	---	---	---	.1
	3	---	.1	.4	---	---	---	.2
	6	---	.2	.3	---	---	---	.2
Barricade	0	---	−.8	0	---	---	---	−.4
	3	---	.2	0	---	---	---	.1
	6	---	.3	.5	---	---	---	.4
Average, by distance of object:								
0 feet	-----	---	−.2	.1	---	---	---	0
3 feet	-----	---	.1	.3	---	---	---	.2
6 feet	-----	---	.2	.4	---	---	---	.3

[1] Traffic volumes are grouped into two classes: below 2,000 v. p. h. and 2,000 v. p. h. and over.

Table 12.—Change in lateral position of vehicles due to an object on one shoulder of a four-lane highway compared with normal conditions

Type of object on shoulder	Distance of object from pavement edge	Change in lateral position for traffic volumes of—						
		1,000 v. p. h.	1,500 v. p. h.	2,000 v. p. h.	2,500 v. p. h.	3,000 v. p h.	3,500 v. p. h.	All volumes
PASSENGER CARS TRAVELING IN RIGHT LANE								
	Feet	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
Car	0	0.9	0.9	0.9	0.9	0.9	0.8	0.9
	3	.4	.4	.4	.4	.4	.3	.4
	6	.2	.2	.2	.2	.2	.1	.2
Truck	0	1.1	1.1	1.0	1.0	.9	.9	1.0
	3	.7	.6	.4	.3	.2	.1	.4
	6	0	0	.1	.1	.1	.2	.1
Barricade	0	.4	.4	.5	.5	.5	.5	.5
	3	.2	.2	.2	.2	.2	.2	.2
	6	−.1	−.1	0	0	0	0	0
Average, by distance of object:								
0 feet	-----	.8	.8	.8	.8	.8	.7	.8
3 feet	-----	.4	.4	.3	.3	.3	.2	.3
6 feet	-----	0	0	.1	.1	.1	.1	.1
COMMERCIAL VEHICLES TRAVELING IN RIGHT LANE								
Car	0	1.0	1.0	0.9	0.9	0.8	0.8	0.9
	3	.1	.1	.1	.1	.1	.1	.1
	6	.2	.1	0	0	−.1	−.2	0
Truck	0	1.1	1.1	1.0	.9	.8	.7	.9
	3	.6	.5	.3	.2	.1	0	.3
	6	0	0	.1	.1	.2	.2	.1
Barricade	0	.4	.4	.4	.4	.4	.4	.4
	3	0	0	0	−.1	−.1	−.1	−.1
	6	−.1	−.1	−.1	−.1	−.1	−.1	−.1
Average, by distance of object:								
0 feet	-----	.8	.8	.4	.7	.7	.6	.7
3 feet	-----	.2	.2	.1	.1	0	0	.1
6 feet	-----	0	0	0	0	0	0	0

right of the centerline of a two-lane two-directional pavement even though it is only 16 feet wide. Figures 5–10 show that when a car, truck, or barricade was placed on one shoulder next to the edge of a 16- or 20-foot pavement, vehicles which normally traveled entirely in the lane adjacent to the occupied shoulder, encroached on the lane used by oncoming traffic. This was the case even in the face of oncoming traffic on a 16-foot surface with the result that oncoming traffic was forced to use the other shoulder (fig. 6).

When the objects were 6 feet from the edge of the pavement, regardless of the pavement width, they caused little change in the lateral positions of the vehicles as shown in figures 5–10. As an object on the shoulder was brought closer than 6 feet, there was an increasing effect on the lateral positions. This is true for all pavement widths but applies to a greater degree on the narrow two-lane pavements. (Figures presenting information on the 26-foot pavement were excluded from this article, because changes in lateral positions resulting from placement of objects on the shoulder were not too significant.) The effect on lateral positions is further illustrated by the chart at the right in figure 11 which combines the information in figures 1 and 2 in a somewhat different form to represent average traffic conditions during the study periods on the two-lane roads. Average traffic consisted of 10 percent commercial vehicles during volumes of 200 to 400 vehicles per hour.

The chart at the right in figure 11 shows the change in lateral positions which the objects caused. When an object was 6 or more feet from the pavement edge, the distance between a vehicle in the traffic stream and the pavement edge was increased by 0.4 foot when the traffic lanes were 8 feet wide and about 0.25 foot when the lanes were 13 feet wide. These measurements correspond to only 5 and 2 percent, respectively, of the lane widths, as shown by the chart at the left in figure 11. From these figures and from the shape of the curves in figure 11, it can be concluded that, for all practical purposes, objects 6 or more feet from the edge of the pavement of a two-lane road of any width have an insignificant effect on driver behavior. The effect of an object at the edge of a two-lane surface of any width is very significant and especially so for the narrower surfaces. Regardless of the surface width, however, an object 2 feet from the edge has only half the effect of an object at the edge of the surface.

Effect on Lateral Positions

Four-lane highways

The traffic volumes on the four-lane facility included in this study varied from 1,000 to over 3,400 vehicles per hour in one direction of travel. It is interesting to see how the normal pattern of vehicle placement on this highway varied with traffic volumes. This is shown in figures 12 and 13. As the volume increased, figure 12 shows that passenger cars in the right lane, on an average, traveled closer to the shoulder and those in the left lane traveled closer to the median. Furthermore, the average lateral position and hourly volume are linearly related. Similar results were obtained for commercial vehicles (fig. 13).

In order to eliminate the effect of volume and to obtain only the effect of objects on the shoulder on vehicle placement, comparisons of placement values were made at the same hourly volume. For this purpose it was necessary to determine graphically the average placements against the recorded volumes. The desired data were thus obtained for each 500-vehicle-per-hour increment within the range of observed volumes.

Vehicles in left lane

Table 11 shows the effect that the objects placed on the shoulder had on the lateral position of vehicles traveling in the left lane. The figures in the table are the differences between the lateral positions during normal conditions and when an object was on the shoulder. It can readily be seen that neither the type of object nor the distance that the object was from the pavement had any significant effect on lateral positions of passenger cars traveling in the left lane. Very few commercial vehicles traveled in the left lane. A detailed analysis of the effect of objects on these vehicles, therefore, could not be made. The limited data, however, do indicate that trucks in the left lane of a four-lane highway were also unaffected by objects on the shoulder.

Vehicles in right lane

Objects on the shoulder do affect the lateral positions of vehicles traveling in the right lane of a four-lane divided highway. The differences between the lateral positions of vehicles during normal conditions and when an object was on the shoulder are shown in table 12. A truck parked at the edge of the pavement or 3 feet away had a slightly greater effect on traffic than a parked car when the total hourly volume was 1,500 or less. Generally,

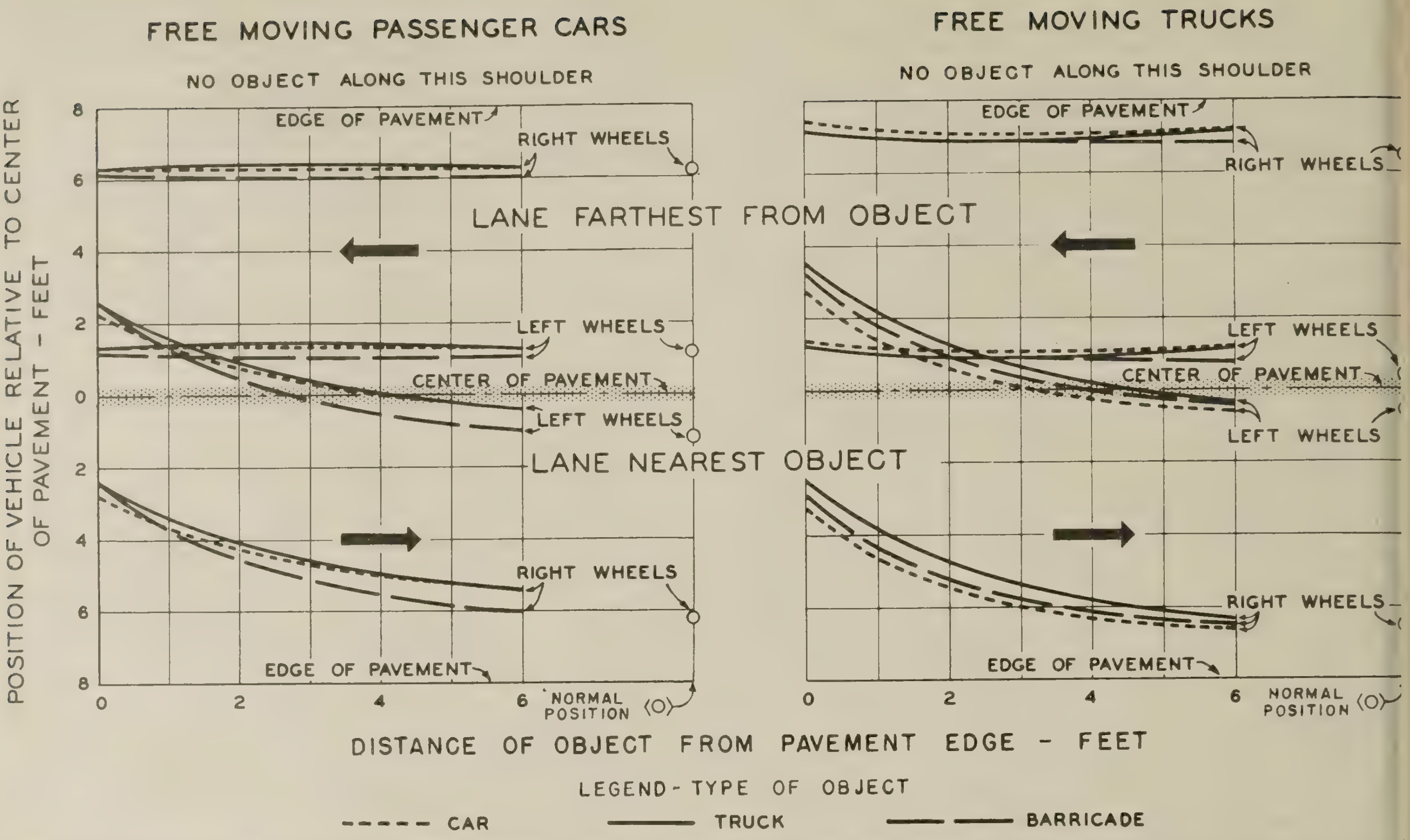

Figure 5.—Average position of free-moving vehicles traveling on a 16-foot concrete pavement with various objects on the shoulder.

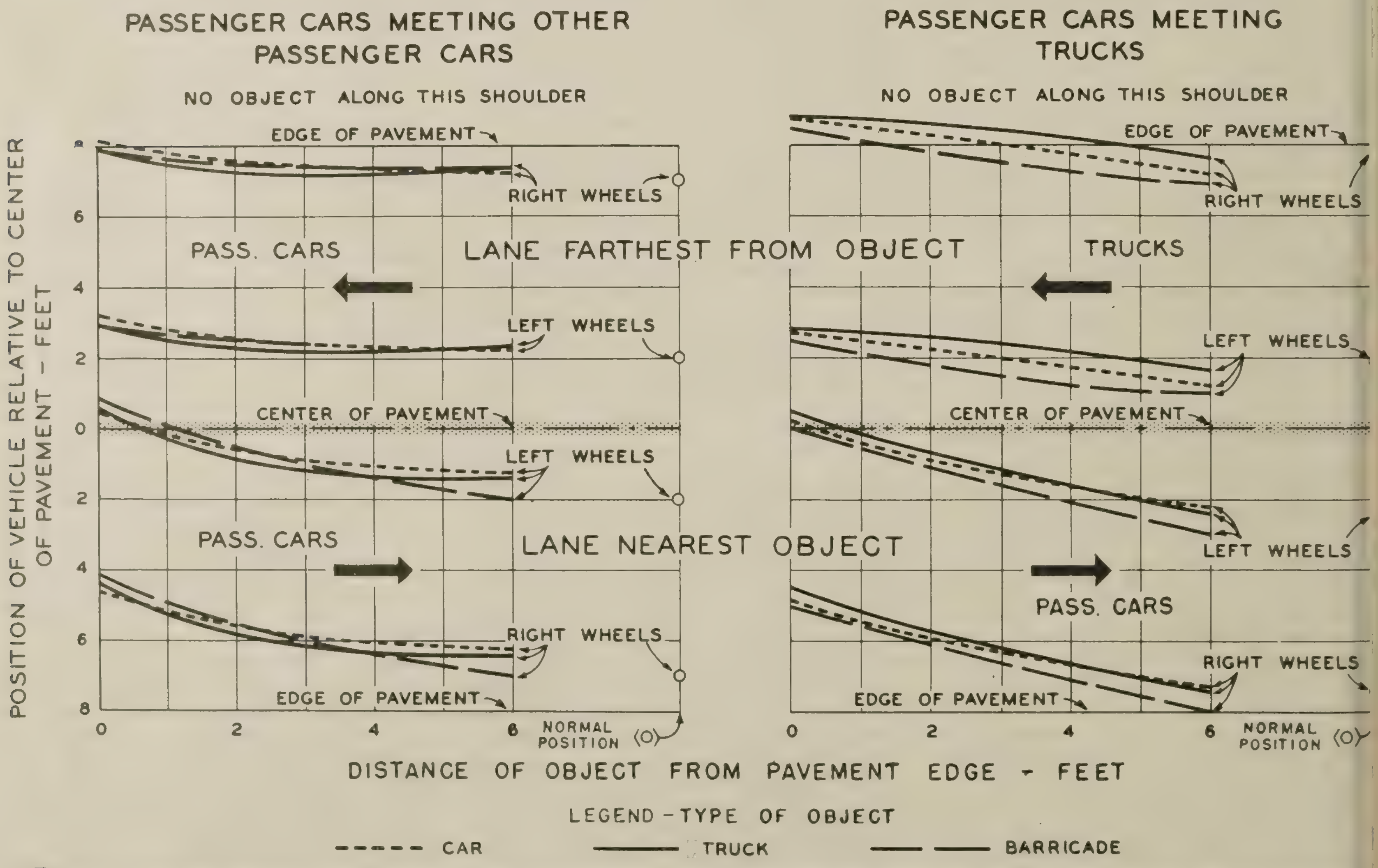

Figure 6.—Average position of vehicles meeting other vehicles on a 16-foot concrete pavement with various objects on the shoulder.

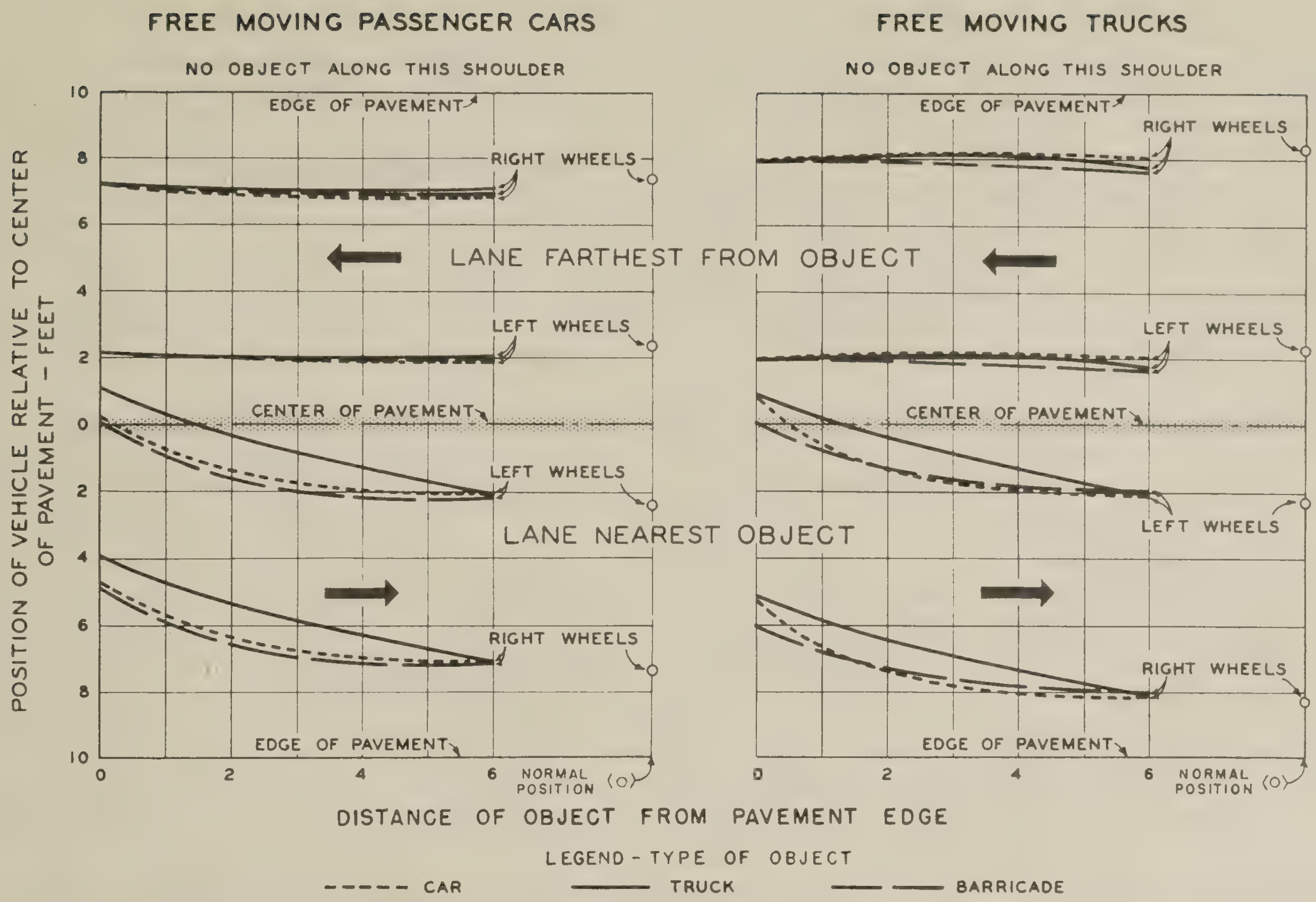

Figure 7.—Average position of free-moving vehicles traveling on a 20-foot concrete pavement with various objects on the shoulder.

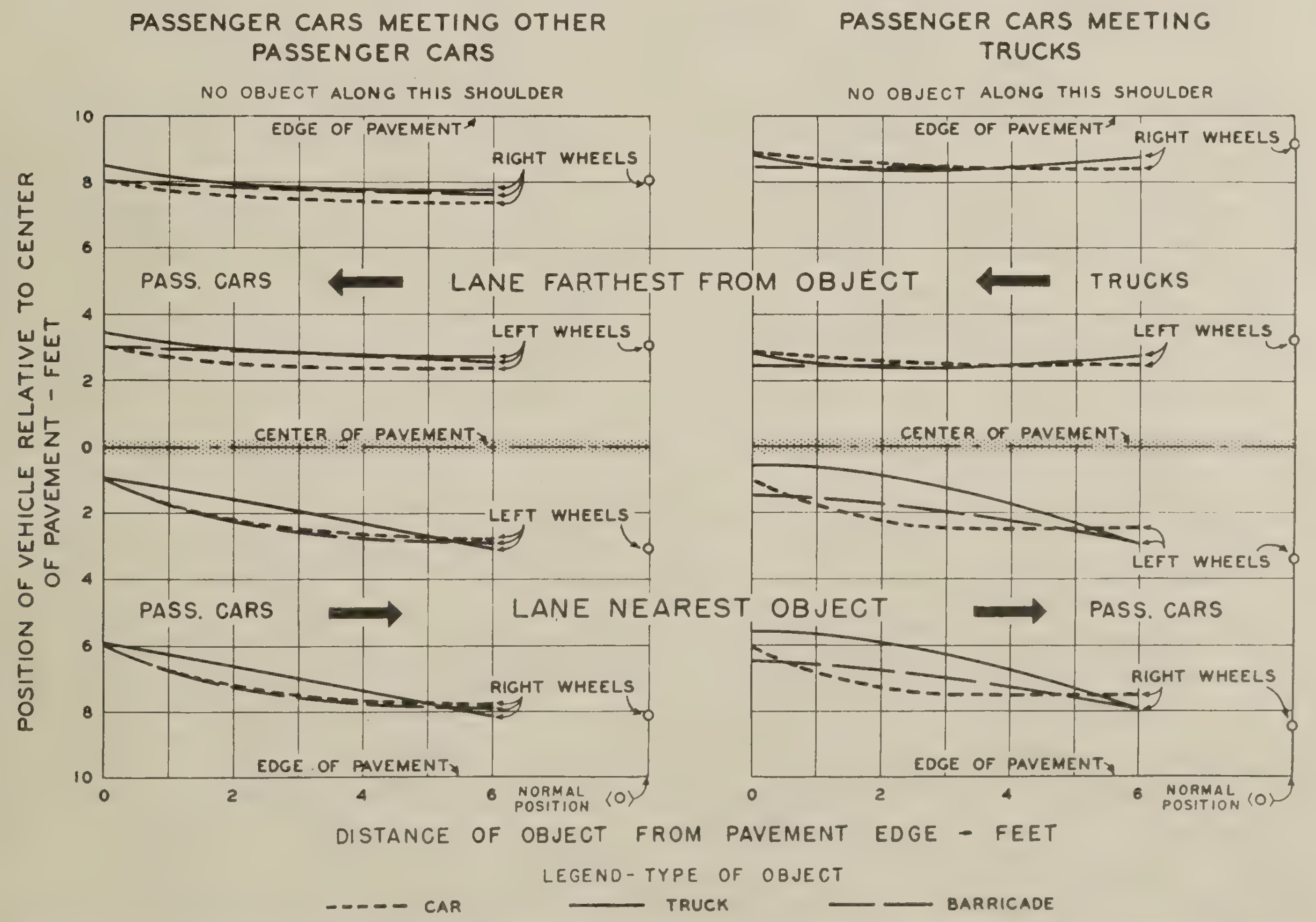

Figure 8.—Average position of vehicles meeting other vehicles on a 20-foot concrete pavement with various objects on the shoulder.

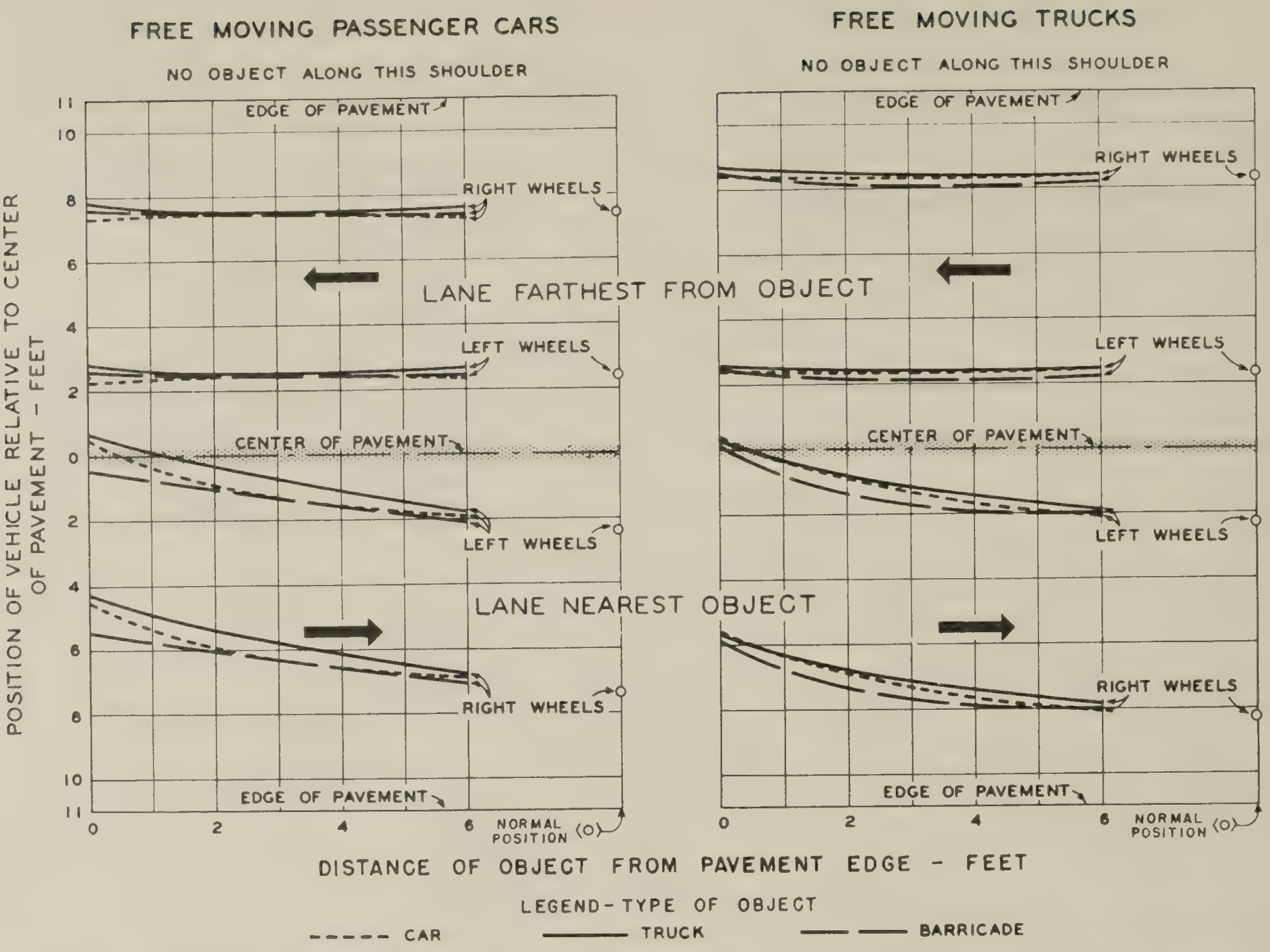

Figure 9.—Average position of free-moving vehicles traveling on a 22-foot concrete pavement with various objects on the shoulder.

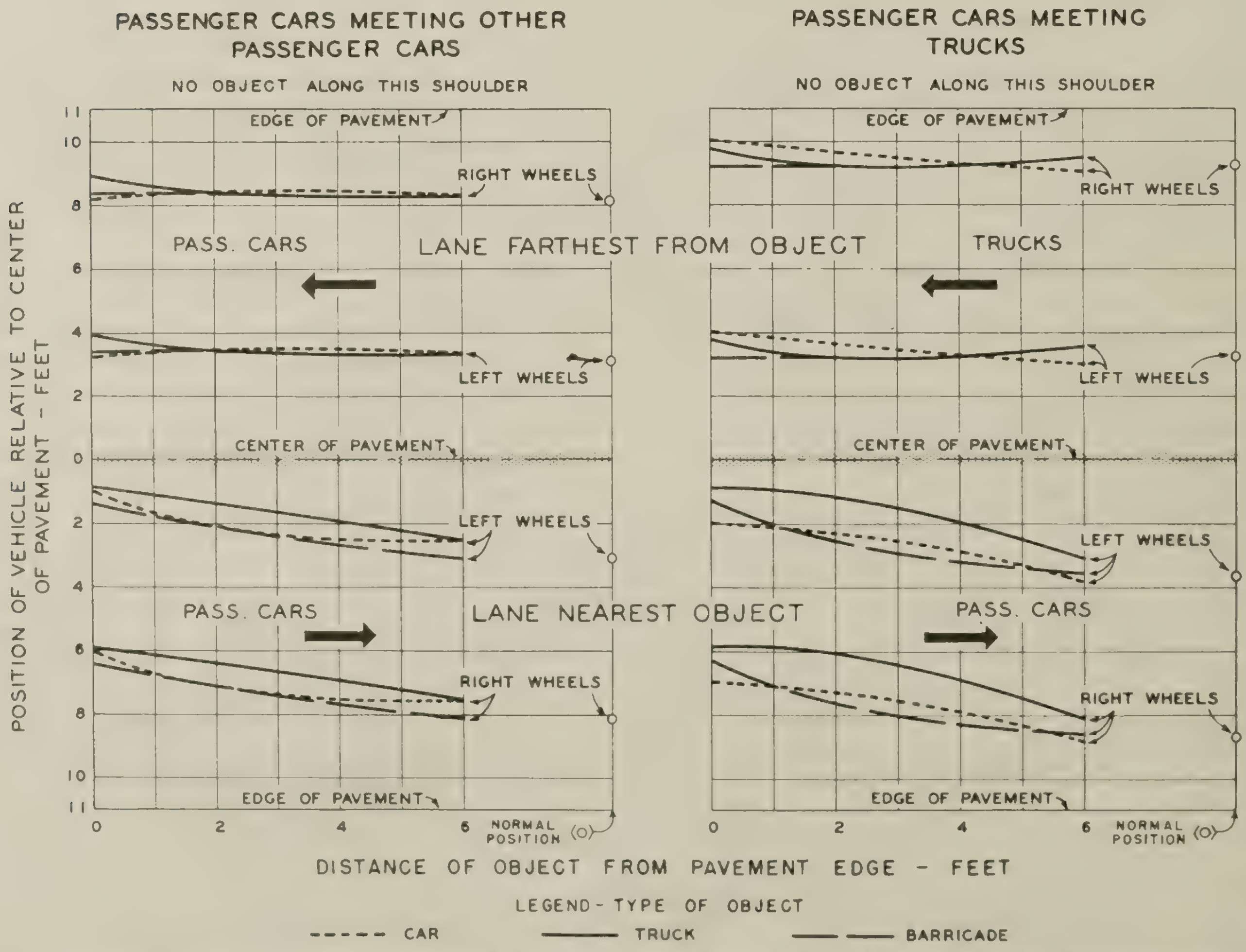

Figure 10.—Average position of vehicles meeting other vehicles on a 22-foot concrete pavement with various objects on the shoulder.

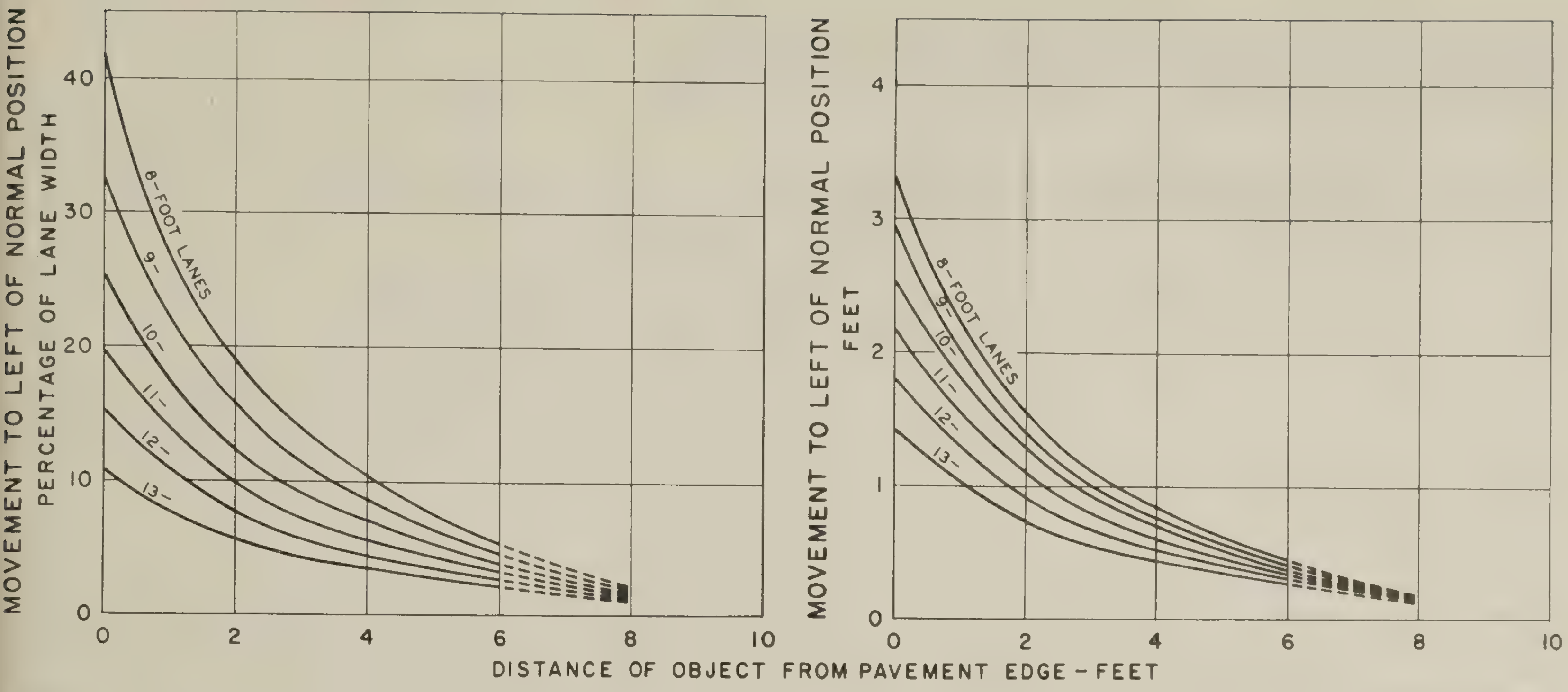

Figure 11.—Lateral movement of traffic, according to width of lanes, for various distances object was placed from pavement edge.

however, the effect of the truck was about the same as that of the car. A barricade placed on the shoulder had considerably less effect both on passenger cars and commercial vehicles than a parked car or truck under all traffic volume conditions.

When the total hourly volume in both traffic lanes was 1,000 vehicles per hour, passenger cars in the right lane traveled about a foot farther from the edge of the pavement when a truck or a car was parked at the pavement edge than when no object was on the shoulder. As the traffic volume increased, the effect of the parked truck or car, on lateral positions of vehicles decreased slightly.

A barricade at the edge of the surface had only about half the effect of a parked truck or car in causing passenger cars in the right lane to veer away from the shoulder. Objects on the shoulder 3 feet from the pavement edge had only half the effect as the same objects placed at the pavement edge. Any of the three objects placed 6 feet from the pavement edge had almost a negligible effect on passenger cars traveling in the right lane.

During low traffic volumes, commercial

(Continued on page 176)

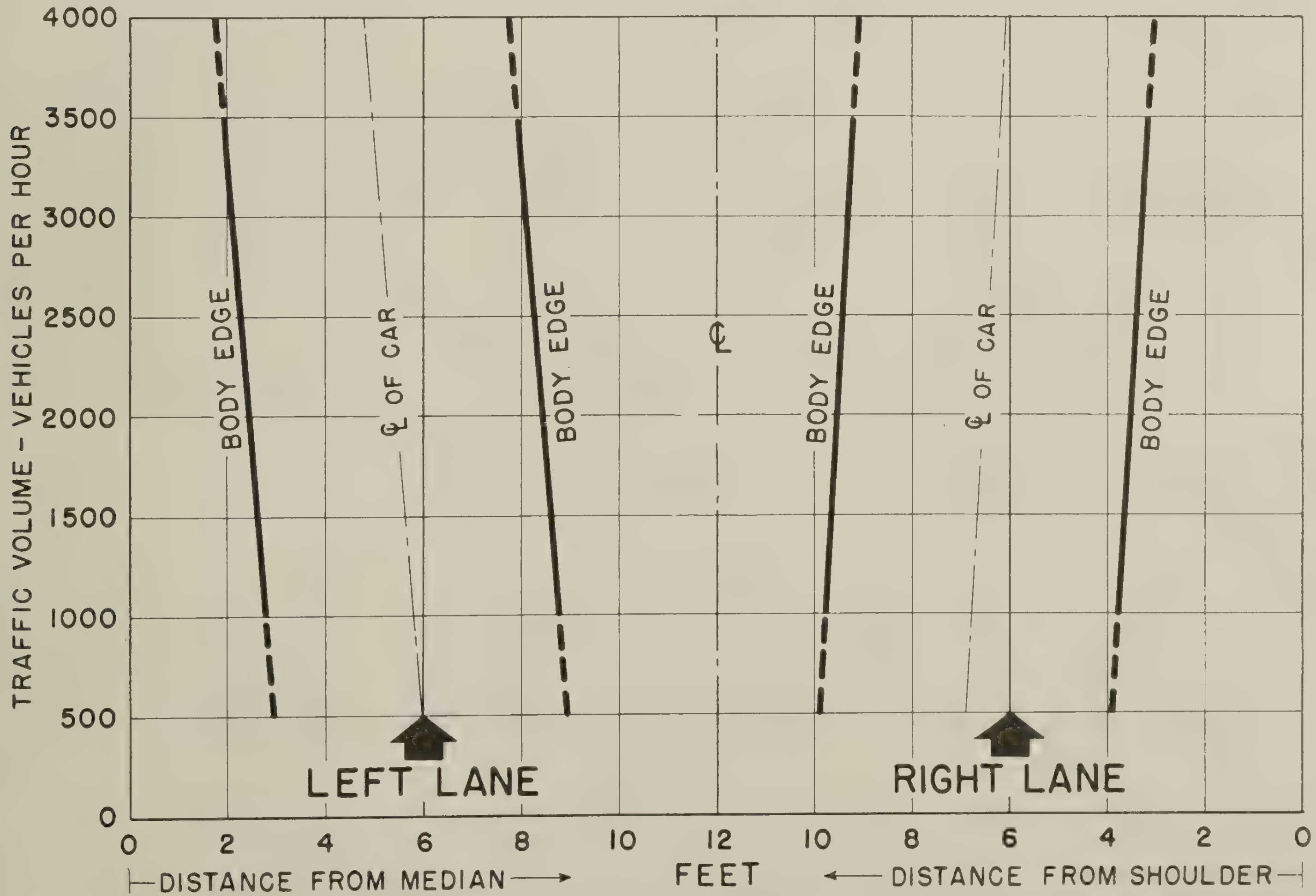

Figure 12.—Average position of passenger cars traveling in one direction on a four-lane divided highway during different traffic volumes.

Aerodynamic Characteristics of a Suspension Bridge

Analysis Based on Tests of a Section Model

BY THE PHYSICAL RESEARCH BRANCH
BUREAU OF PUBLIC ROADS

Reported by GEORGE S. VINCENT
Highway Bridge Engineer

This report is presented as typical of the essential procedures currently recommended in the study of aerodynamic characteristics of a proposed suspension bridge design. The investigation included calculations of natural frequencies and wave forms, section model tests to determine the aerodynamic behavior of the section, and analysis of the model test data to determine probable behavior of the bridge itself in a uniform steady wind.

THE SUSPENSION bridge over the Missouri River at the Paseo, Kansas City, Mo., was designed by Howard, Needles, Tammen, and Bergendoff, consulting engineers. Since it was proposed to use Federal-aid highway funds to help finance the construction, a conference, attended by representatives of the State Highway Department and the Bureau of Public Roads, was held to consider design features. Some thought was given to the matter of aerodynamic stability. It was considered improbable that this heavy, self-anchored bridge would be much affected by the wind, particularly in view of its close resemblance to the Cologne Bridge over the Rhine River in Germany (built in 1929; blown up in 1945). However, advantage was taken of the availability of a section model which could be readily modified at small cost to represent this bridge, and the investigation here reported was made. Although somewhat curtailed, it involves most of the essential procedures currently recommended for this type of investigation as developed in the cooperative research conducted by the Washington Toll Bridge Authority, the University of Washington, and the Bureau of Public Roads.

Scope and Conclusions of Study

The investigation consisted of three parts: Calculations to determine the natural frequencies and wave forms of the vertical and torsional oscillations in the first symmetric and first asymmetric modes; section model tests to determine the aerodynamic behavior of the section; and analysis of section model data to determine the probable behavior of the bridge itself in a uniform steady wind.

As a result of these studies, the following conclusions were reached:

1. The lowest natural frequencies of the bridge occur in the first symmetric mode and are:

Vertical mode---------- 21.8 cycles per minute.
Torsional mode--------- 37.5 cycles per minute.

2. Tendencies to restricted torsional and vertical oscillations shown by the section model at low wind velocities are so weak that, considering the probable nonuniformity of the wind, they will likely be completely inhibited by the structural damping of the bridge.

Catastrophic torsional oscillation is indicated in a *uniform and steady* horizontal wind beginning at a critical velocity of about 63 miles per hour and reaching double amplitudes of about 6° at 85 to 95 miles per hour, depending upon the structural damping to be expected. If the steady uniform wind angles upward as much as 6° the oscillation would be expected to occur at velocities about 5 miles per hour lower.

3. Closing the sidewalk gratings (but not the slot under the steel angle curb) should increase the critical velocity in a horizontal wind nearly 15 miles per hour; similarly closing both the sidewalk and median gratings should raise it nearly 20 miles per hour.

4. Considering the probable nonuniformity and unsteadiness of the wind at the site, it is expected that only small motions of the bridge are likely to occur.

Description of Bridge

The structure is a self-anchored suspension bridge having main and side spans of 616 and 308 feet, respectively, two 26-foot roadways, two 3-foot open-grating sidewalks, and a 4-foot open-grating median strip 9 inches high. The stiffening girders, which also resist the horizontal pull of the cables, are continuous from anchorage to anchorage and consist of steel box girders 10 feet deep and 3½ feet wide. They are fixed to the steel tower at one main pier and are free to move longitudinally at the three other supports. The cables are of preformed strands, each cable having a net area of 72 square inches and a main span sag of 70 feet. Cables and girders are 65.5 feet center to center. The 7-inch concrete floor slab is carried on 21-inch I–beam stringers resting on 6-foot plate-girder floor beams at 25-foot, 8-inch centers. K-type lateral bracing is used in the planes of both flanges of the floor beams.

Computed Natural Modes

Table 1 indicates the frequencies of the first symmetric and asymmetric vertical and torsional modes of oscillation as computed under the different assumptions indicated.[1]

Due to the relatively large ratio of side-span length to main-span length (0.5) these symmetric modes have much lower frequencies than do the asymmetric modes and are the motions to be expected if the wind can cause

Table 1.—Frequencies of modes as computed from bridge properties

Assumption	Frequency in c. p. m.			
	Symmetric		Asymmetric	
	Vertical	Torsional	Vertical	Torsional
Neglecting continuity of girder	21.8	----	36.3	----
Neglecting continuity and torsional stiffness	----	29.7	----	49.5
Considering continuity of girder	21.8	----	36.3	----
Considering torsional stiffness of girders but not of lateral system	----	34.4	----	58.8
Considering torsional stiffness of girders acting with top and bottom lateral systems	----	[1] 37.5	----	63.3

[1] This figure would be increased about 10 percent if th effect of the torsional rigidity of the towers were also considered.

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[1] *Aerodynamic stability of suspension bridges with specia reference to the Tacoma Narrows Bridge.* University o Washington Engineering Experiment Station, Bulletin 116 Part II: *Mathematical Analyses*, by F. C. Smith and G. S Vincent.

The mathematical theory of vibration in suspension bridge by Bleich, McCullough, Rosecrans, and Vincent. Chapter 4 and 5. Bureau of Public Roads. (Published by Government Printing Office.)

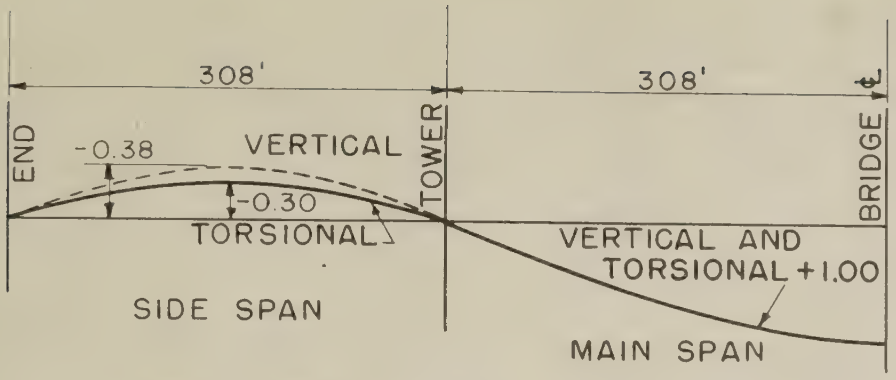

Figure 1.—Wave forms, first symmetric modes.

oscillation of the section. The frequencies of 21.8 and 37.5 c. p. m. (cycles per minute) in vertical and torsional oscillation reflect the influence of vertical and torsional stiffness and of continuity. The other frequencies were computed to show the effects of the different stiffness factors.

The fact that the frequencies of the vertical modes are not affected by girder continuity indicates that the amplitudes of the main-span and side-span waves are such that there is practically no moment at the tower. Mr. J. Karol of Howard, Needles, Tammen, and Bergendoff has calculated the frequency of the symmetric torsional mode as influenced by the torsional resistance of the towers, in addition to the full torsional stiffness of the suspended structure. The tower stiffness increased the frequency about 10 percent.

Figure 1 shows the computed wave forms of the first symmetric vertical and torsional modes. The asymmetric wave forms were not computed. They would be essentially sine curves over the main span with single-wave curves of opposite signs on the side spans (due to the continuity of the trusses).

The ratio of torsional to vertical frequency in the first symmetric modes is 37.5/21.8=1.72. This ratio would be important on a bridge section subject to pronounced flutter involving a coupling of vertical and torsional modes of similar wave form, such as was found on models of the proposed design for the Tacoma Narrows Bridge before the roadway slots and bottom laterals were provided because, for such a bridge, the velocity required to cause flutter increases sharply with an increase in the ratio of frequencies. It is of no special significance on sections showing only weak tendencies to coupling, characteristic of girder-stiffened sections, including the Kansas City Bridge covered by this report.

Section Model Tests

A comparison of dimensions showed that the available 1/50 scale section model of the Bronx-Whitestone Bridge (as originally built) could be quite readily modified to represent satisfactorily a 1/46.3 scale section model of the proposed Kansas City Bridge.[2] Figure 2 shows a cross section of the modified model with dimensions and make-up. Through a misunderstanding, the girder of the model was made to represent the shape of a prototype girder 4 feet wide instead of 3½ feet. This discrepancy was not considered critical and the tests were completed on the model as built. Some other dimensions of the existing model are not in the exact ratio of 1:46.3 to the prototype, but these discrepancies are of no consequence.

The cables are not included in making a section model because full model tests have shown that the wind forces on the cables have no appreciable effect on the oscillation of the structure as a whole. However, the mass of the cables moving in their vertical plane is important. Therefore, it is the practice to increase the weight and mass moment of inertia of the section model by the equivalent of the weight of the cables acting vertically in their planes.

The mass radius of gyration of the bridge cross section as computed by the designer is 24.05 feet, including the cables and hangers acting vertically in their planes. This corresponds to 24.05/46.3=0.52 foot or 6.24 inches on the model. The computed radius of gyration of the model, including attachments, recording pick-up and one-third of the springs, was 6.58 inches, which was considered satisfactory, especially since the ratio of torsional to vertical frequency can be independently controlled on the model.

The dead load of the bridge was given as 12,000 pounds per linear foot, including the cables. This would require a model weight per foot of model of $12{,}000/46.3^2=5.6$ pounds. The actual weight of the model and fittings per foot of model was $(19.6/61.62)\times 12=3.82$ pounds. Thus the model was deficient in weight in the ratio of $3.82/5.6=0.68$. This means that while the wind forces acting on the model were to true scale as compared with the prototype, being dependent on size and shape, the inertial forces of the model in motion were only 68 percent of what they should have been. The correction which this required when the model results were applied to the bridge is explained in the last section of this report, where the prototype response is analyzed.

The model was suspended from four helical springs. These are usually designed to reproduce to scale the frequency of the prototype vertical mode under investigation (in this case, $21.8\ \sqrt{46.3}=148$ c. p. m.). For these tests however, the most suitable available set of springs, giving a frequency in still air of 68.3 c. p. m., was used. This was permissible because of the practically constant ratio of the frequency of an oscillation to the wind velocity required to excite it, a relation found in previous tests and confirmed for this model, as will be shown later.

In the absence of any torsional spring action, the frequency of the torsional mode of the section model would be that of the vertical mode multiplied by $b/2r$, where r is the mass radius of gyration and b the width (center to center of springs in this case). This would give a torsional frequency of $(68.3\times 17.8)\div(2\times 6.58)=92.4$ c. p. m. for this model. However, type I (see fig. 3) restraining wires were used to produce torsional frequencies of 99.7 and 120.5 c. p. m. for two series of tests. Restraining wires, used primarily to prevent swaying of the model in the wind stream, are customarily anchored some 10 feet upwind and downwind from the model. It will be noted that with type II restraining wires, the vertical component of the force in the wires is negligible whether the model

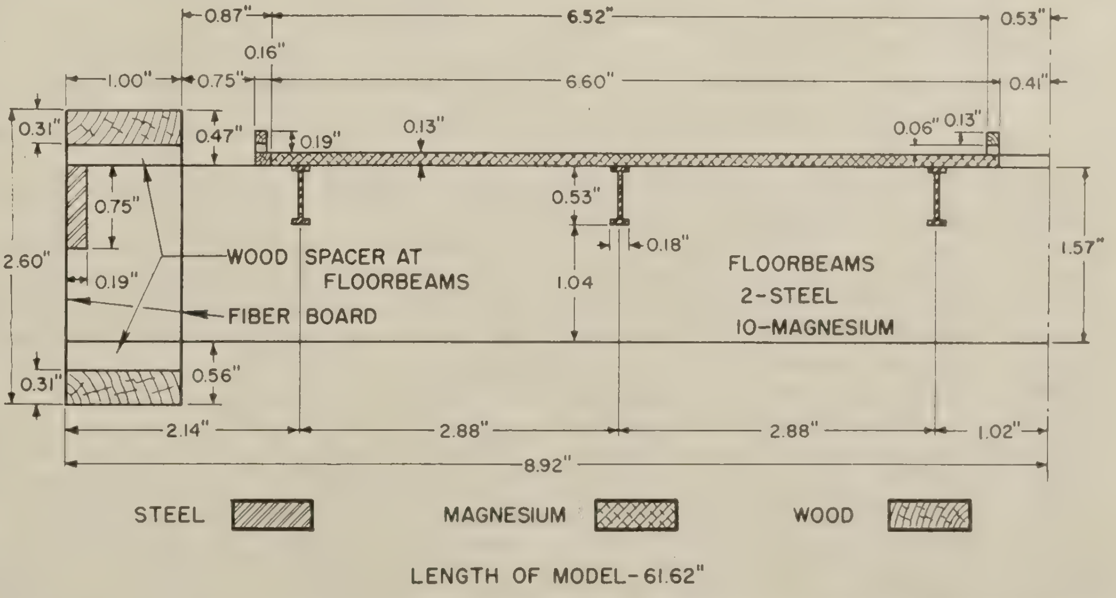

Figure 2.—1/46.3 scale section model of a suspension bridge over the Missouri River, Kansas City, Mo.

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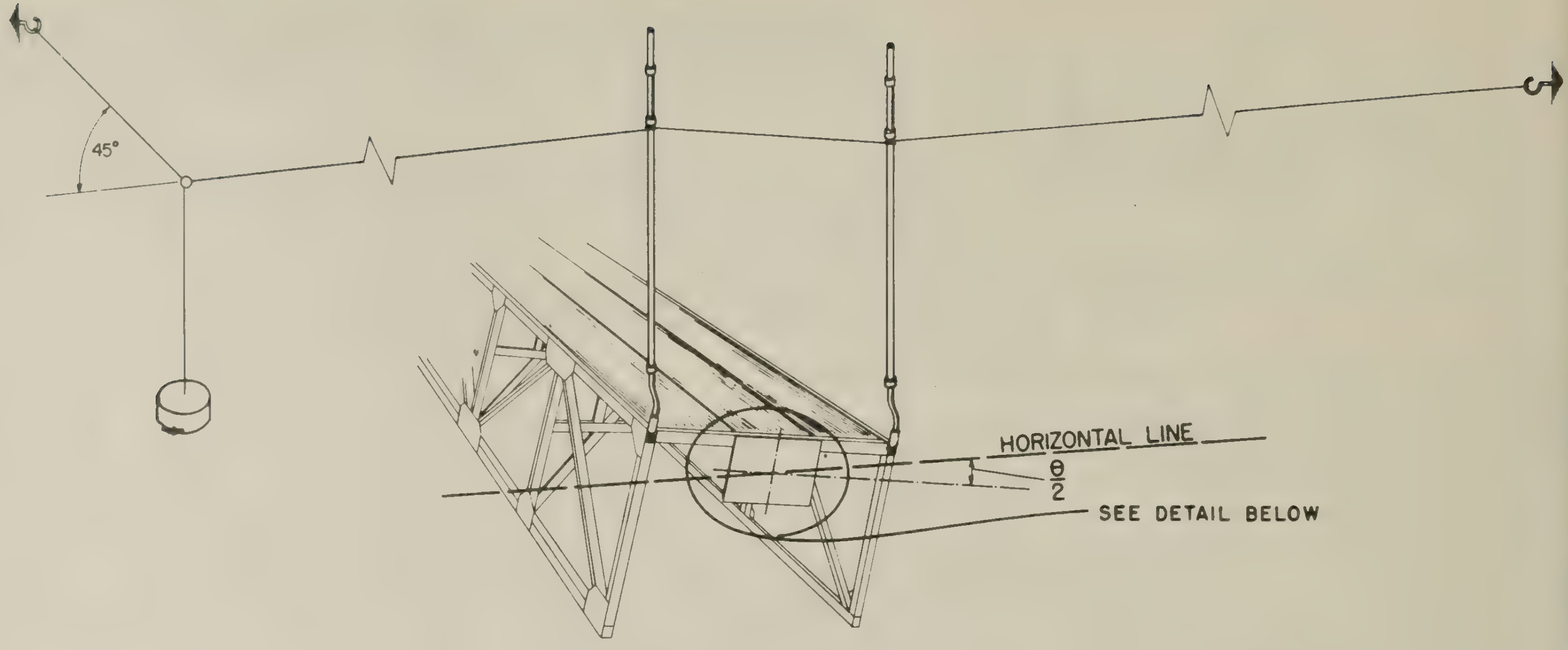
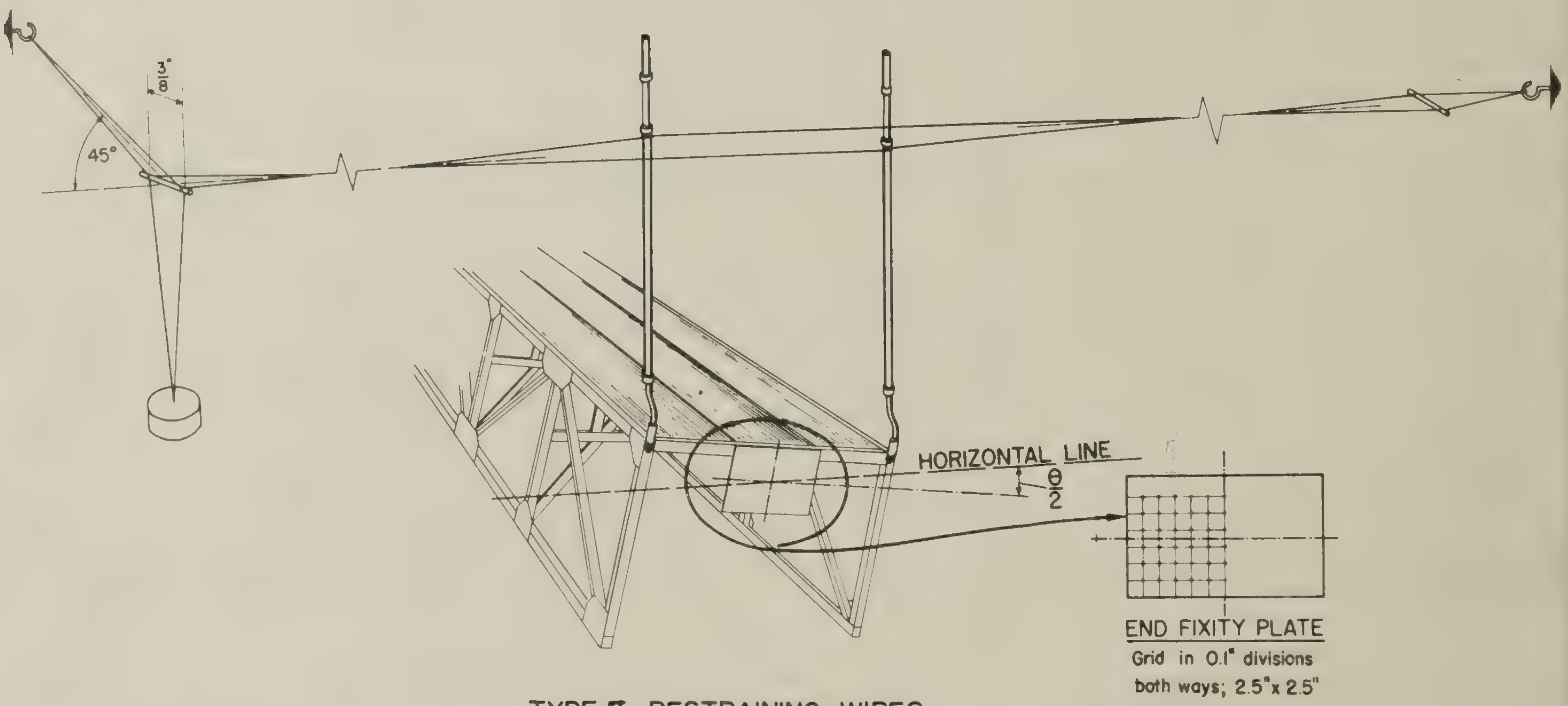
[2] Tests on section models of the Bronx-Whitestone Bridge and the Paseo Bridge, as well as several others, are reported in *Aerodynamic stability of suspension bridges with special reference to the Tacoma Narrows Bridge.* University of Washington Engineering Experiment Station, Bulletin 116. Part V: *Extended studies: logarithmic decrement, field damping, prototype predictions, four other bridges,* by G. S. Vincent.



TYPE I RESTRAINING WIRES



TYPE II RESTRAINING WIRES

Figure 3.—End fixity plates, required for tests on some models, were not used on the Paseo Bridge model.

oscillates in vertical or torsional motion. With the type I restraining wires, this is still true in the case of vertical motion, and is true for torsional motion with respect to the portion of the wire from each end to the model support. However, that portion of the wire between the model supports will have a very significant vertical component in torsion. Thus, the type I wires act as springs to restrain torsional, but not vertical, motion and their effect is to increase the frequency of the torsional oscillation, while having little influence on that of the vertical. The strength of this action is increased by increasing the tension of the restraining wire.

Tests were made in a horizontal wind and at an angle of attack β of $+6°$ (wind angled upward 6°) and $-6°$ (wind angled downward 6°).

A test series was run with the sidewalk grating closed except for a small slot under the curb, and a partial series was run with both the sidewalk and median-strip gratings similarly closed.

Test Data

The solid lines in figure 4 show the amplitude of vertical and torsional oscillation plotted against the wind velocity for the model mounting that gave natural (wind off) frequencies of 68.3 and 99.7 c. p. m. in vertical and torsional oscillation, respectively. It will be noted in this figure that the wind-forced frequencies were only slightly greater in vertical motion and slightly less in t
sional motion than the respective natu
frequencies, which indicates that the coupl
tendency—the wind-induced interaction
torsional and vertical motion—was sm
This was true in all of the tests on this mo
and is, in general, characteristic of gir
stiffened sections with their blunt edges.

Previous tests on these springs and th
mountings had indicated a logarithmic d
rement δ_s due to structural damping al
of about 0.002 on the model, which is,
course, very low compared to the damp
to be expected on a bridge.

The solid lines in figure 5 show the resp
curves obtained after the tension in the
straining wires had been increased to giv

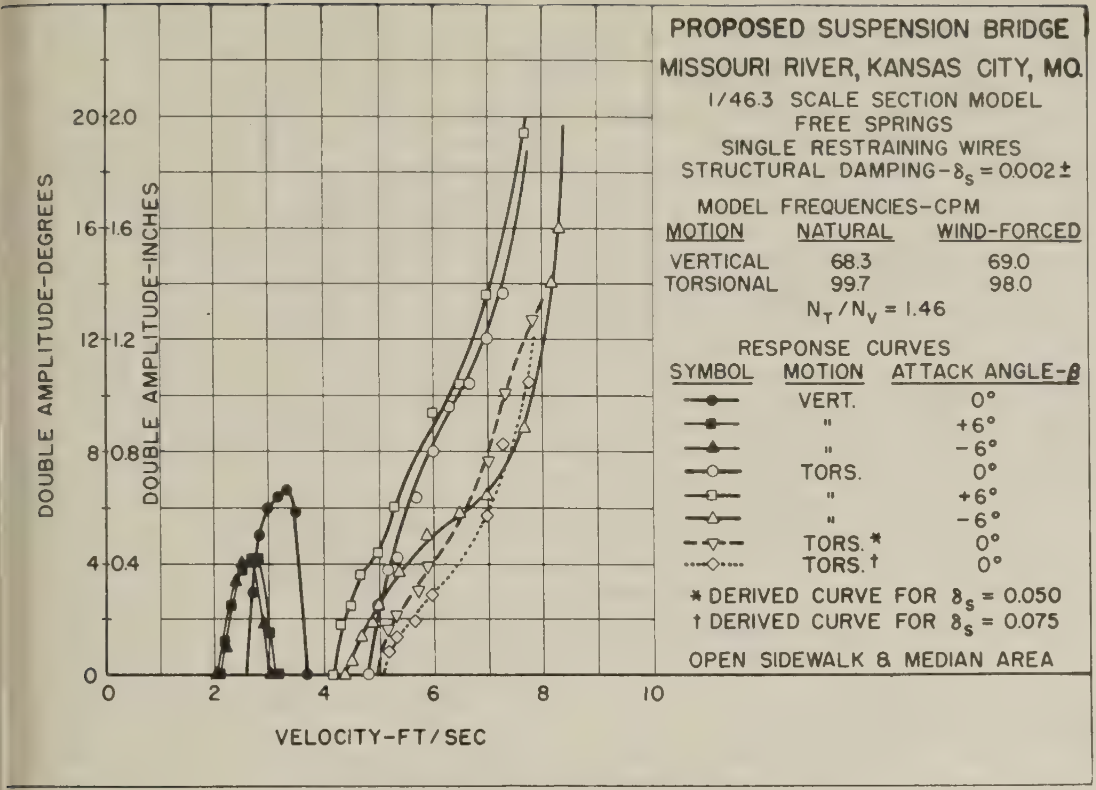


Figure 4.—Model response curves, $N_T/N_V=1.46$.

ratio of torsional to vertical frequency of 1.73. The added tension raised the frequency 21 percent in the torsional mode and only 2 percent in the vertical mode.

It will be noted in both figures 4 and 5 that the vertical oscillation due to a horizontal wind was restricted to the narrow velocity range from about 2¼ to 3½ feet per second and reached a maximum double amplitude of about 0.7 inch over a very restricted range near 3¼ feet per second. Figure 4 shows that when the angle of attack β was $+6°$ or $-6°$ the vertical oscillation was even less and was restricted to a narrower velocity range.

The torsional oscillation, on the other hand, began at a fairly distinct "critical velocity" but increased in amplitude as the velocity was increased and showed no tendency to drop off at higher velocities within the scope of the tests. (The test records for $\beta=0°$, fig. 4, show that the double amplitude exceeded 26° for velocities from 7.77 to 15.06 feet per second.) The model was seized to prevent greater motion, which would have caused damage. It will be noted in both figures 4 and 5 that the torsional oscillation began at a lower critical velocity when the angle of attack was changed from 0° to +6°. Also, the critical velocity for a given angle of attack was increased when the frequency of the torsional oscillation increased (compare figs. 4 and 5).

The solid lines in figure 6 show the amplitudes in vertical and torsional oscillation plotted against the ratio, V/Nb, in which V is the velocity in feet per second, N is the frequency in cycles per second, and b is the width of the model in feet. The curves plotted from model tests made at different frequencies fall so close together as to verify for this section the statement that the wind velocity required to cause a given oscillation varies in direct proportion to the frequency of the oscillation. The dimension b of the model is introduced in the denominator in order to make the ratio nondimensional and thus applicable to the prototype or any scale model of it. Thus, knowing from model tests the critical value of the V/Nb ratio, designated $(V/Nb)_c$, at which a wind-excited oscillation (vertical or torsional) will begin, the wind velocity V_p at which the prototype will begin to oscillate can be determined in feet per second from the equation:

$$V_p/N_p b_p=(V/Nb)_c \qquad (1)$$

by substituting the known frequency N_p and width b_p of the prototype.

Prediction of Prototype Behavior

Whether or not an oscillation observed on the model will appear on the prototype in an ideal wind stream (uniform and steady) at the prototype frequency, amplitude, and wind velocity will depend primarily upon the relative strengths of the exciting wind forces and the damping forces. This cannot be determined directly from the model response curves unless the structural damping of the model set-up happens to be fairly close to that of the prototype, which would only be true by accident, since it is impracticable to attempt to reproduce to proper scale on a model all of the damping influences of a bridge. However, a technique has been developed whereby the structural damping of an existing suspension bridge can be determined with reasonable accuracy by means of dynamic tests on the bridge and wind-tunnel tests on a section model of it, together with a correlating theoretical analysis. The strength of the exciting force, considered mathematically as negative damping, can be determined from the oscillograph records of the motion of the model.

A convenient measure of the strength of the exciting and damping forces is their ability to increase or decrease the amplitude of a vibration. This may be expressed by the logarithmic decrement δ, which is the natural logarithm of the ratio of the peak amplitudes of two successive cycles; that is,

$$\delta=\log_e=\frac{\eta_0}{\eta_1} \qquad (2)$$

in which η_0 and η_1 are, respectively, the amplitude peaks of any cycle and of the cycle immediately following it. For a vibration acted upon only by viscous damping (a damping force proportional to the velocity of vibration), the amplitude decays as a logarithmic or exponential curve and the value of δ is constant for all amplitudes.

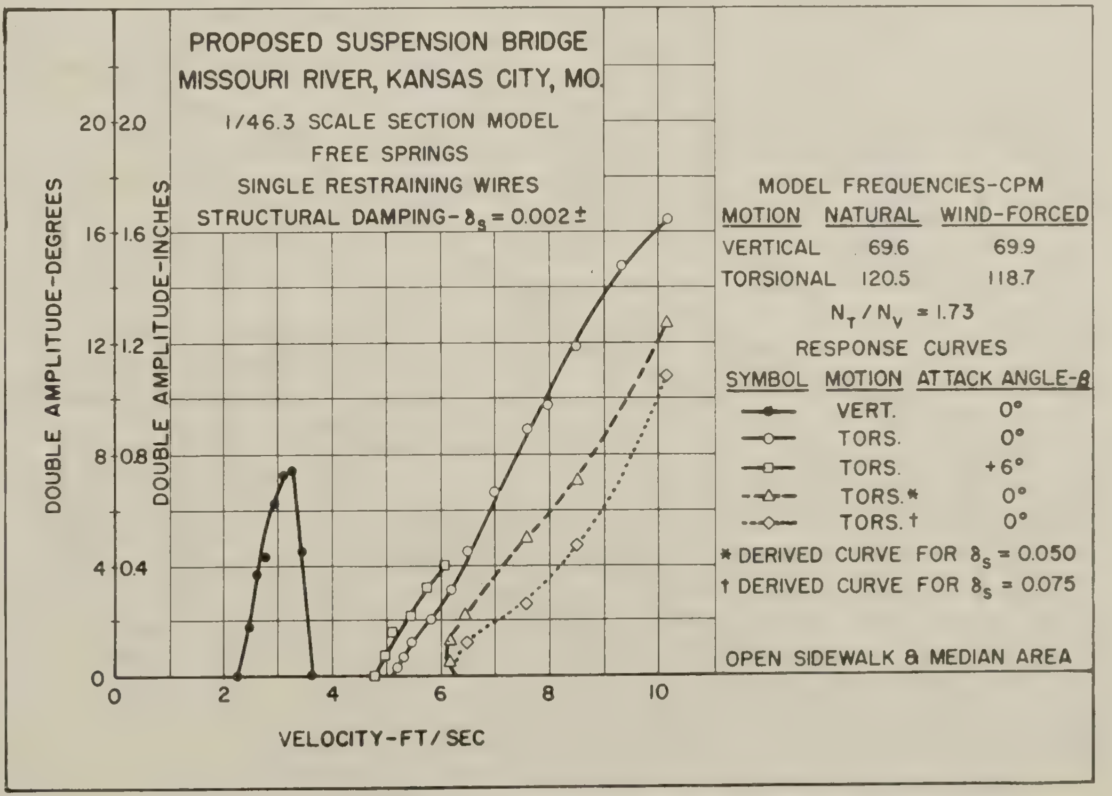


Figure 5.—Model response curves, $N_T/N_V=1.73$.

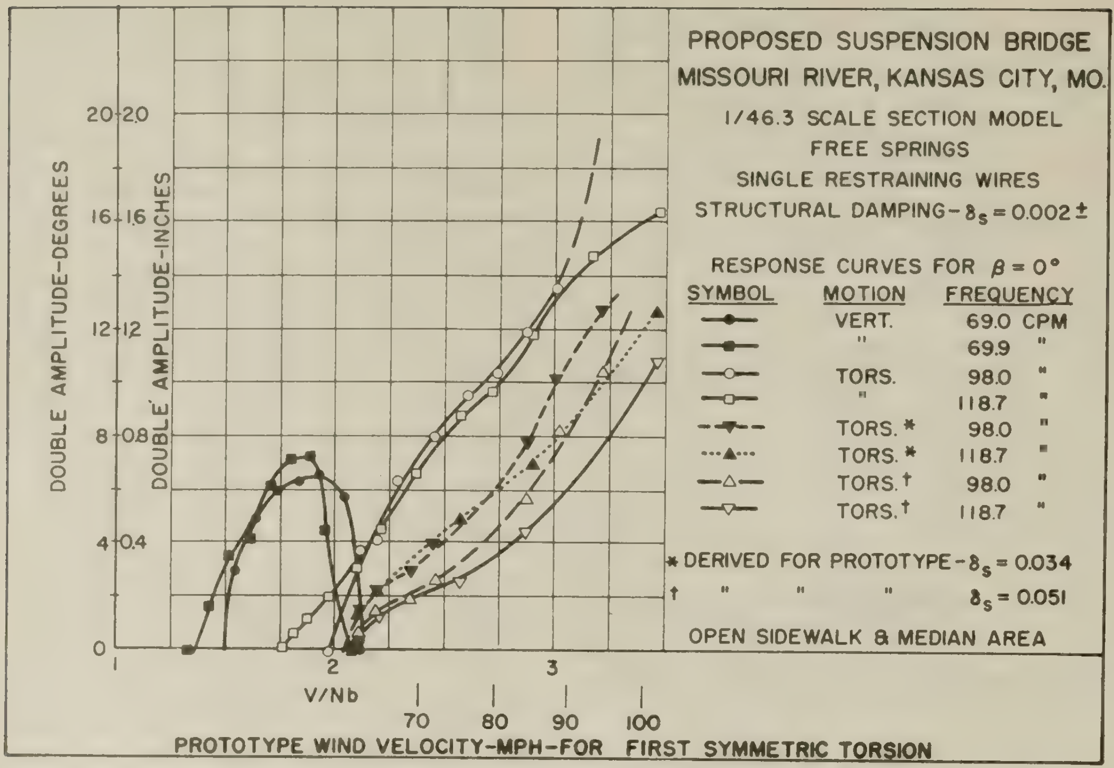


Figure 6.—Model response plotted against V/Nb ratio; also predicted prototype response.

Many forms of damping are not purely viscous, so that the value of δ varies when computed at different points along the curve of amplitude decay. This is true of the aero dynamic damping in still air and especially true of the complex damping due to a wind of constant velocity, which not only varies with the amplitude but may be negative over certain amplitude ranges and positive over others.

The damping affecting the vibration of a model or bridge always includes both the structural damping of the mechanism and the damping due to motion in still air or in a wind. This may be expressed as $\delta=\delta_s+\delta_a$ in which the subscripts $_s$ and $_a$ designate the structural and aerodynamic damping, respectively. The plotted points on response curves such as shown in figures 4 and 5 represent the amplitude which will build up and remain steady when the velocity is maintained constant at the value indicated. At any steady-state amplitude the value of δ must be zero (since $\eta_1=\eta_0$), which can only be true when the negative value of δ_a is just equal numerically to the positive value of δ_s.

The values of δ were determined from the measured amplitudes of the oscillograph record taken while the motion built up from rest to the steady state for several of the wind-velocity test runs used in plotting the response curves for $\beta=0°$ in figures 4 and 5. The values of δ_a were determined by subtracting 0.002, the approximate value of δ_s, from δ as determined from the records, and δ_a was plotted against amplitude in figures 7 and 8, each curve being identified by the wind velocity for which it was determined and by the value of the V/Nb ratio corresponding to that velocity.

The intersections of the decrement curves with the amplitude axis, representing $\delta_a=0$, mark the steady-state amplitude which would be reached at the corresponding velocities if there were no structural damping. If the structural damping δ_s is plotted downward from the axis of zero damping, its intersections with the aerodynamic decrement curves will mark the amplitudes at which $\delta_s=-\delta_a$ or $\delta_s+\delta_a=0$, thus indicating the steady-state amplitudes.

The short- and long-dash horizontal lines in figures 7 and 8 represent $\delta_s=0.05$ and $\delta_s=0.075$, respectively. The amplitudes indicated by their intersections with the aerodynamic decrement curves were plotted in figures 4 and 5 to produce, respectively, the dotted and dashed response curves.

Effect of Underweight Model

Earlier in this report it was mentioned that a correction would be required in applying the model test results to the prototype because the model weight was only 68 percent of that of a truly scaled model. It was noted that this disturbed the relation between the wind forces, dependent upon size and shape, and the inertial forces, dependent upon mass.

Most reference books on vibration show the logarithmic decrement in terms of other properties of the vibrating system, thus:

$$\delta=\frac{cg}{2wN}$$

in which c is the damping force per unit velocity, g is the acceleration of gravity, w is the weight, and N is the frequency. In the tests, the aerodynamic damping force corresponding to c in the expression for δ was correctly scaled but the weight w was only 68 percent of the correct value. It follows that δ_a as determined from the tests was too large and should be multiplied by 0.68 to obtain the correct value. This correction could be made graphically in figures 7 and 8 by simply multiplying the ordinate scale by 0.68. If this were done the ordinates of the short- and long-dash curves for $-\delta_s$ would represent values of 0.034 and 0.051 instead of 0.05 and 0.075. The steady-state amplitudes indicated by the intersections of these curves with the aerodynamic decrement curves were therefore plotted against the V/Nb ratio in figure 6 and identified as derived curves for the prototype for $\delta_s=0.034$ and $\delta_s=0.051$. The prototype wind velocity scale corresponding to the

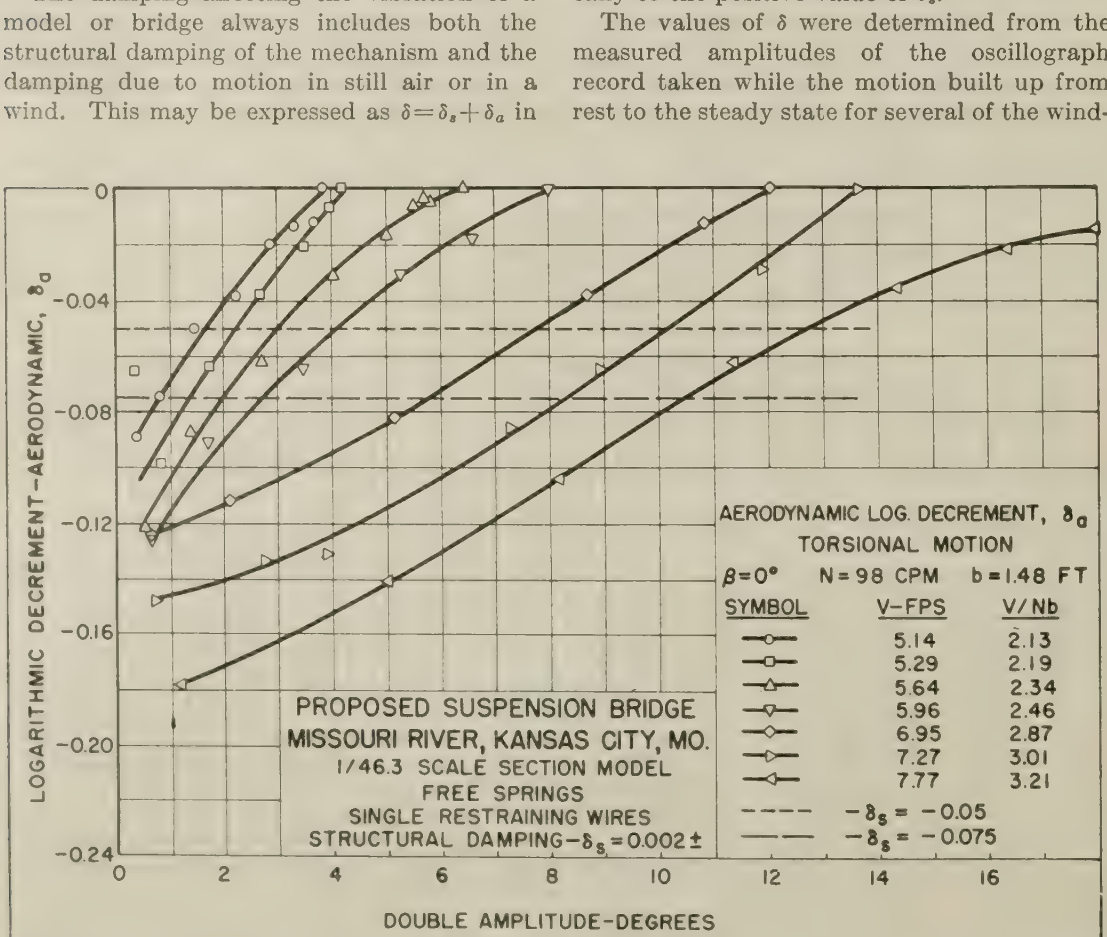


Figure 7.—Decrement curves for torsional oscillation at 98 cycles per minute.

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[3] For a fuller discussion of damping in relation to suspension bridges see Appendix II.—*Energy and damping*, in *aerodynamic stability of suspension bridges: progress report of the advisory board on the investigation of suspension bridges.* Proceedings of the American Society of Civil Engineers, vol 8, Separate Nos. 144A, 144B, Aug. 1952.

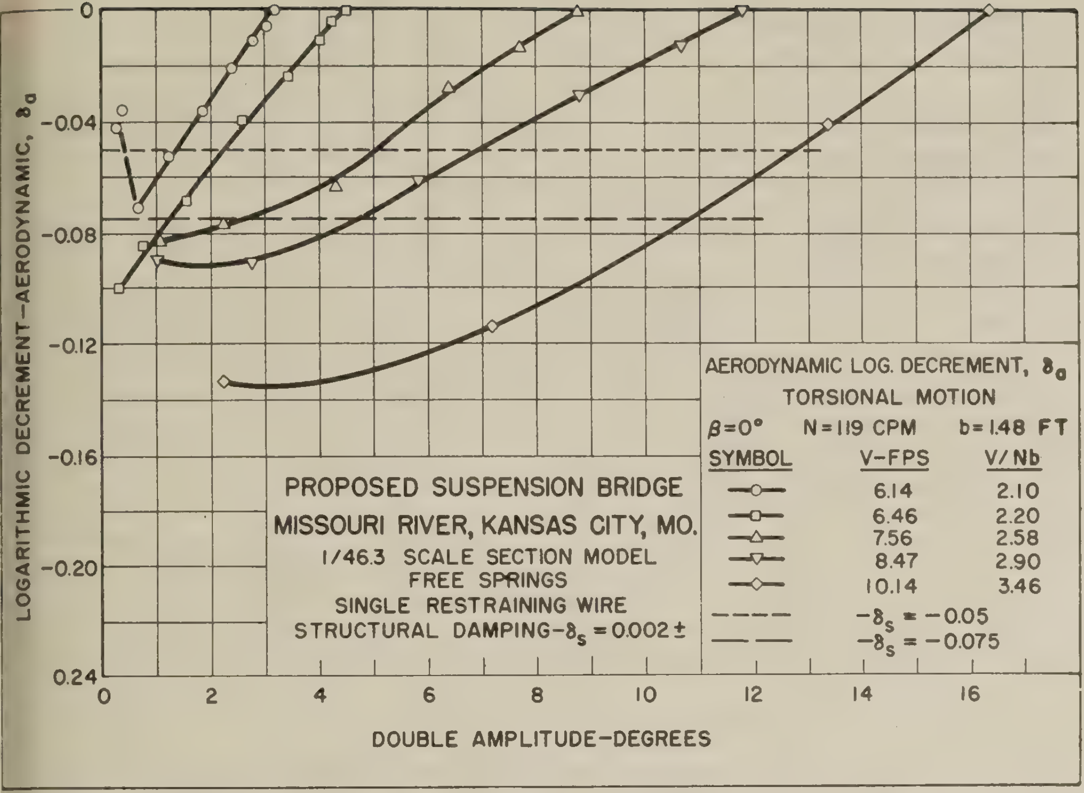

Figure 8.—Decrement curves for torsional oscillation at 119 cycles per minute.

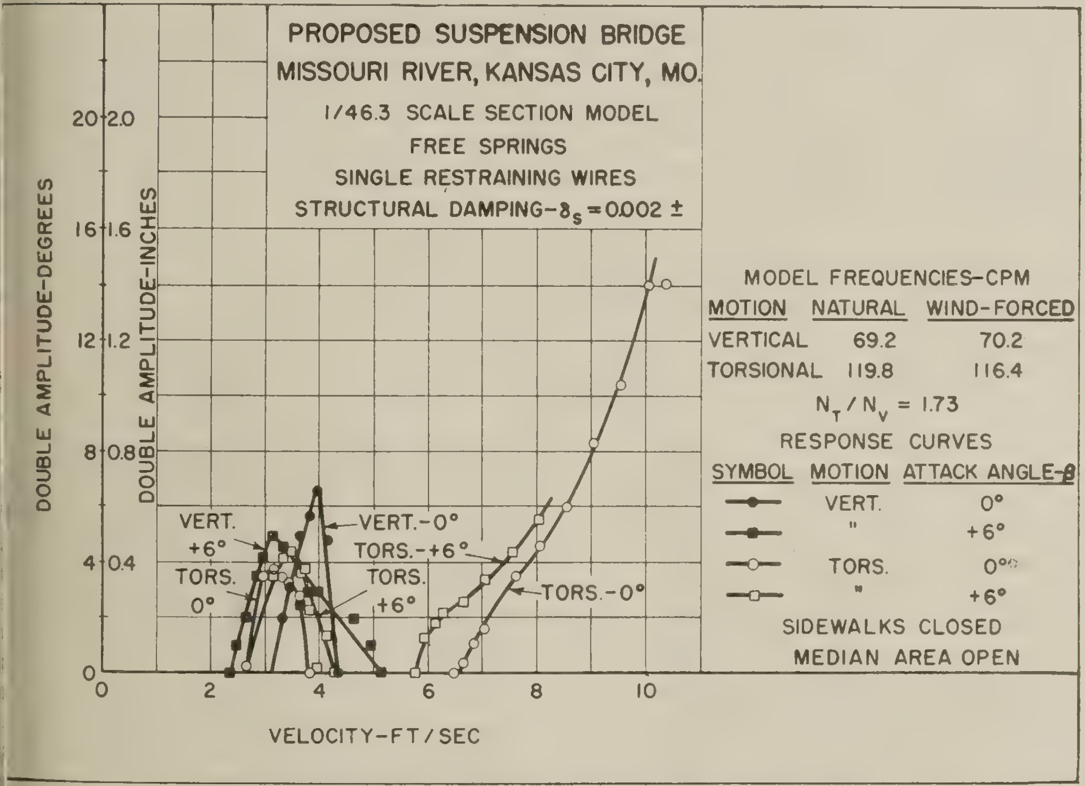

Figure 9.—Response curves with sidewalk grating closed.

V/Nb scale for the first symmetric torsional mode is shown in figure 6. It was computed from equation (1), using the prototype values N_p=37.5 c. p. m. and b_p=69 feet, thus:

$$V_p=(V/Nb)N_pb_p=\frac{37.5}{60}\times 69(V/Nb)$$
$$=43.12(V/Nb)\text{ feet per second}$$
$$=29.4(V/Nb)\text{ miles per hour.}$$

Probable Behavior of Bridge

Torsional oscillation.—There is evidence that δ_s for the Golden Gate Bridge and the original Tacoma Narrows Bridge is well below 0.05. By comparison with these, the bridge at Kansas City, with a much greater proportion of the total energy stored in bending and twisting the heavy girders and with top and bottom lateral systems forcing more participation of the concrete deck, should have a structural decrement somewhat more than 0.05. Using the predicted response curve for δ_s=0.051 in figure 6, the first symmetric torsional mode would be expected to appear at a velocity of about 62 miles per hour and reach about 6° of double amplitude at 85 to 90 miles per hour in a *steady uniform wind.* Unless the wind is unusually steady and uniform along the bridge, however, it is likely that even maximum storms will cause only small, more or less spasmodic oscillation, perhaps enough over a few cycles to be identified as to frequency and general wave form.

Vertical motion.—Figure 6 shows the maximum amplitude of the vertical oscillation of the section model occurring at about V/Nb=1.85. For the first symmetric vertical mode of the prototype N_p=21.8 c. p. m. and the peak amplitude would be expected at:

$$V_p=1.85\times\frac{21.8}{60}\times 69\times\frac{3{,}600}{5{,}280}=31.6\ \text{miles per hour}$$

However, variations of only a few miles per hour above or below this figure would greatly reduce the effectiveness of the wind ($-\delta_a$ was generally less than 0.04 and reached 0.06 to 0.07 within a very narrow velocity range).

Although δ_s for the vertical motion may be less than 0.05, it is unlikely that vertical oscillation will appear except in random form or for a few cycles.

Effect of closing slots.—Figure 9 shows model response curves with the sidewalks covered but with a small gap under the curbs. By comparison with the solid-line curves of figure 5, it is seen that closing the sidewalk grating raised the critical velocity of the torsional mode about 1.0 foot per second for $\beta=+6°$ and about 1.5 for $\beta=0°$. The increases in $(V/Nb)_c$ are about 0.3 and 0.5, corresponding to 10 to 15 miles per hour for the first symmetric torsional mode of the prototype.

Figure 10 shows the response at $\beta=0°$ when the sidewalks and median strip were covered except for the small curb slot. Comparing this with figure 5 shows an increase of more than 2 feet per second in critical velocity or over 20 miles per hour on the prototype.

These tests support others indicating that roadway slots which are beneficial in combatting flutter of thin sections are often detrimental in dealing with torsional oscillation of the blunt sections of girder-stiffened suspension bridges. The excitation of the latter arises largely from the wind flow adjacent to the girders, while the roadway slots seem to reduce the damping effect of the deck.

Acknowledgment

The section model tests were made in the suspension bridge wind tunnel at the University of Washington under the cooperative agreement of the University and the Bureau of Public Roads covering the studies on the Tacoma Narrows Bridge and a number of other suspension bridges. Professor F. B. Farquharson, Director of the Engineering Experiment Station, approved the added tests on behalf of the University. Robert E. McHugh, Jr., Junior Research Engineer for the University of Washington, made the tests. The writer, representing the Bureau of Public Roads, computed the vibration characteristics of the bridge, made the required modifications in the model, and analyzed the data. The designers of the bridge, Howard, Needles, Tammen, and Bergendoff, also checked the vibration calculations for this report.

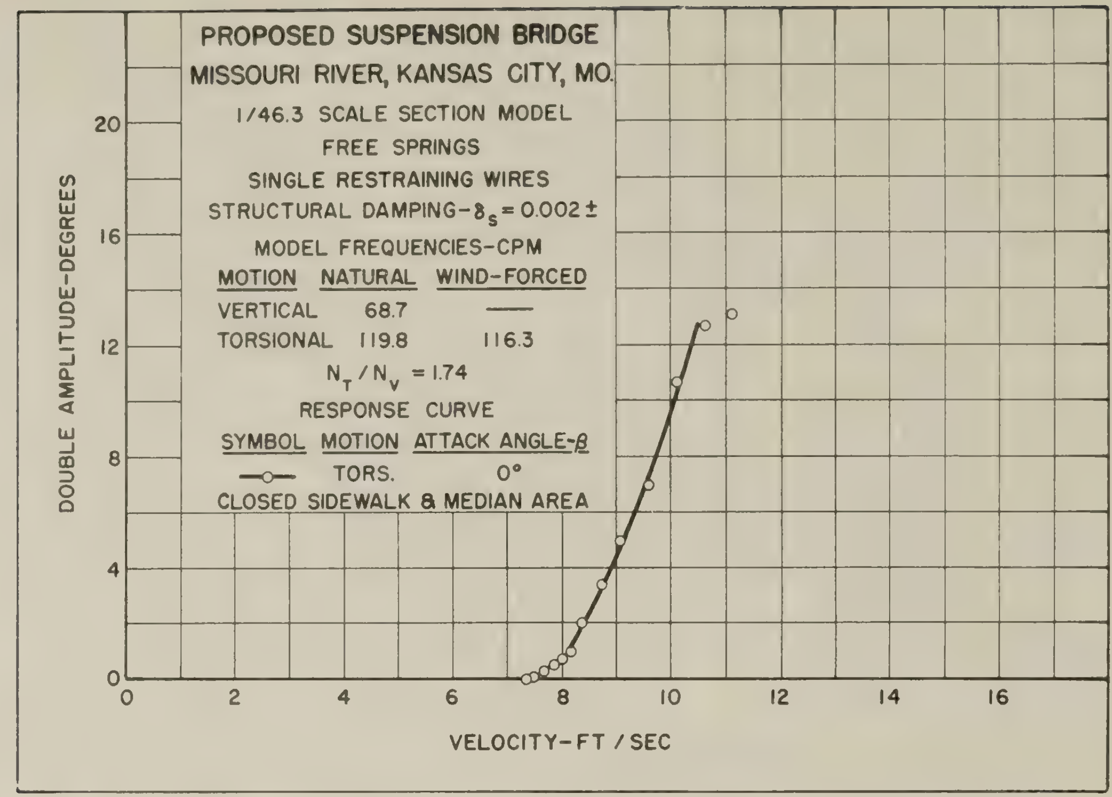

Figure 10.—Response curve with sidewalk and median area gratings closed.

Driver Behavior

(Continued from page 169)

vehicles traveling in the right lane were affected approximately the same as passenger cars by objects at the pavement edge. At the higher volumes, the effect on commercial vehicles was slightly less than on passenger cars. The lateral positions of commercial vehicles were not influenced by a barricade placed either 3 or 6 feet from the pavement or by a truck or car parked 6 feet therefrom.

Although the lateral positions of vehicles in the right lane were affected by objects on the shoulder, the objects did not cause change in the distribution of traffic betwe the two lanes. The objects on the should did, however, cause an increase in the pe centage of commercial vehicles that straddl the lane marking

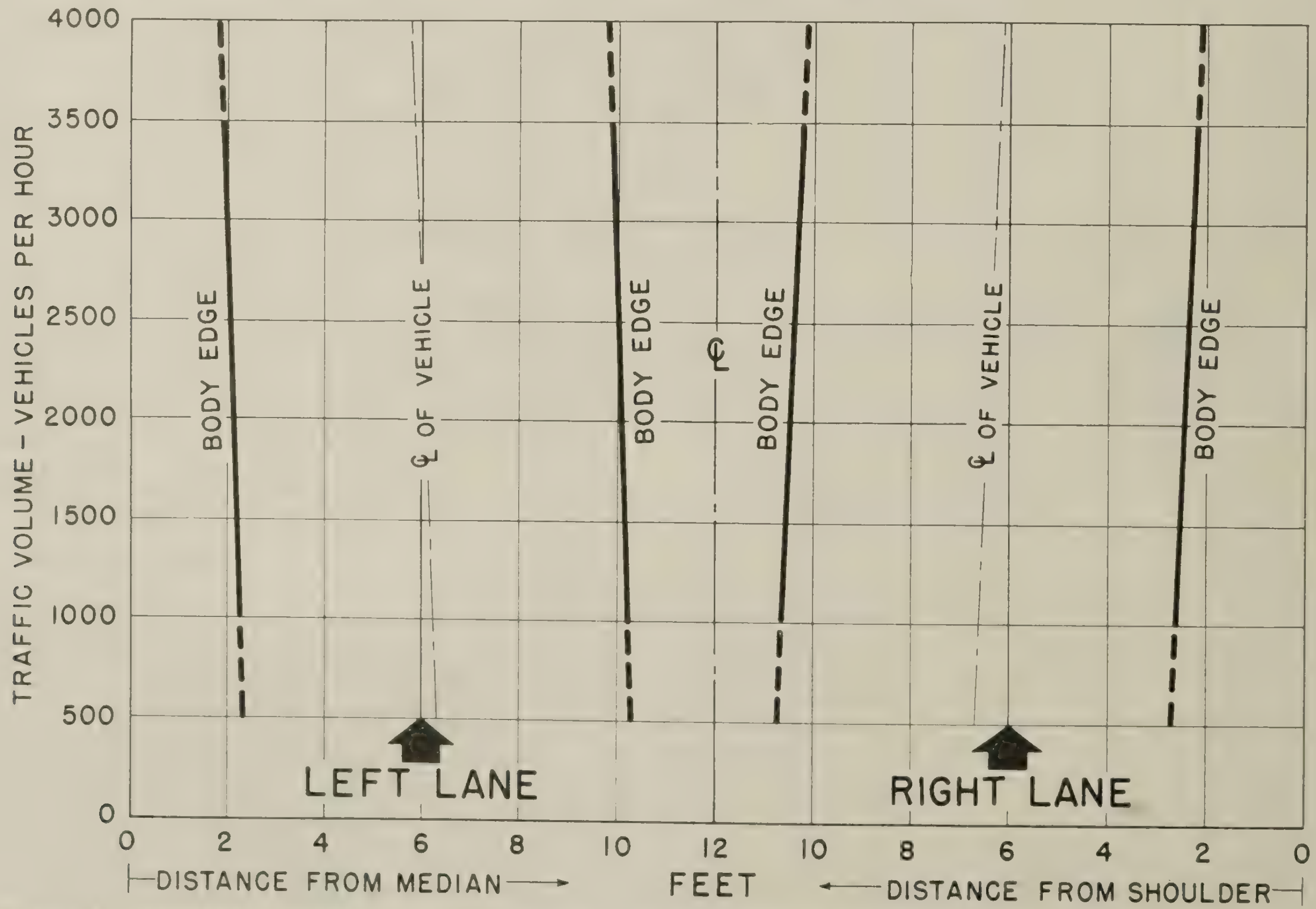

Figure 13.—Average position of commercial vehicles traveling in one direction on a four lane divided highway during different traffic volumes.

Needs of the Highway Systems, 1955-84

On March 25, 1955, the Secretary of Commerce transmitted to the Congress a report on the cost of construction needed to modernize the Nation's highways, prepared by the Bureau of Public Roads in cooperation with the State highway departments, pursuant to the requirement in section 13 of the Federal-Aid Highway Act of 1954.

This report, titled *Needs of the Highway Systems, 1955–84,* has been published as House Document No. 120, 84th Congress, 1st Session, and is available from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., at 15 cents a copy.

The cost of construction needed to modernize the Nation's roads and streets within the 10-year period 1955–64 would amount to $101 billion, the report shows. Construction needs for the following 20 years, 1965–84, to sustain adequacy and provide for expanding traffic growth, were estimated to cost $114 billion.

Maintenance needs and administrative costs must also be considered in the total cost of a highway program. Maintenance needs for the initial 10-year period were estimated to total $19.4 billion, and for the 1955–84 period, $48.8 billion. The estimates of administrative costs were $5.9 billion for the first 10-year period and $7.8 billion for 1965–84.

The total estimated needs for the 30 years from 1955 to 1984 thus amount to $297.1 billion, of which 72 percent is for construction. The total needs over the entire period average out to $9.9 billion a year. By way of comparison, the total expenditure (exclusive of debt service) for all roads and streets in 1954 was $6.1 billion, of which 64 percent was for construction.

The several estimates were made for five major systems: Interstate, other Federal-aid primary, Federal-aid secondary, other State highways, and all other roads and streets. Each of these was divided into rural and urban except the Federal-aid secondary system, which is almost wholly rural. The estimates for this system were divided according to State or local control. The estimated construction needs for the initial 10-year period were reported by States, and these data are reproduced as table 1 on page 178.

In a statement on highway financing included in the report, it is noted that the established flow of funds for highways at current tax rates, taking into account increasing motor-vehicle usage, should produce $47 billion for highway construction in the 10-year period 1955–64. A deficit of $54 billion must be overcome if the $101 billion needs are to be met.

Decision as to a financing program should take into account the division of cost burden among various levels of government, the amount that can be spent for highways in view of other public needs, and the suitability of various methods of obtaining funds for highways.

The President's Advisory Committee on a National Highway Program, headed by Gen. Lucius D. Clay, presented its recommendations in a January 1955 report, *A Ten-Year Highway Program* (available from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., at 20 cents per copy). The Committee proposes a total construction expenditure by the Federal Government of $31.225 billion over the next 10 years. Of the total, $25 billion is for the interstate system including essential urban arterial connections, $3.15 billion for the remainder of the Federal-aid primary system, $2.10 billion for the Federal-aid secondary system, $0.75 billion for the Federal-aid urban system, and $0.225 billion for forest highways. Financial participation by State and local governments would amount to $2 billion on the interstate system including essential urban arterial connections. For the other Federal-aid systems, statutory matching requirements would remain unchanged and would amount to slightly less than the Federal contributions of $6.225 billion.

Progress and Feasibility of Toll Roads and Their Relation to the Federal-Aid Program

The Secretary of Commerce transmitted to the Congress on April 14, 1955, a report on the progress and feasibility of toll roads and their possible effects on the Federal-aid highway program, in accordance with section 13 of the Federal-Aid Highway Act of 1954. The study was made by the Bureau of Public Roads in cooperation with the State highway departments.

The report, entitled *Progress and Feasibility of Toll Roads and Their Relation to the Federal-Aid Program,* has been published as House Document No. 139, Eighty-fourth Congress, first session, and is available from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., at 15 cents a copy.

The study found that highways feasible of construction as toll roads lie almost entirely within the 40,000-mile network of the National System of Interstate Highways. This interstate system, linking industrial and commercial centers from coast to coast, embraces all but about 200 miles of the 6,900-mile total which the report regards as now feasible for additional toll-road construction.

In making this estimate of toll-road feasibility the investigation excluded routes on which present improvements or those already programed for early construction were expected to meet traffic demands of the future. Thus the toll-road potential is in addition to mileage, either toll or free, that now meets traffic requirements and those sections which definitely programed improvements will make satisfactory.

Feasibility of potential toll roads was determined by dividing the estimated yearly net operating income for a particular section of road by the annual cost of debt service resulting from the issuance of revenue bonds. Recent experience shows that bonds offered to finance toll roads when the annual net revenue is one and one-half times the yearly debt service would be marketable. Therefore, any section of road having a revenue-debt service ratio of 1.5 was regarded as feasible for toll-road construction and financing.

The report estimates that the construction cost of the 6,700-mile potential which lies within the interstate system would be $4,260,000,000. Some of this mileage is located in States that have not authorized toll financing and which may not do so in the future. Other sections lie in States where authority to construct toll roads is limited to particular routes and may not include some of the sections which are considered feasible in this report. To the extent that these conditions prevail, the 6,700-mile figure might be reduced.

The greatest uncertainty, however, centers on the policies of the States and the Federal Government with respect to the public funds from taxes or bond issues that will be applied to the improvement of the interstate system. The report points out that assurance of public funds to provide reasonably early completion of this vital network would soon spell the end of revenue-bond financing of roads in the system. If the present inadequate allocation of funds to this system is continued, the mileage of potentially feasible toll roads will increase.

These findings not only show the importance of the interstate system, they also raise questions concerning Federal participation in toll roads. As directed by the Federal-Aid Highway Act of 1954, the report includes recommendations covering this point:

1. *No Federal participation in toll roads.*—The present law forbidding the collection of tolls on highways constructed with Federal-aid funds should be continued.

2. *Inclusion of toll roads in Federal-aid systems.*—The present law should be changed to permit the inclusion of toll roads as part of the National System of Interstate Highways when they meet the standards for that system, *and when there are reasonably satisfactory alternate free roads* on the Federal-aid primary or secondary systems which permit traffic to bypass the toll roads.

This recommendation is made to meet present-day conditions. A number of toll roads which are in operation, under construction, or authorized, lie along the preferred location of interstate routes; duplication of these roads would generally be an economic waste. Accordingly, if there is to be a continuous integrated interstate system, it is reasonable that these toll roads be included in it. The inclusion of a toll road in the interstate system would not be contrary to recommendation 1. It would merely make it unnecessary to construct a free road to interstate standards closely paralleling the toll road.

No toll roads should be permitted on any Federal-aid system except as provided in the first paragraph of this recommendation. Continuous travel over free roads will then be possible except over those portions of the interstate system on which tolls are collected. On those portions, drivers will have the alternative of travel over a toll road built to interstate standards, or over a reasonabl satisfactory free road of another Federal-ai route.

Some of the adverse effects of toll roads o the programing of public highway improve ments and many problems of integration c toll roads with public highway networks woul be greatly alleviated if the responsibility fo toll roads were vested in State highwa departments. The consolidation of respons bility for toll and free highways would permi the most effective use of available engineerin and technical personnel, avoid duplicatin administrative organizations, and promot orderly development of all highway improve ments.

Table 1.—Highway construction needs, 1955–64, by system and State

[All amounts in millions of dollars] [1]

State	Federal-aid Systems												Non Federal-aid systems									All roads and streets		
	Interstate			Other Federal-aid primary			Federal-aid secondary			Total			Other State highways			Other roads and streets			Total					
	Rural	Urban	Total	Rural	Urban	Total	State	Local	Total	Rural	Urban	Total	Rural	Urban	Total	Rural	Urban	Total	Rural	Urban	Total	Rural	Urban	Total
Alabama	316	50	366	139	153	292	23	111	134	589	203	792	2	11	13	780	469	1,249	782	480	1,262	1,371	683	2,054
Arizona	193	17	210	120	12	132	94	49	143	456	29	485	------	------	------	135	36	171	135	36	171	591	65	656
Arkansas	171	32	203	223	26	249	271	78	349	743	58	801	10	5	15	107	161	268	117	166	283	860	224	1,084
California	592	1,729	2,321	859	677	1,536	360	288	648	2,099	2,406	4,505	351	423	774	1,385	1,545	2,930	1,736	1,968	3,704	3,835	4,374	8,209
Colorado	130	27	157	321	60	381	197	------	197	648	87	735	6	------	6	473	236	709	479	236	715	1,127	323	1,450
Connecticut	185	370	555	237	381	618	166	41	207	629	751	1,380	229	144	373	157	144	301	386	288	674	1,015	1,039	2,054
Delaware	45	21	66	81	26	107	83	------	83	209	47	256	28	2	30	9	13	22	37	15	52	246	62	308
Florida	360	136	496	107	724	831	242	74	316	783	860	1,643	62	158	220	124	43	167	186	201	387	969	1,061	2,030
Georgia	569	131	700	467	174	641	189	166	355	1,391	305	1,696	56	31	87	268	206	474	324	237	561	1,715	542	2,257
Idaho	98	9	107	169	9	178	64	35	99	366	18	384	8	1	9	153	21	174	161	22	183	527	40	567
Illinois	547	518	1,065	726	256	982	31	108	139	1,412	774	2,186	223	182	405	439	1,447	1,886	662	1,629	2,291	2,074	2,403	4,477
Indiana	475	392	867	816	303	1,119	385	362	747	2,038	695	2,733	18	33	51	741	681	1,422	759	714	1,473	2,797	1,409	4,206
Iowa	220	55	275	978	194	1,172	------	514	514	1,712	249	1,961	3	1	4	390	132	522	393	133	526	2,105	382	2,487
Kansas	191	16	207	570	96	666	107	207	314	1,075	112	1,187	------	------	------	277	198	475	277	198	475	1,352	310	1,662
Kentucky	363	129	492	355	132	487	416	79	495	1,213	261	1,474	215	71	286	108	69	177	323	140	463	1,536	401	1,937
Louisiana	246	247	493	159	73	232	256	3	259	664	320	984	215	56	271	66	241	307	281	297	578	945	617	1,562
Maine	140	7	147	219	126	345	140	------	140	499	133	632	105	18	123	84	31	115	189	49	238	688	182	870
Maryland	155	279	434	212	284	496	201	57	258	625	563	1,188	14	14	28	219	89	308	233	103	336	858	666	1,524
Massachusetts	144	694	838	340	285	625	94	318	412	896	979	1,875	9	3	12	361	201	562	370	204	574	1,266	1,183	2,449
Michigan	807	488	1,295	1,385	440	1,825	532	736	1,268	3,460	928	4,388	57	105	162	655	1,496	2,151	712	1,601	2,313	4,172	2,529	6,701
Minnesota	262	221	483	305	189	494	113	116	229	796	410	1,206	2	5	7	198	239	437	200	244	444	996	654	1,650
Mississippi	222	24	246	270	33	303	80	47	127	619	57	676	17	4	21	128	98	226	145	102	247	764	159	923
Missouri	436	163	599	699	178	877	308	------	308	1,443	341	1,784	22	8	30	290	427	717	312	435	747	1,755	776	2,531
Montana	141	12	153	317	4	321	------	79	79	537	16	553	------	1	1	170	25	195	170	26	196	707	42	749
Nebraska	90	16	106	159	31	190	112	57	169	418	47	465	2	2	4	191	161	352	193	163	356	611	210	821
Nevada	63	10	73	83	10	93	20	21	41	187	20	207	2	------	2	3	8	11	5	8	13	192	28	220
New Hampshire	42	24	66	159	45	204	82	2	84	285	69	354	67	8	75	46	83	129	113	91	204	398	160	558
New Jersey	223	1,134	1,357	625	1,081	1,706	17	232	249	1,097	2,215	3,312	22	70	92	344	875	1,219	366	945	1,311	1,463	3,160	4,623
New Mexico	176	59	235	201	46	247	117	------	117	494	105	599	74	23	97	182	128	310	256	151	407	750	256	1,006
New York	638	698	1,336	2,063	1,293	3,356	483	406	889	3,590	1,991	5,581	7	18	25	268	553	821	275	571	846	3,865	2,562	6,427
North Carolina	226	21	247	314	42	356	255	------	255	795	63	858	6	15	21	182	155	337	188	170	358	983	233	1,216
North Dakota	103	4	107	74	8	82	120	68	188	365	12	377	------	1	1	49	57	106	49	58	107	414	70	484
Ohio	537	824	1,361	622	578	1,200	384	91	475	1,634	1,402	3,036	238	82	320	794	886	1,680	1,032	968	2,000	2,666	2,370	5,036
Oklahoma	296	81	377	505	104	609	117	118	235	1,036	185	1,221	24	13	37	144	137	281	168	150	318	1,204	335	1,539
Oregon	170	149	319	187	146	333	73	33	106	463	295	758	4	18	22	182	109	291	186	127	313	649	422	1,071
Pennsylvania	360	400	760	1,074	482	1,556	1,422	18	1,440	2,874	882	3,756	1,165	85	1,250	433	275	708	1,598	360	1,958	4,472	1,242	5,714
Rhode Island	7	116	123	117	128	245	28	10	38	162	244	406	13	11	24	25	31	56	38	42	80	200	286	486
South Carolina	140	43	183	93	30	123	72	5	77	310	73	383	79	19	98	79	30	109	158	49	207	468	122	590
South Dakota	86	9	95	141	23	164	100	57	157	384	32	416	7	------	7	61	41	102	68	41	109	452	73	525
Tennessee	261	119	380	472	115	587	184	61	245	978	234	1,212	------	7	7	321	260	581	321	267	588	1,299	501	1,800
Texas	515	357	872	520	135	655	464	------	464	1,499	492	1,991	260	29	289	651	743	1,394	911	772	1,683	2,410	1,264	3,674
Utah	189	49	238	100	29	129	48	15	63	352	78	430	39	2	41	104	57	161	143	59	202	495	137	632
Vermont	169	9	178	167	12	179	46	28	74	410	21	431	2	------	2	35	5	40	37	5	42	447	26	473
Virginia	386	183	569	308	159	467	207	21	228	922	342	1,264	1	19	20	283	190	473	284	209	493	1,206	551	1,757
Washington	193	274	467	427	57	484	257	50	307	927	331	1,258	64	33	97	283	331	614	347	364	711	1,274	695	1,969
West Virginia	168	90	258	516	152	668	485	------	485	1,169	242	1,411	------	1	1	304	62	366	304	63	367	1,473	305	1,778
Wisconsin	208	115	323	523	202	725	411	136	547	1,278	317	1,595	------	------	------	366	424	790	366	424	790	1,644	741	2,385
Wyoming	282	14	296	216	10	226	95	10	105	603	24	627	1	------	1	179	24	203	180	24	204	783	48	831
District of Columbia	------	152	152	------	153	153	9	------	9	9	305	314	------	10	10	------	------	------	------	10	10	9	315	324
Subtotal, Continental United States	12,536	10,717	23,253	19,740	9,906	29,646	9,960	4,907	14,867	47,143	20,623	67,766	3,729	1,742	5,471	13,226	13,873	27,099	16,955	15,615	32,570	64,098	36,238	100,336
Hawaii	------	------	------	59	41	100	52	------	52	111	41	152	------	------	------	13	21	34	13	21	34	124	62	186
Puerto Rico	------	------	------	90	46	136	64	------	64	154	46	200	6	23	29	39	14	53	45	37	82	199	83	282
Grand total	12,536	10,717	23,253	19,889	9,993	29,882	10,076	4,907	14,983	47,408	20,710	68,118	3,735	1,765	5,500	13,278	13,908	27,186	17,013	15,673	32,686	64,421	36,383	100,804

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[1] Individual entries may vary slightly from original reported data due to rounding in millions of dollars.

U. S. GOVERNMENT PRINTING OFFICE: 1955

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Bibliography of Highway Planning Reports (1950). 30 cents.
Braking Performance of Motor Vehicles (1954). 55 cents.
Construction of Private Driveways, No. 272MP (1937). 15 cents.
Criteria for Prestressed Concrete Bridges (1954). 15 cents.
Design Capacity Charts for Signalized Street and Highway Intersections (reprint from PUBLIC ROADS, Feb. 1951). 25 cents.
Electrical Equipment on Movable Bridges, No. 265T (1931). 40 cents.
Factual Discussion of Motortruck Operation, Regulation, and Taxation (1951). 30 cents.
Federal Legislation and Regulations Relating to Highway Construction (1948). Out of print.
Financing of Highways by Counties and Local Rural Governments, 1931-41. 45 cents.
Highway Bond Calculations (1936). 10 cents.
Highway Bridge Location No. 1486D (1927). 15 cents.
Highway Capacity Manual (1950). 75 cents.
Highway Needs of the National Defense, House Document No. 249 (1949). 50 cents.
Highway Practice in the United States of America (1949). 75 cents.
Highway Statistics (annual):

1945, 35 cents.	1948, 65 cents.	1951, 60 cents.
1946, 50 cents.	1949, 55 cents.	1952, 75 cents.
1947, 45 cents.	1950 (out of print).	1953, $1.00.

Highway Statistics, Summary to 1945. 40 cents.
Highways in the United States, *nontechnical* (1954). 20 cents.
Highways of History (1939). 25 cents.
Identification of Rock Types (1950). Out of print.
Interregional Highways, House Document No. 379 (1944). 75 cents.
Legal Aspects of Controlling Highway Access (1945). 15 cents.
Local Rural Road Problem (1950). 20 cents.
Manual on Uniform Traffic Control Devices for Streets and Highways (1948) (*including 1954 revisions supplement*). $1.00.
  Revisions to the Manual on Uniform Traffic Control Devices for Streets and Highways (1954). *Separate,* 15 cents.
Mathematical Theory of Vibration in Suspension Bridges (1950). $1.25.
Model Traffic Ordinance (revised 1953). 20 cents.

PUBLICATIONS (Continued)

Motor-Vehicle Traffic Conditions in the United States, House Document No. 462 (1938). Out of print.
  Part 1.—Nonuniformity of State Motor-Vehicle Traffic Laws.
  Part 2.—Skilled Investigation at the Scene of the Accident Needed to Develop Causes.
  Part 3.—Inadequacy of State Motor-Vehicle Accident Reporting.
  Part 4.—Official Inspection of Vehicles.
  Part 5.—Case Histories of Fatal Highway Accidents.
  Part 6.—The Accident-Prone Driver.
Needs of the Highway Systems, 1955–84, House Document No. 120 (1955). 15 cents.
Principles of Highway Construction as Applied to Airports, Flight Strips, and Other Landing Areas for Aircraft (1943). $2.00.
Public Control of Highway Access and Roadside Development (1947). 35 cents.
Public Land Acquisition for Highway Purposes (1943). 10 cents.
Results of Physical Tests of Road-Building Aggregate (1953). $1.00.
Roadside Improvement, No. 191MP (1934). 10 cents.
Selected Bibliography on Highway Finance (1951). 60 cents.
Specifications for Construction of Roads and Bridges in National Forests and National Parks, FP-41 (1948). $1.50.
Standard Plans for Highway Bridge Superstructures (1953). $1.25.
Taxation of Motor Vehicles in 1932. 35 cents.
Tire Wear and Tire Failures on Various Road Surfaces (1943). 10 cents.
Transition Curves for Highways (1940). $1.75.

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State Transportation Map series (available for 39 States). Uniform sheets 26 by 36 inches, scale 1 inch equals 4 miles. Shows in colors Federal-aid and State highways with surface types, principal connecting roads, railroads, airports, waterways, National and State forests, parks, and other reservations. Prices and number of sheets for each State vary—see Superintendent of Documents price list 53.
United States System of Numbered Highways together with the Federal-Aid Highway System (also shows in color National forests, parks, and other reservations). 5 by 7 feet (in 2 sheets), scale 1 inch equals 37 miles. $1.25.
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Bibliography on Automobile Parking in the United States (1946).
Bibliography on Highway Lighting (1937).
Bibliography on Highway Safety (1938).
Bibliography on Land Acquisition for Public Roads (1947).
Bibliography on Roadside Control (1949).
Express Highways in the United States: a Bibliography (1945).
Indexes to PUBLIC ROADS, volumes 17–19 and 23.
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DEPARTMENT OF COMMERCE - BUREAU OF PUBLIC ROADS

STATUS OF FEDERAL-AID HIGHWAY PROGRAM

AS OF APRIL 30, 1955

(Thousand Dollars)

STATE	UNPROGRAMMED BALANCES	ACTIVE PROGRAM											
		PROGRAMMED ONLY			PLANS APPROVED, CONSTRUCTION NOT STARTED			CONSTRUCTION UNDER WAY			TOTAL		
		Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles
Alabama	$13,410	$10,778	$5,730	322.9	$4,801	$2,510	48.1	$45,442	$22,874	696.5	$61,021	$31,114	1,067.5
Arizona	3,599	6,696	4,281	134.0	1,090	831	39.4	9,021	6,430	150.0	16,807	11,542	323.4
Arkansas	7,990	11,948	6,499	406.8	5,007	2,652	66.9	18,027	9,003	511.2	34,982	18,154	984.9
California	3,592	25,163	11,016	214.4	6,777	3,458	12.1	131,476	65,208	363.9	163,416	79,682	590.4
Colorado	13,726	2,957	1,737	34.4	3,448	1,854	64.9	17,585	9,733	200.8	23,990	13,324	300.1
Connecticut	15,772	537	268	1.7	2,745	1,364	2.7	11,006	5,294	10.7	14,288	6,926	15.1
Delaware	3,997	1,091	550	15.4	2,302	1,150	4.0	7,298	3,987	29.5	10,691	5,687	48.9
Florida	7,060	25,217	13,089	335.4	2,956	1,495	40.7	27,536	14,141	336.5	55,709	28,725	712.6
Georgia	17,470	11,449	5,804	171.2	6,518	2,843	33.1	54,480	25,735	995.8	72,447	34,382	1,200.1
Idaho	3,517	6,327	3,967	114.9	5,627	3,640	88.9	12,646	7,947	205.3	24,600	15,554	409.1
Illinois	12,195	54,195	30,261	646.6	19,920	10,469	73.5	79,426	41,465	564.7	153,541	82,195	1,284.8
Indiana	13,270	26,150	14,153	104.2	19,353	9,739	105.1	47,162	24,746	143.7	92,665	48,638	353.0
Iowa	7,253	20,561	10,781	969.9	6,520	3,650	100.2	22,587	12,418	808.8	49,668	26,849	1,878.9
Kansas	10,044	13,219	6,766	1,105.9	5,272	2,631	111.7	21,053	10,590	831.1	39,544	19,987	2,048.7
Kentucky	10,598	12,909	6,904	344.6	4,101	2,134	22.8	31,393	15,736	323.5	48,403	24,774	690.9
Louisiana	6,120	17,013	8,506	239.4	13,028	6,514	134.8	30,809	14,242	230.3	60,850	29,262	604.5
Maine	3,934	8,570	4,570	55.4	2,483	1,315	9.8	15,155	7,687	128.8	26,208	13,572	194.0
Maryland	5,780	23,722	12,465	76.6	3,885	1,837	8.2	11,182	5,984	101.2	38,789	20,286	186.0
Massachusetts	15,418	8,099	4,039	30.5	1,806	903		49,372	23,098	45.2	59,277	28,040	75.7
Michigan	12,357	45,773	23,785	654.6	11,764	5,941	140.1	41,535	20,954	340.9	99,072	50,680	1,135.6
Minnesota	11,537	14,866	7,716	859.3	16,174	8,208	1,094.1	16,247	8,740	423.9	47,287	24,664	2,377.3
Mississippi	5,252	16,961	8,036	527.6	5,763	3,025	152.3	23,000	11,820	515.9	45,724	22,881	1,195.8
Missouri	12,657	17,353	8,986	1,027.6	7,792	4,321	41.3	71,801	37,138	1,163.6	96,946	50,445	2,232.5
Montana	12,492	12,800	7,872	262.1	3,668	2,256	121.1	23,265	14,418	459.2	39,733	24,546	842.4
Nebraska	8,605	28,751	15,068	1,092.5	4,486	2,248	91.3	23,602	13,260	628.9	56,839	30,576	1,812.7
Nevada	9,850	1,700	1,421	77.2	2,626	2,322	42.7	6,801	5,557	86.3	11,127	9,300	206.2
New Hampshire	4,490	3,217	1,608	21.7	1,141	732	1.3	6,658	3,252	40.3	11,016	5,592	63.3
New Jersey	18,170	10,744	5,065	75.6	3,562	1,780	6.7	24,891	11,315	33.1	39,197	18,160	115.4
New Mexico	5,587	4,287	2,698	123.2	2,156	1,371	39.0	13,098	8,316	232.0	19,541	12,385	394.2
New York	35,424	50,081	26,254	126.3	24,351	11,829	75.8	202,022	94,748	243.8	276,454	132,831	445.9
North Carolina	10,846	22,714	11,263	449.1	5,009	2,546	85.1	42,525	20,257	572.1	70,248	34,066	1,106.3
North Dakota	2,734	14,744	7,390	1,646.2	10,174	5,259	578.6	5,604	2,804	311.8	30,522	15,453	2,536.6
Ohio	14,439	52,290	26,221	115.8	9,104	4,842	35.2	61,775	28,941	112.5	123,169	60,004	263.5
Oklahoma	20,015	5,854	3,164	185.5	9,008	4,577	125.0	24,350	12,893	337.9	39,212	20,634	648.4
Oregon	7,047	7,133	4,236	105.8	1,130	694	16.5	13,144	8,136	169.8	21,407	13,066	292.1
Pennsylvania	6,905	70,533	36,789	182.2	11,645	5,815	30.5	93,690	46,131	185.4	175,868	88,735	398.1
Rhode Island	3,607	4,854	2,427	7.4	1,138	569	7.8	10,407	5,204	30.3	16,399	8,200	45.5
South Carolina	11,433	8,246	4,502	201.2	1,675	916	9.0	16,811	8,861	285.5	26,732	14,279	495.7
South Dakota	3,770	20,069	11,625	968.5	2,259	1,266	126.0	7,929	4,477	422.8	30,257	17,368	1,517.3
Tennessee	12,409	17,759	8,833	373.7	10,109	5,054	86.7	34,945	15,554	509.5	62,813	29,441	969.9
Texas	26,725	17,067	9,415	323.2	23,110	12,386	195.1	77,180	41,230	1,272.3	117,357	63,031	1,790.6
Utah	1,548	8,457	6,389	158.4	3,618	2,632	50.2	6,543	5,013	105.0	18,618	14,034	313.6
Vermont	3,913	2,189	1,065	33.4	854	439	2.4	7,457	3,714	64.2	10,500	5,218	100.0
Virginia	15,535	10,867	5,369	205.9	3,798	1,885	19.7	20,818	10,260	295.1	35,483	17,514	520.7
Washington	5,770	16,275	9,004	236.5	3,460	2,032	90.9	21,921	11,357	152.0	41,656	22,393	479.4
West Virginia	11,618	10,695	5,427	67.2	3,351	1,698	35.4	14,352	7,190	50.0	28,398	14,315	152.6
Wisconsin	8,421	26,908	13,114	478.8	10,521	5,271	116.8	30,342	15,449	319.6	67,771	33,834	915.2
Wyoming	1,083	8,229	5,333	173.1	3,194	2,142	135.1	9,549	6,043	178.6	20,972	13,518	486.8
Hawaii	3,926	1,722	861	2.5	2,004	1,002	.8	6,034	2,680	15.9	9,760	4,543	19.2
District of Columbia	5,454	5,325	2,662	7.1	439	219	1.2	12,330	5,818	1.6	18,094	8,699	9.9
Puerto Rico	8,408	7,878	3,871	35.6	1,801	863	9.0	12,278	5,430	40.6	21,957	10,164	85.2
TOTAL	496,772	832,942	438,855	16,129.0	318,523	167,129	4,529.6	1,625,560	823,278	16,277.9	2,777,025	1,429,262	36,936.5

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