

A SURVEY OF MEDIAN BARRIERS
AND HIGHWAY SAFETY

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Research Project 78 TI-522
Research Report No. R-1106

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Lansing, January 1979

History

The question of guardrail and median barrier installation at a particular location is complicated by the considerable doubts expressed in the literature as to net safety benefits. In general, it is acknowledged that any barrier, sufficiently strong to contain high velocity impact, is itself a hazard. Therefore, engineers are cautioned as to the complex, 'trade-off' nature of decision making in this area. There are numerous publications issued over the past 20 years that point up the mixed benefit nature of guardrails and median barriers. Generally it is found, particularly with narrow medians, that while fatal accidents remain the same or decrease slightly after barrier installation, injury and property damage accidents substantially increase.

Pennsylvania, for example, found that barrier installation in a narrow (4 to 10 ft) median dividing roadways of high volume (up to 130,000 ADT) seemed to affect fatal accident expectations (four occurring rather than the expected six; a decrease not considered statistically significant) and definitely affected injury and property damage accidents:

In 1964 the Pennsylvania Department of Highways published the technical report "Effects of Guard Rail in a Narrow Median Upon the Pennsylvania Driver." Part II of that report was concerned with a 'before' and 'after' accident study related to the installation of a back-to-back beam-type median barrier. The accident study was based on State Police and City of Philadelphia Police accident reports. It was concluded using police data that in a one-year period before and after installation of the median barrier accident frequencies increased 73 percent and 38 percent in each of two sections studied with a 10 percent increase in volume. (1)

California, in a 1958 study, found that the fatality rate for traversable medians was lower than that for non-traversable medians. In explaining this finding, they say:

On the other hand, the introduction of a physical barrier in a traversable or deterring median reduces the usable width of the median. If this usable width of the median is a factor in the over-all safety of a freeway, it would be a rational explanation of the noted increase in the accident rates with the installation of a barrier. A driver's freedom to maneuver to avoid collision with other vehicles is reduced by a median barrier. There are undoubtedly vehicles which enter and in some cases cross the median and recover without a reportable accident when no barrier is present. More important, perhaps, is the fact that stalled vehicles are observed daily in median areas. (2)

Elsewhere in that study, the authors couch the question of median barriers in the form of a dilemma:

In the basic study it was seen that if past experience is a guide, the installation of positive barriers in 'detering-type' medians, when the volume is less than about 130,000 vehicles per day, would increase not only the total number of accidents, but the number of injuries and fatalities. On the other hand, the fact that, in three years, 19 percent of all fatalities on freeways were caused by cross-median collisions is extremely serious. The question is: would a reduction in the cross-median fatalities, accomplished by installing positive barriers, be accompanied by a rise in other types of fatalities that would more than offset the benefit? (2)

While the question of median width is not addressed, the authors conclude, in general, that barriers may be desirable even though some accident types will be increased by them:

1. The type of median influences the number of accidents on divided highways. On highways with traffic volume between 15,000 and 130,000 vehicles per day, the accident rate was 92 accidents per hundred-million vehicle-miles for earth and low curb medians, and 136 accidents per hundred-million vehicle-miles for the guardrail or concrete-wall-type median. Separate roadways had a rate of 139 in this volume range.
2. Traffic volume appears to be a factor in the relative safety of the various types of medians. Where traffic volumes

were between 15,000 and 130,000 vehicles per day, the non-barrier-type median was superior. Where traffic volumes exceeded 130,000 vehicles per day, the advantage shifted to the non-traversable barrier-type median. (2)

In a later California study, designed to evaluate the effectiveness of barriers installed in the 1960's, Johnson writes that despite a drop in fatal accidents, narrow median roadways with either cable or beam barriers separating high opposing traffic volumes experience a definite rise in barrier-induced accidents:

The effect of median barrier installation on accident rates is indicated by Table 1. Sections of highway where the beam barrier was installed had higher rates in both the before and after periods. Generally the beam barrier has been installed on freeways with narrower medians (less than 16 ft) which also tend to be the older freeways with higher volumes and lower geometric standards with an adverse effect on accident rates.

The rise in accident rates can be attributed primarily to the median barrier installation. The accident rate on all urban freeways has increased slightly during the past few years. However, the accident rate on urban freeways with median barriers has increased more than the statewide average for urban freeways. It is believed that the primary reason for the increase in accident rates is that the median barrier is a fixed object struck by out-of-control vehicles that might have recovered without incident if the barrier had not been installed. (3)

For these types of freeways, even cable barriers increase certain types of accidents over the traversable median:

Injury and fatal accidents combined increased after median barrier installation (Table 1). The beam barrier increases injury and fatal accidents approximately twice as much as does the cable barrier and it is believed that this is the reason for the increased severity.

The ratio of the all accident rate to the injury and fatal accident rate is given in Table 1. The ratios in the before

period are almost equal (2.2:1) and are normal for California freeways. In the after period, the ratio for the beam barrier is considerably lower than that for the cable, which is further evidence that the beam barrier increases the severity of accidents more than the cable barrier. (3)

TABLE 1.
EFFECT OF MEDIAN BARRIER INSTALLATION ON ACCIDENTS

Barrier Type	Length (mi)	MVM	All Accidents				Injury and Fatal Accidents				Ratio ^a
			No.	Rate	Rate Change		No.	Rate	Rate Change		
					Abs.	Percent			Abs.	Percent	
(a) Before Installation											
Cable	26.6	1,195.6	1,586	1.33	---	---	713	0.60	---	---	2.22:1
Beam	27.6	1,633.8	2,690	1.65	---	---	1,204	0.74	---	---	2.23:1
Total	54.2	2,829.4	4,276	1.51	---	---	1,917	0.68	---	---	2.22:1
(b) After Installation											
Cable	26.6	1,277.8	2,231	1.75	+0.42	+32	904	0.71	+0.11	18	2.46:1
Beam	27.6	1,608.5	3,330	1.98	+0.33	+20	1,612	0.96	+0.22	30	2.06:1
Total	54.2	2,958.3	5,561	1.88	+0.37	+25	2,516	0.85	+0.17	25	2.21:1

^a Of all accident rate to injury and fatal accident rate.

In an early California study, traversable (paved or hard earth median), deterring (raised bar and berm, mountable double curb, and earth type), and non-traversable (physical obstruction) medians were compared. It was found that while traversable median accidents tended to be more severe, non-traversable median accidents were more frequent:

When the sample was sorted on the basis of median width, the lowest accident and injury accident rates for deterring medians were definitely in the 4-to-6 ft range. Traversable medians showed lowest total accident rates in the 6-to-10 ft range and lowest injury accident rates in the 20-to-30 ft width group. Widths of non-traversable medians were not significant in this study.

A breakdown on the basis of type of accident shows that approach type accidents are significant only for the undivided highway. Overtaking accidents increase slightly from traversable to non-traversable medians. The single-vehicle-accident rate for non-traversable medians is double that for other types.

On the basis of severity, deterring types of medians are lowest in casualty accidents per MVM, casualties per MVM, and casualties per 100 accidents. Non-traversable medians have markedly higher rates than all other types for casualty accidents and casualties per MVM, but the higher percentage of multiple-vehicle accidents occurring on traversable medians results in this group having the highest number of casualties per 100 accidents. (4)

The authors point out that from the perspective of total accidents, as well as injury accidents, traversable type medians appear superior:

In total accident rates, traversable types of median strips show a substantial advantage with a rate of 0.91 accidents per million vehicle-miles. Detering type medians are second with a rate of 1.00 and the undivided highway at 1.18 exhibited a markedly lower accident rate than the non-traversable group at 1.35 accidents per million vehicle-miles. In injury accidents there was very little difference between deterring and traversable medians with rates of 0.56 and 0.58 per million vehicle-miles, respectively. The undivided followed closely with a rate of 0.62 and non-traversable medians were again last with 0.78 injury accidents per million vehicle-miles. (4)

Finally, in a discussion closure, the authors question the wisdom of median barrier installations available at that time:

It is interesting to note in this connection that the non-traversable medians made a better showing in the higher traffic flows, although the sample was so small as to be merely indicative rather than conclusive.

Our observations over a period of years have tended to support the conclusion that non-traversable medians, or medians which have within their limits such obstacles as trees, power poles, etc., have a tendency toward a higher rate of reported accidents than those medians which are traversable and free of obstacles. It appears that with either the traversable or non-traversable median, substantially the same percentage of vehicles would enter the median for one reason or another. In the case of the non-traversable median, this inadvertent use of the median would result in a reportable accident, whereas, with a traversable median, a

substantial portion of those entering the median would recover control and continue on their way.

The value of a positive barrier may, in some cases, offset the hazard it creates, but our belief is that it is a poor substitute for usable space. (4)

For various median widths and types, a New York study found that, in general, earth type medians appeared to be superior to other median types when using injuries per 100 million vehicles-miles (MVM) as a criterion. Fatalities per MVM could not be readily compared because of small sample sizes:

The severity of accidents for the two types of medians is given in Table 4. Using the number of injuries per 100 MVM of travel as an index of severity, it is seen that both the earth and miscellaneous features medians had the smallest contribution to severity (47) in the deterring group. The curbed median was next with a rate of 55. For the non-traversable type the index of severity ranged from 79 for the double guide rail to 108 for the concrete posts. This concrete posts median index was more than twice that for the deterring. It is also higher than the index for any of the other median subgroups. (5)

TABLE 4
FATALITIES AND INJURY RATES BY TYPE OF MEDIAN
FOR ACCIDENTS BETWEEN INTERSECTIONS

Type of Median	No. All Accidents		Accident Rates Per 100 MVM Travel		
	Injury	Fatalities	Injury Accidents	Injuries	Fatalities
<u>Deterring</u>					
Earth	250	6	28	47	0.67 ^a
Curbed	316	3	40	55	0.38 ^a
Miscellaneous features	31	1	35	47	1.14 ^a
Subtotal	597	10	34	51	0.57
<u>Non-Traversable</u>					
Double guide rail	20	0	16	79	0 ^a
Concrete posts	93	2	70	108	1.51 ^a
Single guide rail	5	0	64 ^a	77 ^a	0 ^a
Guide rail and ditch	2	0	20 ^a	61 ^a	0 ^a
Subtotal	120	2	43	92	0.72 ^a
Total	717	12	35	56	0.59

^a Number of accidents less than 10 for period of study.

Sacks, in a Pennsylvania study conducted in the mid-1960's, found that while barriers on narrow medians eliminated head-on collisions, total accidents—including injury accidents—increased considerably:

Overall accident resumes are presented in Tables 5 and 6. Conventional classification based upon severity suffered by individuals is used to define accident types.

The number of traffic accidents in Contract I increased from 50 before median barrier installation to 87 afterward. Based on the 'before' period, this represents an increase of 74 percent. If it is assumed that accident frequency is linearly influenced by amount of travel (vehicle mileage), then, for a constant roadway length, it is also linearly affected by volume. Thus, for a 10 percent volume increase approximately 55 accidents should have occurred. Therefore, 32 accidents represent a certain deviation from the 'expected norm,' a 64 percent 'abnormal' increase.

The accident frequency increase in Contract II was 112, representing a total percentage increase of 38 percent over the 'before' period. By similar reasoning to that presented above the 'abnormal' increase was 82 accidents or 28 percent. (6)

In conclusion, Sacks states that:

Although the median barrier does eliminate, for all intensive purposes, the accident severity associated with the cross-median fatality, the frequency of injury accidents was found to increase.

'Abnormal' accident frequency increase attributed to the median barrier is found normally distributed throughout all time periods.

Total property damage costs suffered, as well as costs of congestion arising from accidents occurring during peak periods, increased after median barrier construction. (6)

A later Pennsylvania study, covering a 4-ft median with a concrete barrier, did not show that this barrier installation was advantageous from either an injury or fatality point of view:

Accidents were analyzed for a one-year period May 1, 1965, to April 30, 1966, before the box-beam median barrier was installed, and police reports of accidents were analyzed for a one-year period, May 1, 1967, to April 30, 1968, after it was installed. The first year, 1965-1966, will be referred to as the 'before' period, and the second year, 1967-1968, as the 'after' period.

There were a total of 81 accidents reported by the police in the before period, and the ADT was 44,000. In the after period the police reported 93 accidents, and the ADT was 46,000. Volume increased 4.5 percent, whereas accidents increased 14 percent. The severity of these accidents is given in Table 3. The increase in the number of accidents and the reduction in the number of injury accidents are reflected in a 50 percent increase in property damage accidents. The number of persons injured increased 21 percent, though injury accidents were reduced 20 percent. (7)

TABLE 3
ACCIDENT SEVERITY DURING BEFORE
AND AFTER STUDY PERIODS

ADT and Severity	Before (1965-1966)	After (1967-1968)	Percent Difference
Average daily volume	44,000	46,000	+ 4.5
Total accidents	81	93	+14
Fatal accidents	2	2	0
Injury accidents	39	31	-20
Property damage accidents	40	60	+50
Total killed	2	2	0
Total injured	43	52	+21

Median Barrier Installation Practice

Even though the history of median barrier research has not provided clear policy direction, various departments and national highway research organizations have felt the necessity to provide direction in this uncertain, yet urgent, situation (8). Despite accident research in the 1950's and early

1960's, by the year 1967 no understanding of guardrail benefits had emerged which would guide decision making in any but the most obvious cases.

Operational experience with cable-chain link fence and double blocked-out beam median barriers reported by the State of California shows that although both types have been effective in reducing the frequency of cross-median accidents, the rate of accidents involving the median has increased at locations where barriers have been installed. An increase in accident frequency after median barrier installation was also revealed in before-and-after studies in Pennsylvania. The California studies revealed that, for the most part, both types of barriers were performing effectively, but that the cable-chain link fence median barriers were sometimes penetrated or vaulted in areas where it was installed on saw-tooth-type medians. Another observed undesirable characteristic of the cable-chain link median barrier is that the impacting vehicles frequently undergo rather violent spinouts that can cause the occupants to be ejected and to thereby be exposed to greater danger. (9)

By 1968, median barrier 'warrants' were considered in the NCHRP state-of-the-art literature. Apparently these warrants were based on California's policy, although no references or supporting research was cited. However, doubts concerning the wisdom of guardrail installation remained, as seen in NCHRP Report No. 54 (1968):

Even properly designed guardrail and median barrier installations are formidable roadside hazards and provide errant vehicles with only a relative degree of protection. Although guardrail and median barrier installations should decrease accident severity, frequency of accident occurrence may increase with the added installations. This is because the guardrail/barrier system is usually a larger target and is located closer to the roadway than the roadside hazard itself. For this reason, guardrail and median barrier installations should be kept to a minimum, and highway designers should consider such installations only where they are clearly justified. Where guardrail and median barrier requirements are indicated, the designer should examine the roadway to determine the feasibility of adjusting site

features so that guardrails will not be required (e. g., flattening an embankment slope or removing a tree). For borderline warranting cases, the action guideline is: When in doubt, omit the guardrail or median barrier. (10)

At about this time, the Organization for Economic Co-operation and Development reviewed worldwide guardrail practice and in a discussion of median warranting in the United States concluded:

Where median width is the only factor considered it is doubtful if barriers are justified in medians wider than about 25 feet, since the possible hazard of a vehicle crossing a relatively wide median and colliding with a vehicle in the opposite roadway must be weighed against the increased hazard of reducing to less than half the manoeuvring space within the median. Traffic volume is also important, however, because the probability of both crossing the median and of striking a vehicle in the opposite roadway increases as the product of the two flows. (11).

By 1971, the situation had not changed, at least as far as the NCHRP literature reviews were concerned. Michie, Calcote, and Bronstad reiterate the apparent California warranting formula again with the same proviso:

A basic aspect of the guardrail and median barrier technology is identification of locations along highways where protective installations are needed. Specific decision criteria to use a guardrail or median barrier in a given location are referred to as warrants. An ideal guardrail system—that is, one that safely redirects errant vehicles without endangering other traffic and without causing injuries or fatalities among the occupants—would improve safety at most highway sites, with the possible exception of those with flat embankments that are clear of obstacles. However, such ideal systems do not exist; guardrail and median barrier systems are intrinsic roadside hazards and provide the errant vehicles with only a relative degree of protection.

Many existing installations are more hazardous than the roadside condition and may increase rather than reduce severity of ran-off-the-road accidents at a given site. For the period 1965-67, the California Highway Traffic Department has

shown that in 33.8 percent of freeway fatal accidents involving single vehicles, the vehicles hit off-road fixed objects. Furthermore, 34.6 percent of these off-road fixed object fatal accidents involved a highway guardrail; therefore, it can be concluded that 11.7 percent* of single vehicle fatal accidents involved a barrier. From statistics compiled by Hosea on completed sections of the Interstate System for 1968, the percentage of single-vehicle fatal accidents involving guardrail and median divider—364 and 71 accidents, respectively—is determined to be 23.6 percent* (i. e. , 435 out of 1,842 single-vehicle accidents). Although these accident statistics reflect performance of adequate as well as unsatisfactory barrier designs, the fact remains that highway barrier installations constitute a major roadside hazard. For this reason, highways should be designed with the specific intent of eliminating, or at least minimizing, the use of barrier systems, and at the same time upgrading the performance and functional capabilities of existing installations.

At some locations, guardrails and median barriers may decrease accident severity, but accident frequencies actually increase because these systems usually constitute larger targets and are located closer to traffic than a roadside hazard. This aspect adds to the basic concept that guardrails and median barriers should be kept to a minimum. Accordingly, highway designers are well advised to examine the feasibility of adjusting site features (e. g. , flattening an embankment slope or removing a tree) so that such installations will not be required. (12) See also (13).

* Discrepancy between these figures (i. e. , 11.7 versus 23.6) is attributed in large part to definition of single- and multi-vehicle accidents.

The Transportation Research Board recommendations of that time are presented in HRB Special Report 81 (14), but appear to reiterate the previously mentioned California practice. To this day, the research substantiating the California practice has not been published in any standard journal in the field. Thus, one cannot, through use of the standard literature, evaluate any California findings used to rationalize the state's median barrier policies.

Aside from the desirability of publishing barrier warrant research, it is essential that the safety criterion used as a warranting basis be widely understood. There are many criteria by which highway safety can be optimized. However, they may not all indicate the same response to a hazard.

NCHRP Report No. 148 surveys several potential criteria:

As previously mentioned, any one of several different accident severity indices can be selected, depending on the objective of the roadside safety improvement program. The severity index is a numerical weighting scheme that ranks roadside obstacles by degree of accident consequence.

Generally, a safety improvement program is aimed at reducing total fatalities, injuries, and property damage. Therefore, any improvement program that assigns higher weights to the more severe accidents will tend to satisfy these aims. Basically, severity indices applied to obstacles could be based on any of the following measures:

1. Average property damage cost per accident.
2. Average direct cost per accident (includes property damage, hospitalization, insurance premiums, funeral expenses).
3. Average total cost per accident (in addition to direct cost, the total cost includes loss of future earnings and values for human suffering).
4. Average number of fatalities per accident.
5. Average number of fatal and nonfatal injuries per accident.
6. Proportion of fatal accidents.
7. Proportion of fatal and nonfatal injury accidents.

Severity indices are used solely for comparative purposes—for instance, comparison of the accident consequences of protective guardrail with those of bridge abutments. Because the severity indices for these obstacles are computed from historical accident data, the precision of the weighting scheme will depend on the accuracy and availability of accident records for each obstacle.

Fatal accidents are rare occurrences. They are rare enough that large volumes of accident data are needed to render the

proportion of fatal accidents statistically reliable. As indicated in Appendix A, large volumes of accident data are not generally available for all types of roadside hazard situations. Therefore, even if a specific program objective is to reduce fatalities or fatal accidents, weighting scheme measures (Nos. 1, 2, 3, 4, and 6) that give greater weight to fatal accidents than injury accidents will not necessarily be more successful in achieving that objective.

For a comprehensive program on roadside safety improvement, the weighting scheme that ranks the severity of obstacles on the basis of the proportion of fatal and nonfatal injury accidents associated with each obstacle is recommended. This measure is used in this report. (15)

Median Barrier Warranting Criteria

The research literature cited suggests that barriers installed in narrow medians of high traffic volume roadways may slightly decrease fatalities resulting from head-on collisions, but will also produce a substantial increase in property damage and injury accidents. This injury accident increase is generally substantial enough to be considered statistically reliable, whereas this is not the case with fatality reductions. If the safety criterion selected is fatality reduction, median barriers may or may not be justified for these particular highway configurations. On the other hand, if, as recommended in the NCHRP report on fixed object accidents (No. 148), the combined injury-fatal accident rate is selected, then median barrier probably would not be justified even for the narrowest of medians. The problem is that median safety policy depends not only on data but on definition; namely, the accident statistic selected as criterion.

While the standard literature does not make it clear, California probably uses an accident index developed from an economic assessment of each

accident type for median barrier warranting (16, 17, 18). As of the early 1960's, the relative cost, according to an Illinois study (19), of fatal, injury, and property damage accidents was 25, 6, and 1, respectively (figures adjusted to California's experience). This is an attempt to weight each type of accident—not by pain or other human consequences—but by relative dollar costs. The attractiveness, if not the virtue, of this measure is its computational ease.

Because accident criteria and measurement indices are necessarily based on value considerations, it should be abundantly clear that no highway department should adopt guardrail warrants based on California's or any other measure unless it is in full agreement with that measure as a matter of public policy.

We have seen that 'before and after' empirical examinations of median barrier installations leave doubt as to the circumstances under which these installations provide clear safety benefits. It appears that high traffic volume roadways, separated by narrow medians require barriers, at least from an injury accident perspective. Yet, 'high traffic volume' and 'narrow' remain undefined over the range of traffic and width combinations encountered in practice. Uncertainty is exacerbated by the absence of a standardized safety benefit measure. Injuries, injury accidents, fatalities, and fatal accidents all used singly and in both simple and economically weighted combinations have served as the crucial safety statistic. Unfortunately, the decision to install median barriers takes on a certain arbi-

rariness as it depends upon which statistic is selected. These problems are not endemic, but result from examinations curtailed by insufficient and consequently unreliable cross-median fatality data and by the inability to control those variables of vital research interest.

In view of the deficiencies of empirical examination, it is desirable that we strengthen our understanding particularly of the effects of traffic volume and median width. Improved understanding can be obtained from a theoretical analysis of the relative risks of the barrier—no barrier alternatives. The analysis can take the form of a model which predicts cross-median collisions without barrier, and single vehicle accidents with barrier in place. This is the approach we have undertaken. The model is designed to predict accident occurrence with and without median barrier for any combination of traffic volume and median width. The estimated barrier—no barrier accident ratios together with any one of the aforementioned accident statistic measures (severity) can then be used to assess the effectiveness of barrier installations.

COLLISION PROBABILITY MODEL

The review of research literature on the safety advantages of median barriers indicated that the installation of a barrier is often not unambiguously supported by the accident statistics, even if the safety criterion was agreed upon. It is in this context that we feel a theoretical approach is appropriate.

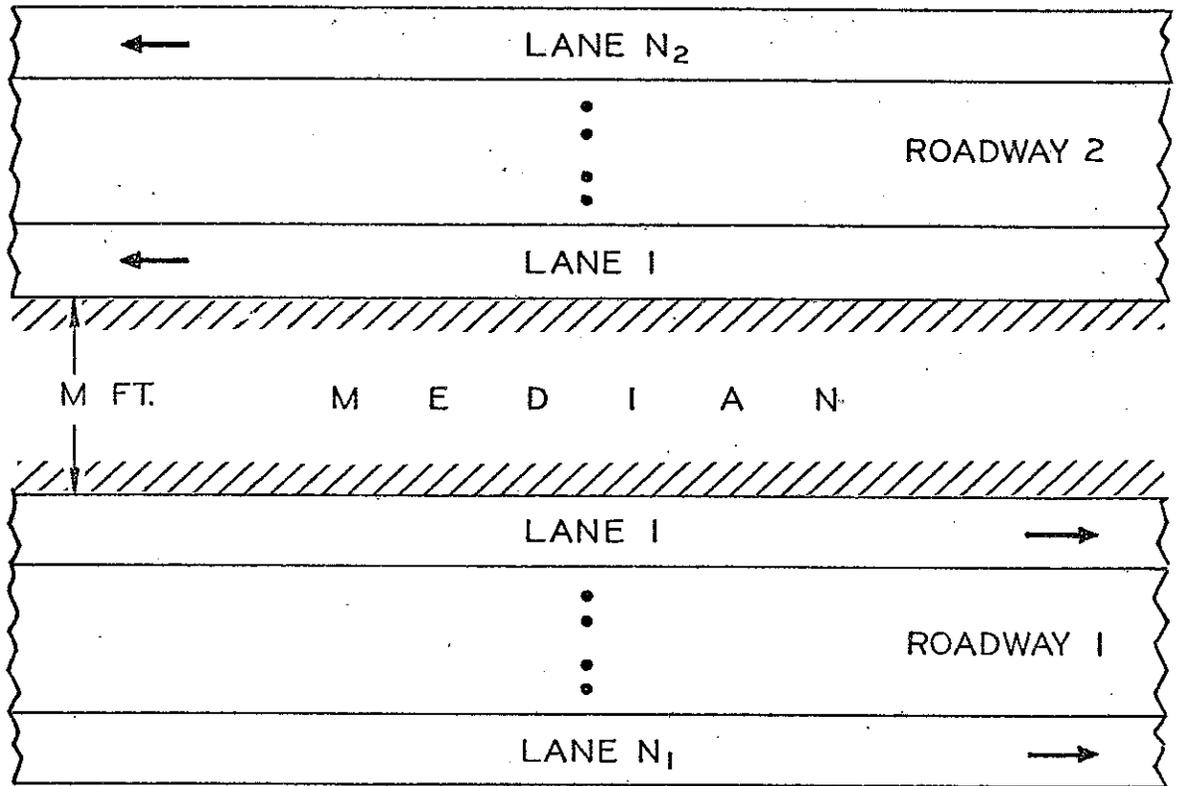


Figure 1. The roadway system in concern.

Fixed-object accident models have been prepared in the past in an attempt to rationalize guardrail warrants (15). However, no moving object collision model is currently available in the literature. Our development is similar in approach to the fixed-object model presented in NCHRP Report No. 148, but since moving objects raise additional analytical problems, we found it necessary to devise a more elaborate treatment.

Consider two opposing roadways identified as Roadway 1 and 2, separated by a median of M ft. Roadway i has N_i lanes, $i = 1, 2$, as shown in Figure 1. In order to evaluate the net safety benefit of median barrier installation, it is essential to know, for a given vehicle encroaching onto the median, the following probabilities:

a) The probability P_B that the encroaching vehicle will be involved in an accident with a barrier installed at M_i ft from the edge of Roadway i , $i = 1, 2$. Note that $M_1 + M_2 = M$.

b) The probability P_H that, if no barrier is installed between the roadways, the encroaching vehicle will cross over the median and collide with a vehicle in the opposite roadway.

Before we proceed to develop a probability model for computing P_B and P_H defined in a) and b), respectively, we present for the reader's convenience, the notation to be used throughout.

Θ : the vehicle encroachment angle onto the median.

Y_Θ : the maximal lateral encroachment distance of a vehicle encroaching onto the median with angle Θ .

X_Θ : the longitudinal distance, corresponding to Y_Θ , of a vehicle encroaching onto the median with angle Θ .

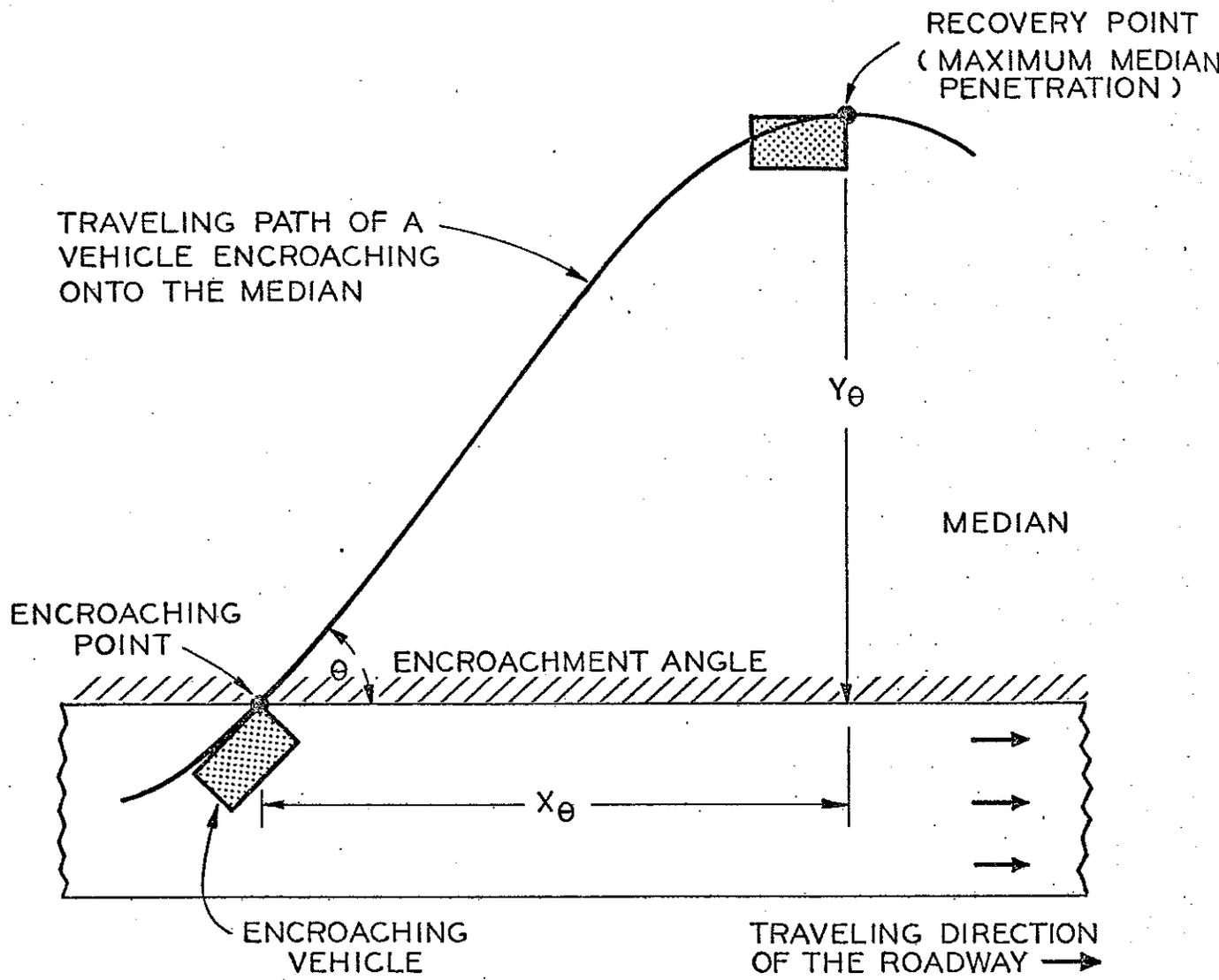


Figure 2. Illustration of a vehicle encroaching onto the median.

G : the probability distribution function of the encroachment angle θ .

F_θ : the probability distribution function of Y_θ .

E_i : the probability that a vehicle traveling on Roadway i will encroach onto the median.

The definitions of θ , Y_θ and X_θ can be readily understood by reference to Figure 2. We are now ready to discuss the probability model for computing P_B and P_H .

Collision Probabilities

Case 1: Barrier in Median

Given that a vehicle from Roadway i , $i = 1, 2$; has encroached onto the median, this vehicle will strike the barrier installed at M_i ft from the edge of Roadway i if the maximal lateral encroachment distance is greater than M_i . That is, the probability $P_B^{(i)}$ that this encroachment will strike the barrier is:

$$P_B^{(i)} = \int_{\theta} \int_{y=M_i} dF_\theta(y) dG(\theta) \quad (1)$$

Since the barrier can be struck by a vehicle from either roadway, we have

$$P_B = \sum_{i=1}^2 E_i P_B^{(i)} \quad (2)$$

We note from Hutchinson and Kennedy's study (20), E_i is a sectionally linear function of the average daily traffic volume of Roadway i . Thus, if two roadways have equal traffic volumes, $E_1 = E_2 = 1/2$. Using encroachment frequencies obtained from (20) we may evaluate the integrand (Fig. 3).

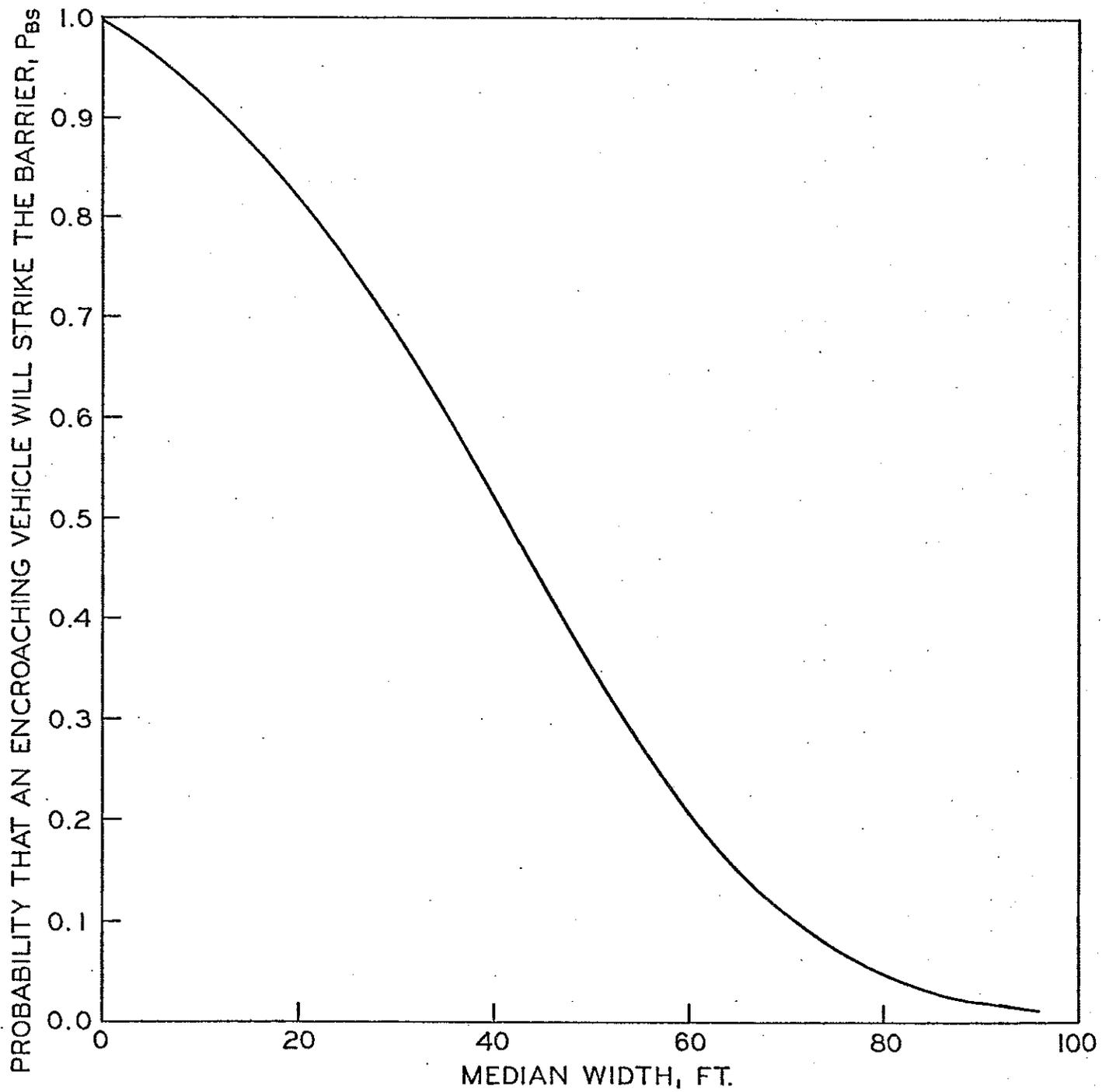


Figure 3. The probability that an encroaching vehicle will strike the median barrier.

Case 2: No barrier in median

Given that a vehicle from Roadway i has encroached onto the median, the probability $P_H^{(i)}$ that this encroachment will result in a collision with a vehicle traveling on the opposite roadway is:

$$P_H^{(i)} = \int_{\theta} \int_M C_j(M, y_{\theta}) dF_{\theta}(y) dG(\theta) \quad (3)$$

where $j = 3 - i$ and $C_j(M, y_{\theta})$ is the probability that a vehicle on a trajectory of maximal lateral encroachment Y_{θ} will collide with a vehicle traveling on Roadway j . Again, because of encroachments from both roadways, we have:

$$P_H = \sum_{i=1}^2 E_i P_H^{(i)} \quad (4)$$

In order to compute P_B and P_H , we need to know G , F_{θ} , E_i , and $C_i(M, y_{\theta})$ defined in (1) through (4). In the following sections, we shall demonstrate how G and F_{θ} can be obtained from survey data $(\theta, Y_{\theta}, X_{\theta})$ provided by Hutchinson and Kennedy (20).

Encroachment Angle Distribution

We first convert the observed θ into the empirical cumulative distribution $\bar{G}(\theta)$. It is clear graphically that $\bar{G}(\theta)$ is a distribution of the gamma type. Thus, we use G defined as

$$G(\theta) = \int_0^{\theta} \frac{1}{\Gamma(\alpha)\beta^{\alpha}} \theta^{\alpha-1} e^{-y/\theta} dy \quad (5)$$

to fit the empirical distribution \bar{G} . Therefore, we estimate α and β in the

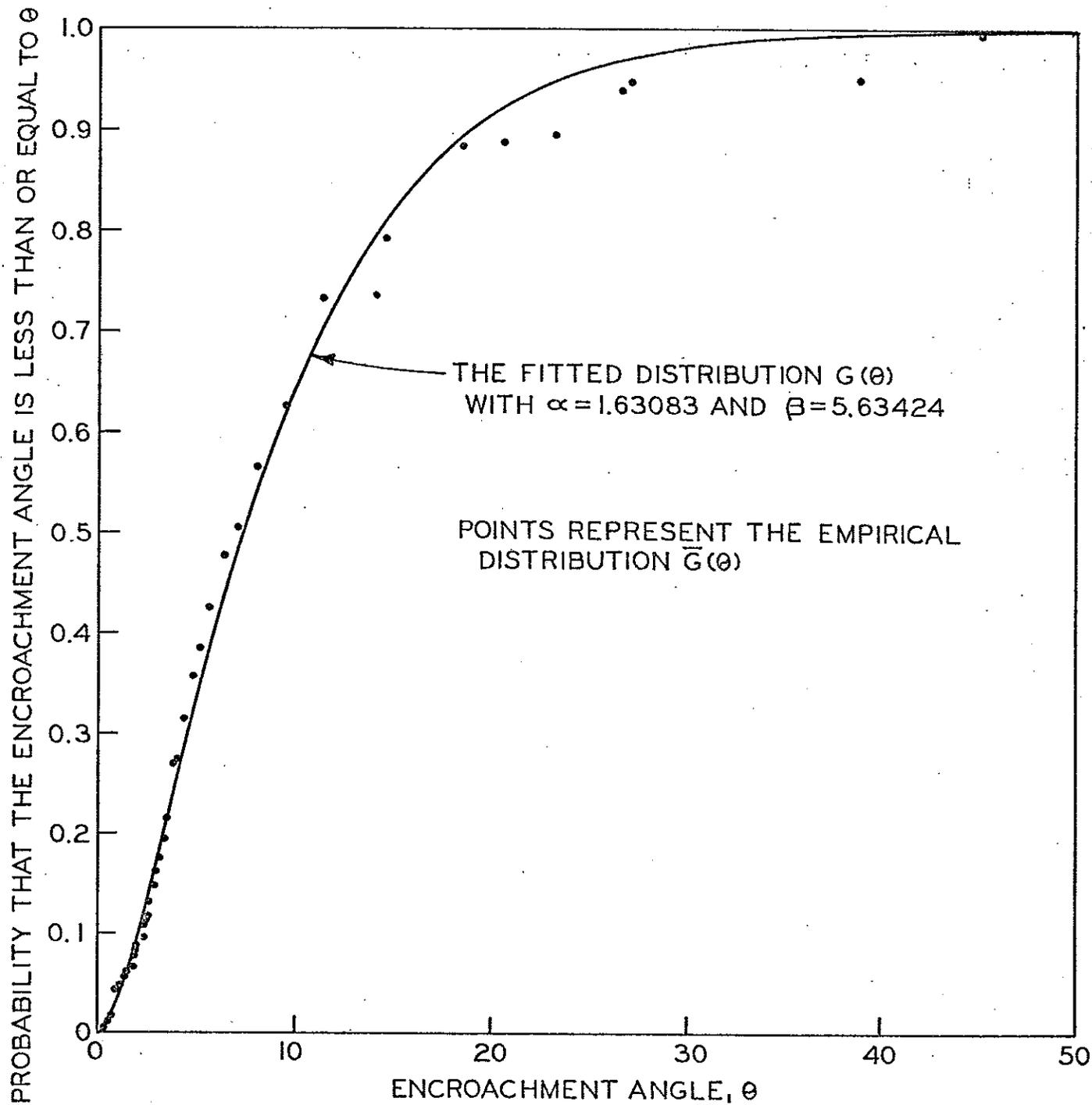


Figure 4. The empirical and fitted distributions of the encroachment angle θ .

sense that $\sum_i [G_i(\theta) - \bar{G}(\theta)]^2$ is minimal. Using a non-linear least squares computer program and a gamma distribution subroutine (21), we find that $\alpha = 1.63083$ and $\beta = 5.63424$. The fitted and empirical distributions of the encroachment angle θ are presented in Figure 4.

The above fitting is acceptable in the sense that the Kolmogorov-Smirnov test does not reject the null hypothesis that the encroachment angle was sampled from a population having the distribution G specified in (5) with parameters $\alpha = 1.63083$ and $\beta = 5.63424$.

The Conditional Probability Distribution Function F_θ of the Maximal Lateral Encroachment Distance, Given that the Encroachment Angle is θ

Since the number of observations on Y_θ for a given encroachment angle θ is not large enough to obtain a reliable empirical distribution of Y_θ , we use observations on Y_θ for θ in a given interval $I = (\theta_1, \theta_2)$ to obtain the empirical distribution denoted by $\bar{F}(y/\theta \text{ in } I)$ for the purpose of approximating $F_\theta(y)$. The interval size is chosen as small as possible, but contains enough observations to obtain a reliable empirical distribution. This empirical distribution is then fitted by $F(y/\theta \text{ in } I)$ defined as

$$F(y/\theta \text{ in } I) = \frac{1}{G(I)} \int_{\theta_1}^{\theta_2} F_\theta(y) dG(\theta) \quad (6)$$

where G was defined in (5) with $\alpha = 1.63083$ and $\beta = 5.63424$ and $F_\theta(y)$ is to be specified.

By the well-known mean-value theorem, there exists an angle δ , depending on I and y such that

TABLE 1
 THE FITTED PARAMETERS OF $F(y/\theta \text{ in } I)$
 FOR VARIOUS INTERVALS $I = (\theta_1, \theta_2)$

θ_1	θ_2	Average θ in I	Fitted Parameters	
			μ_{θ} in I	σ_{θ} in I
0.00	1.10	0.854	8.75556	13.79640
0.00	1.90	1.186	8.80056	15.39680
0.00	2.30	1.367	8.72961	15.98530
1.10	2.30	1.843	4.62786	23.23010
1.90	2.90	2.521	15.39470	15.62440
2.30	2.90	2.650	18.15080	14.14130
2.30	3.40	2.925	22.27920	10.30130
2.90	3.40	3.200	22.91880	7.83612
2.90	3.80	3.533	17.76600	10.08370
3.40	4.10	3.761	12.81340	10.41560
3.80	5.20	4.728	20.54350	11.49310
4.10	4.80	4.617	20.73780	12.60750
4.10	5.20	4.748	21.14960	11.14460
4.40	6.40	5.600	17.08210	12.19330
4.80	5.70	5.516	15.73870	8.75378
5.20	6.40	6.089	13.67130	10.27880
5.70	6.40	6.400	9.95238	15.88370
5.70	7.10	6.643	12.81550	12.15330
6.40	8.10	7.780	19.30110	10.21000
6.40	9.50	8.476	20.60220	10.97330
7.10	11.30	9.992	21.68550	11.63890
7.10	18.40	12.721	22.36580	11.39600
7.10	20.60	12.794	22.38760	11.23690
7.10	23.20	12.981	22.42780	11.07010
7.10	27.00	14.609	23.21420	11.10810
8.10	9.50	9.500	20.69990	9.94794
8.10	18.40	13.585	22.26650	11.81360
8.10	20.60	13.661	22.29930	11.60900
8.10	23.20	13.864	22.35470	11.39270
8.10	27.00	15.624	23.29400	11.40930
9.50	9.50	9.500	20.69990	9.94794
9.50	14.50	12.423	21.25520	12.26010
9.50	18.40	14.523	22.27660	11.52090
9.50	20.60	14.604	22.30970	11.29090
9.50	23.20	14.827	22.36260	11.06370
9.50	27.00	16.755	23.43800	11.12620
11.30	14.50	14.471	21.35750	12.25840
14.00	20.60	17.000	22.87030	10.90850
14.50	23.20	18.807	23.37310	8.73342
14.50	27.00	21.482	25.06230	9.19946
18.40	45.00	34.078	26.85110	8.12058
10.60	45.00	34.513	27.11420	8.39423
20.60	90.00	36.247	27.12670	8.06347
23.20	27.00	26.653	28.06220	9.11606
23.20	45.00	35.293	27.51020	8.43546
23.20	90.00	37.117	27.49430	8.06662
26.60	45.00	42.356	26.25380	8.14392
26.60	90.00	45.159	26.60290	7.91612
27.00	90.00	47.580	26.65850	7.63441
45.00	45.00	45.000	25.41430	7.22221

$$F(y/\theta \text{ in } I) = F_{\delta}(y) \quad (7)$$

If the interval I is not large, δ might not vary significantly. In this situation, the empirical distribution $\bar{F}(y/\theta \text{ in } I)$ can be considered as the empirical distribution of Y_{δ} . By examining empirical distributions of Y_{θ} for θ in various intervals, we find that $\bar{F}(y/\theta \text{ in } I)$ takes the form of a normal distribution and is skewed when the end points of I are small. That is, $\bar{F}(y/\theta \text{ in } I)$ can be approximated by $F_{\delta}(y)$, for some δ in I , which is either gamma distributed with parameters α_{δ} and β_{δ} can be defined as:

$$F_{\delta}(y) = \frac{N(y; \mu_{\delta}, \sigma_{\delta}^2) - N(0; \mu_{\delta}, \sigma_{\delta}^2)}{1 - N(0; \mu_{\delta}, \sigma_{\delta}^2)} \quad (8)$$

where $N(y; \mu_{\delta}, \sigma_{\delta}^2)$ is a normal distribution with mean μ_{δ} and variance σ_{δ}^2 . It turns out that the distribution $F_{\delta}(y)$ defined in (8) fits empirical distributions reasonably well. The fitted results for various chosen intervals are presented in Table 1. For the purpose of finding functional forms of μ_{θ} and σ_{θ} , we use the average of angles in I as the δ defined in (7). That is, $\mu_{\theta \text{ in } I} = \mu_{\delta}$ and $\sigma_{\theta \text{ in } I} = \sigma_{\delta}$. We then plot (δ, μ_{δ}) , $(\delta, \sigma_{\delta}^2)$ and $(\mu_{\delta}, \sigma_{\delta}^2)$ in Figures 5, 6, and 7, respectively. We see from these figures that μ_{δ} and σ_{δ}^2 can be described by any one of the following functions:

$$\begin{aligned} \mu_{\delta} &= a_1 - a_2 e^{-a_3 \delta} \\ \mu_{\delta} &= a_1 + a_2 \delta + a_3 \delta^2 \\ \mu_{\delta} &= a_1 + a_2 \delta^{a_3} \end{aligned} \quad (9)$$

and

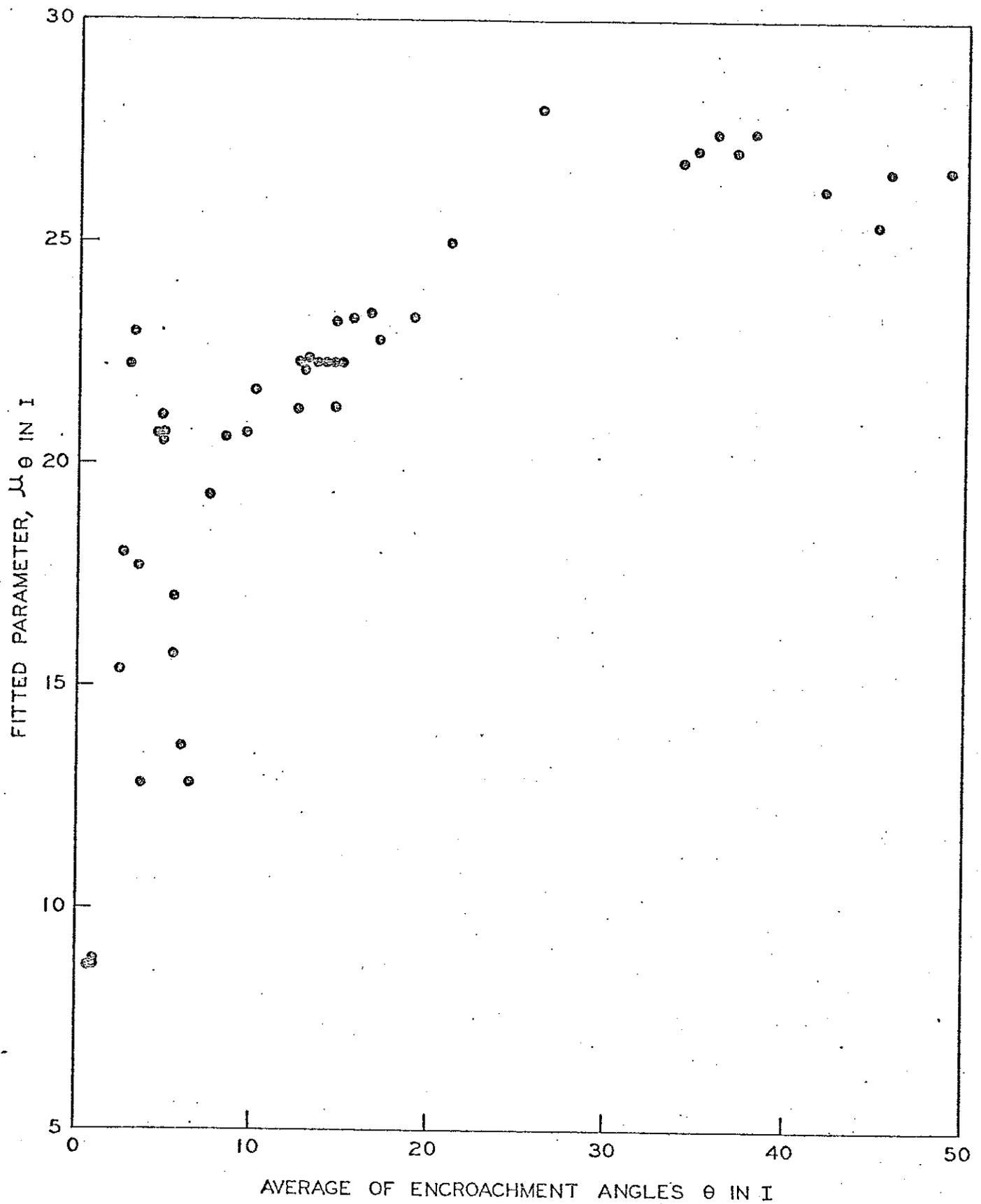


Figure 5. Relationship of the fitted parameter $\mu_{\theta \text{ in } I}$ and the average of encroachment angles θ in I for various intervals I.

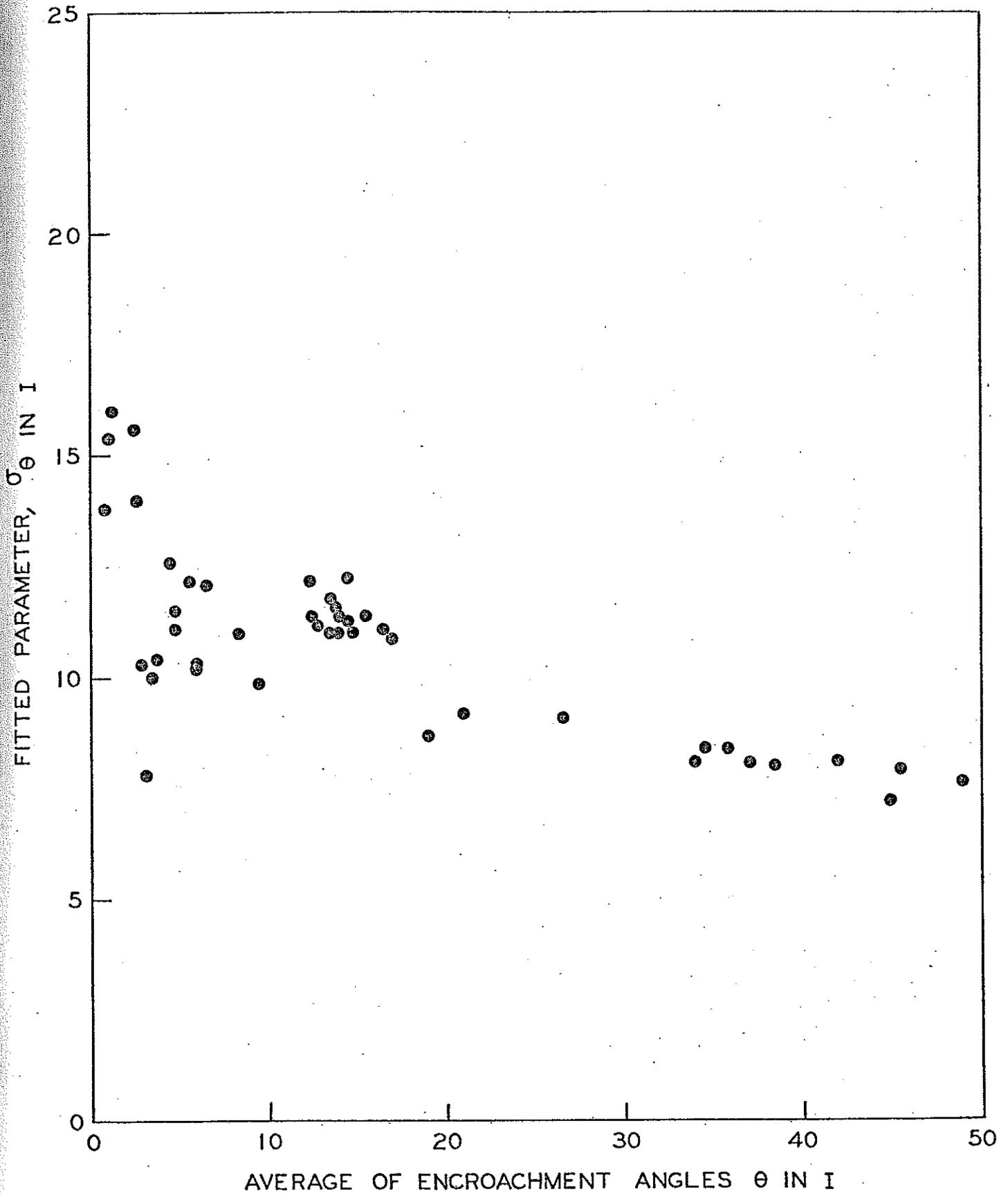
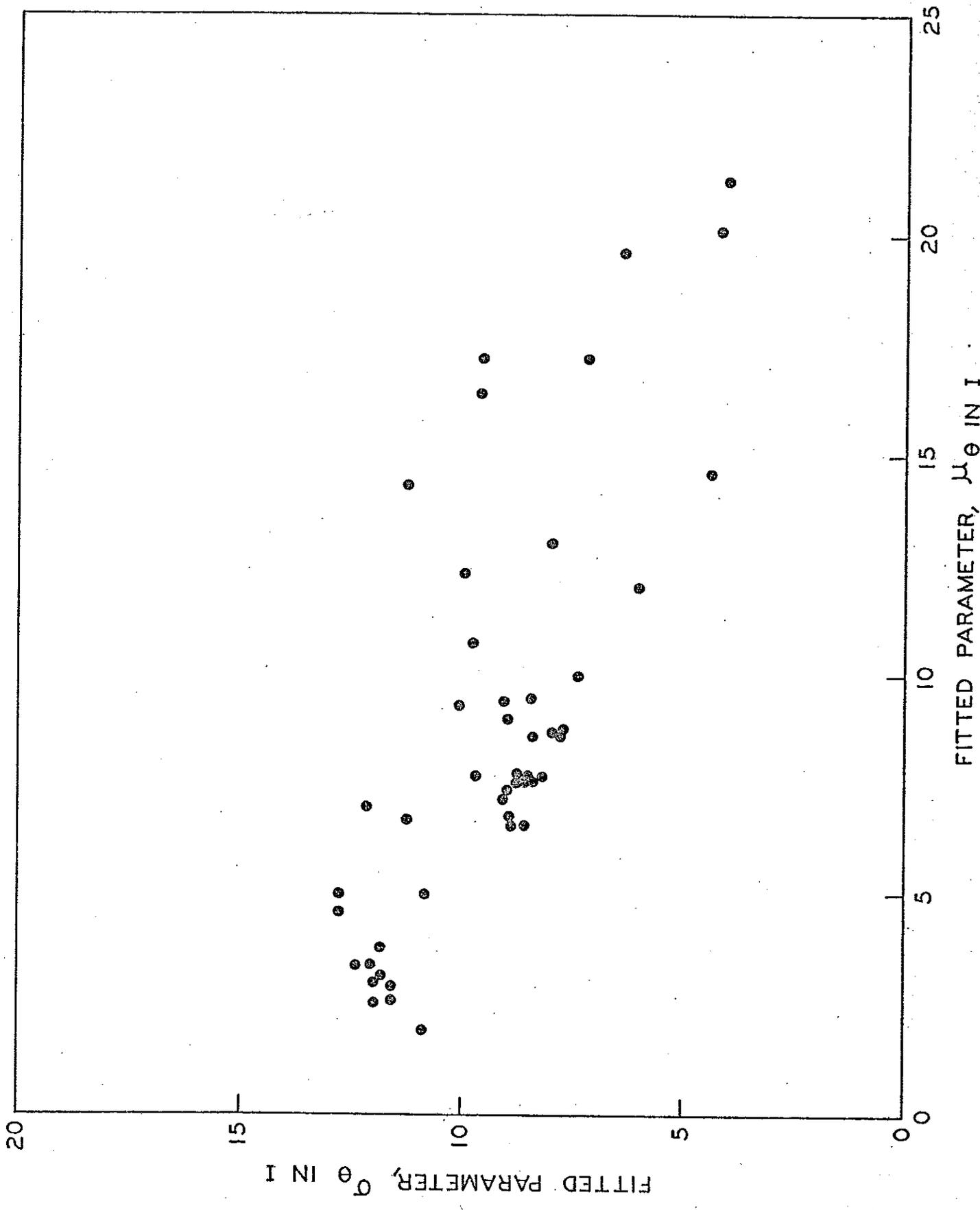


Figure 6. Relationship of the fitted parameter σ_{θ} in I and the average encroachment angles θ in I for various intervals I.



$$\begin{aligned}\sigma_{\delta} &= b_1 e^{-b_2 \theta} \\ \sigma_{\delta} &= b_1 - b_2 \mu_{\delta}\end{aligned}\quad (10)$$

To estimate coefficients of μ_{δ} and σ_{δ} , we first partition θ observations into nine mutually exclusive intervals in which sample sizes are large enough to obtain a reliable empirical distribution of Y_{θ} for θ in various intervals. Then, we use the distribution defined in (6) to fit nine empirical distributions simultaneously. Among those functional forms of μ_{θ} and σ_{θ} defined in (9) and (10), we conclude that $F_{\theta}(y)$ defined in (8) with parameters μ_{θ} and σ_{θ} estimated as

$$\mu_{\theta} = 26.8841 - 16.9943 e^{-0.103498\theta} \quad (11)$$

and

$$\sigma_{\theta} = 22.417 - 0.539499 \mu_{\theta} \quad (12)$$

fits empirical distributions the best. Again, the above fitting is acceptable in the sense that the Kolmogorov-Smirnov test does not reject the null hypothesis at the 0.05 significance level that the data for maximal lateral encroachment distances were sampled from a population having the distribution $F(y)$ defined as

$$F(y) = \int_{\theta} F_{\theta}(y) dG(\theta) \quad (13)$$

where $F_{\theta}(y)$ was defined in (8) with parameters μ_{θ} and σ_{θ} defined in (11) and (12), respectively.

It can be shown that the mean and variance of Y_{θ} are, respectively,

$$E(Y_{\theta}) = \mu_{\theta} + \sigma_{\theta} W(\theta) \quad (14)$$

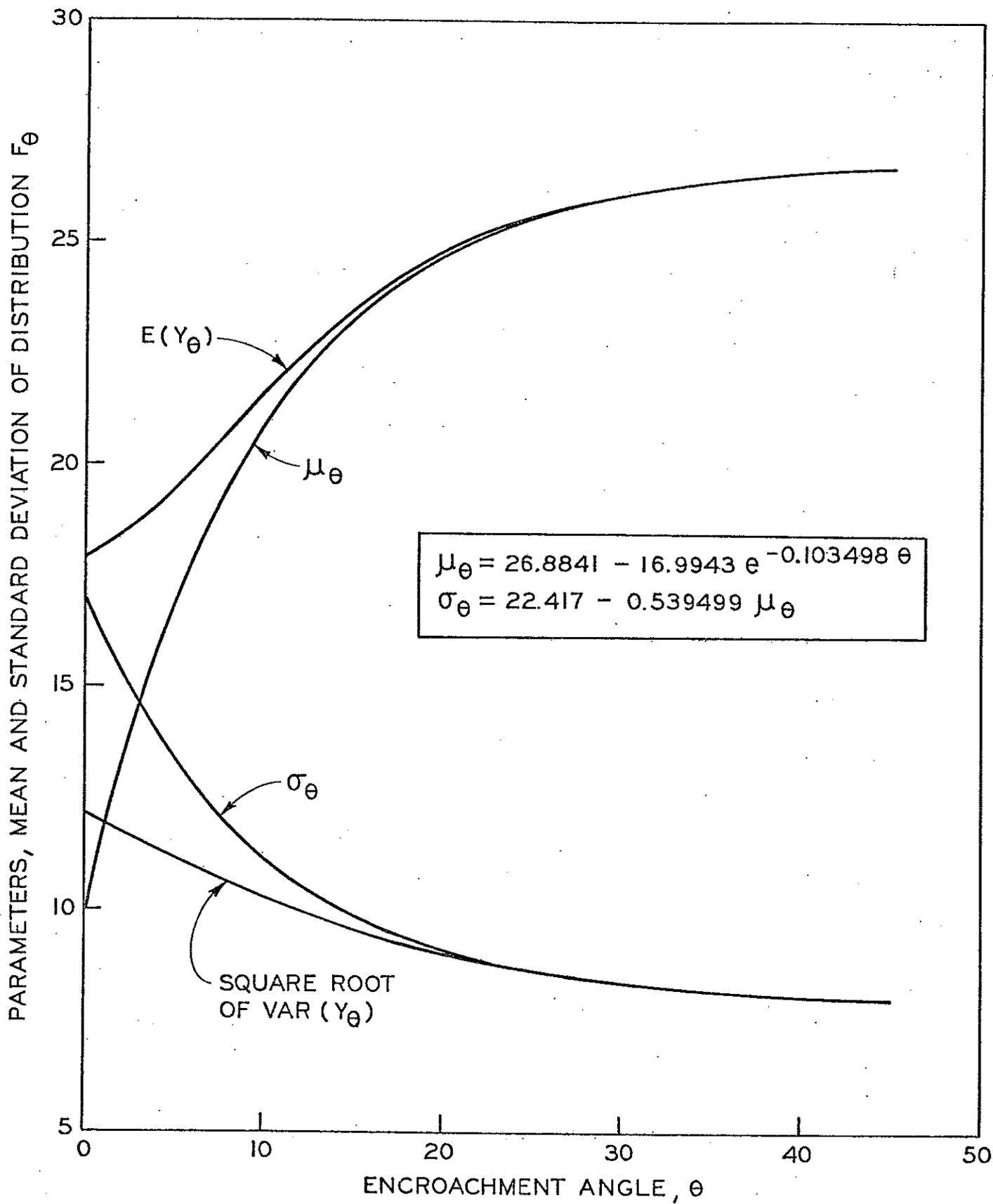


Figure 8. Parameters, mean and standard deviation of distribution F_θ .

and

$$\text{Var}(Y_\theta) = \sigma_\theta^2 \left[1 - W(\theta) \frac{\mu_\theta}{\sigma_\theta} - W^2(\theta) \right] \quad (15)$$

where

$$W(\theta) = \frac{1}{1 - N(0; \mu_\theta, \sigma_\theta)} \cdot \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{\mu_\theta}{\sigma_\theta} \right)^2} \quad (16)$$

These are plotted as a function of θ in Figure 8.

Once $G(\theta)$ and $F_\theta(y)$ are defined, $P_B^{(i)}$ defined in (1) can then be computed. However, we must still determine $C_j(M, y_\theta)$ in order to compute $P_H^{(i)}$ defined in (3). This is discussed in the following section.

Collision Probability with Vehicles Traveling on Opposite Roadways

Given that a vehicle enters the opposite roadway, what is the probability that it will collide with a vehicle traveling on this roadway? In general, the longer time the encroaching vehicle travels on the opposite roadway, the higher the probability that this vehicle will collide with another vehicle. If the traveling path of the encroaching vehicle is known, the total time t_j during which the encroaching vehicle travels on Roadway j , and, hence, is exposed to a multi-vehicle collision can be determined. A vehicle entering the opposite roadway will first conflict with the traffic stream of the lane nearest the median. Then, if the encroaching vehicle manages to penetrate the next lane, it will conflict with the traffic stream of this lane and so on, depending on Y_θ . Thus, t_j can be broken down into many time components $t_{j, k}$, $k = 1, 2, \dots$, such that for each time component indexed by k , the encroaching vehicle conflicts with (is exposed to) the traffic stream charac-

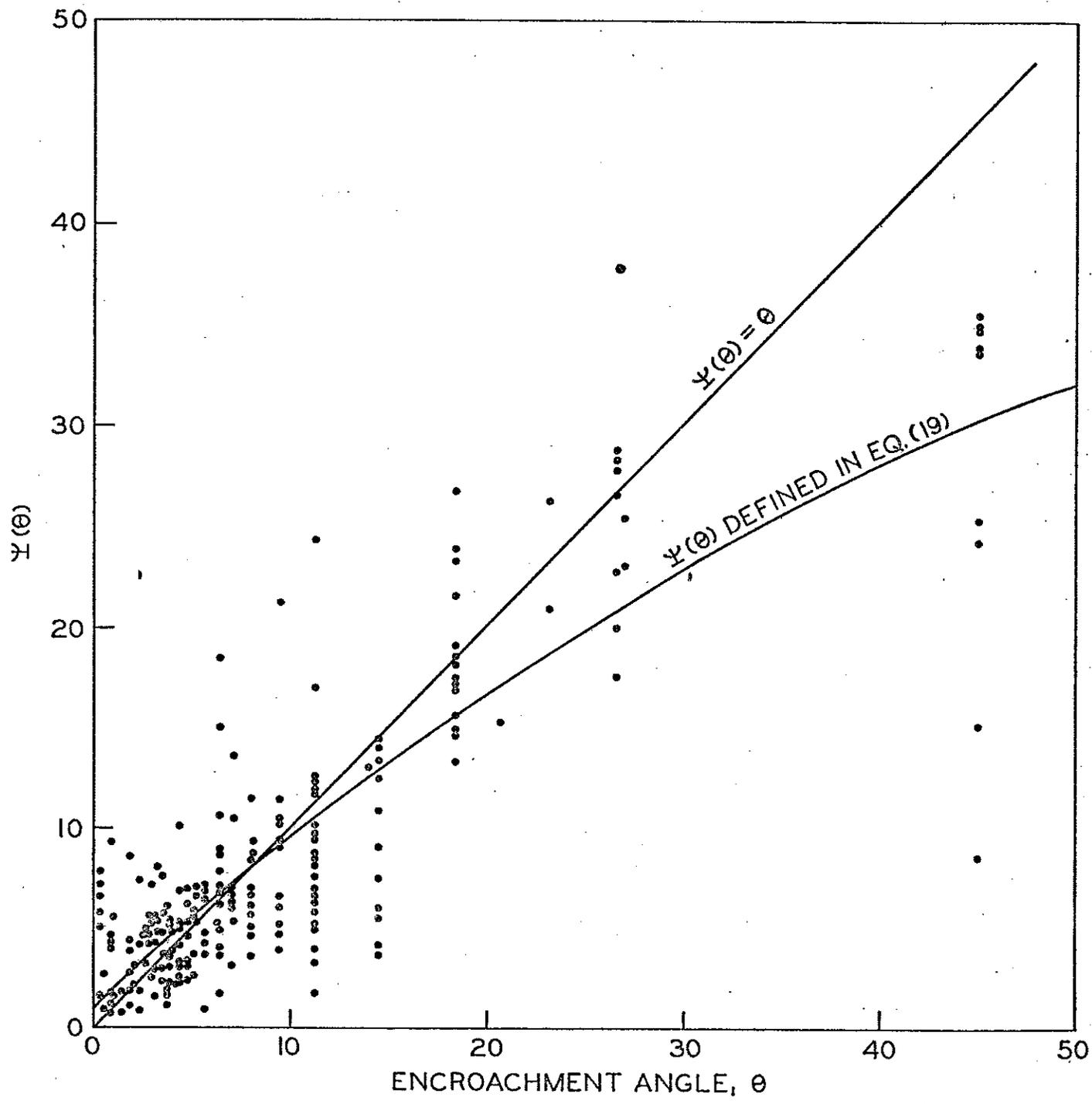


Figure 9. Relationship of θ and $\Psi(\theta)$ defined as $\Psi(\theta) = \tan^{-1} (Y_{\theta} / X_{\theta})$.

terized by rate λ_{jk} (e.g., number of vehicles per second passing over a random point). Note that $\sum_k \lambda_{jk} = \lambda_j$. If we further assume that the traffic pattern is a Poisson process (22), then

$$C_j(M, y_\theta) = 1 - e^{-\sum_k \lambda_{jk} t_{jk}} \tag{17}$$

Note that t_{jk} is a function of M, lane width, vehicle width and length and the speed of the encroaching vehicle at various points along the encroachment path.

The traveling path of the encroaching vehicle now remains to be determined. For a given encroachment angle θ , define

$$\Psi(\theta) = \tan^{-1}(Y_\theta / X_\theta) \tag{18}$$

We plot θ versus $\Psi(\theta)$ in Figure 9. Using non-linear least squares methods to fit $(\theta, \Psi(\theta))$, we obtain:

$$\Psi(\theta) = 1.10377 + 0.890244\theta - 0.0054231\theta^2 \tag{19}$$

This fitted equation is also plotted in Figure 8 where we see that $\Psi(\theta) \geq \theta$ for small θ and $\Psi(\theta) < \theta$ for large θ . This indicates that the traveling path of a vehicle encroaching onto the median can be described by a polynomial $T_\theta(z)$ of degree 3 satisfying the following conditions (Fig. 2).

- a) $T_\theta(z) = 0$ at the encroaching point (i.e., $z = 0$).
- b) Differentiation of $T_\theta(z)$ with respect to z , evaluated at the encroaching point, is equal to $\tan(\theta)$.
- c) Differentiation of $T_\theta(z)$ with respect to z , evaluated at the recovery point, is equal to 0, and
- d) $Y_\theta = T_\theta(x_\theta)$.

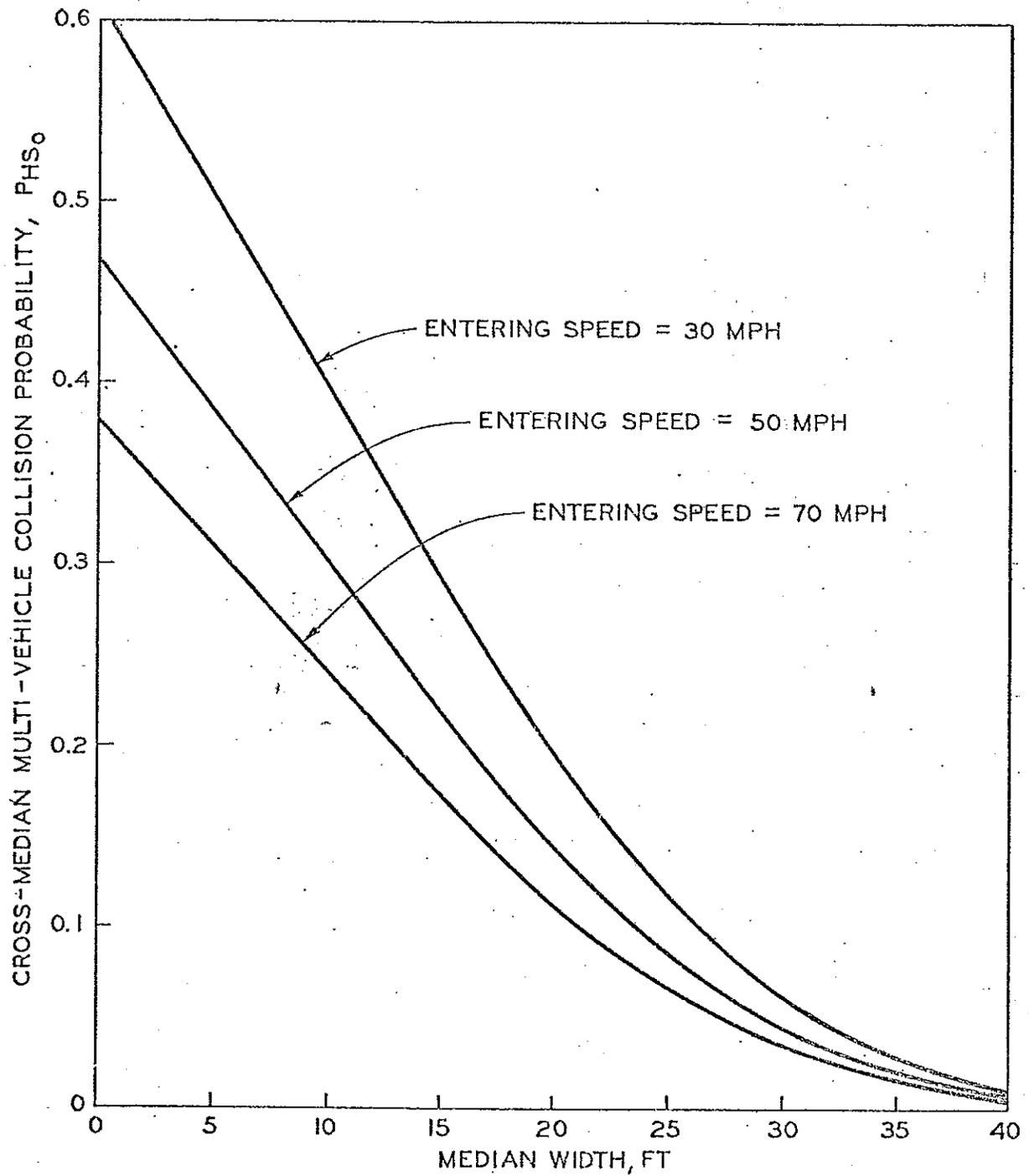


Figure 10. The probability that an encroaching vehicle will cross over a barrier-free median and collide with a vehicle traveling on the opposite roadway.

Under these conditions, it can be shown that

$$T_{\theta}(z) = (\tan \theta)z + \frac{3Y_{\theta} - 2X_{\theta}\tan \theta}{X_{\theta}^2} z^2 + \frac{X_{\theta}\tan \theta - 2Y_{\theta}}{X_{\theta}^3} z^3 \quad (20)$$

We end this section by noting that another application of the traveling path $T_{\theta}(z)$ is the determination of the angle at which an encroaching vehicle would strike the barrier. For example, if the barrier is installed at M ft from the edge of Roadway i , the impact angle $\varphi(\theta)$ of an encroaching vehicle with trajectory Y_{θ} can be expressed as

$$\varphi(\theta) = \tan^{-1} \left[\frac{dT_{\theta}(z)}{dz} \right]_{\text{evaluated at } (T_{\theta}^{-1}(M_i), M_i)} \quad (21)$$

An Example

We present P_B , P_H and the ratio of P_B to P_H in Figures (10) and (11) which are obtained by using the above model, together with the following assumptions:

- a) Each roadway has three lanes; the width of each is 12 ft.
- b) Two roadways are long enough so that we may ignore the collision probability at the end points of roadways and the barrier.
- c) The width and length of the vehicle are 6 ft and 18 ft, respectively.
- d) The ADT of highway is 162,000. Each roadway is assumed to carry 81,000 vehicles each 24-hour day. Thus, $E_1 = E_2 = 1/2$.
- e) The proportions of total traffic traveling on the traffic, central and passing lanes are 0.26, 0.40, and 0.34, respectively.
- f) All vehicles are traveling in the center of their respective lanes.

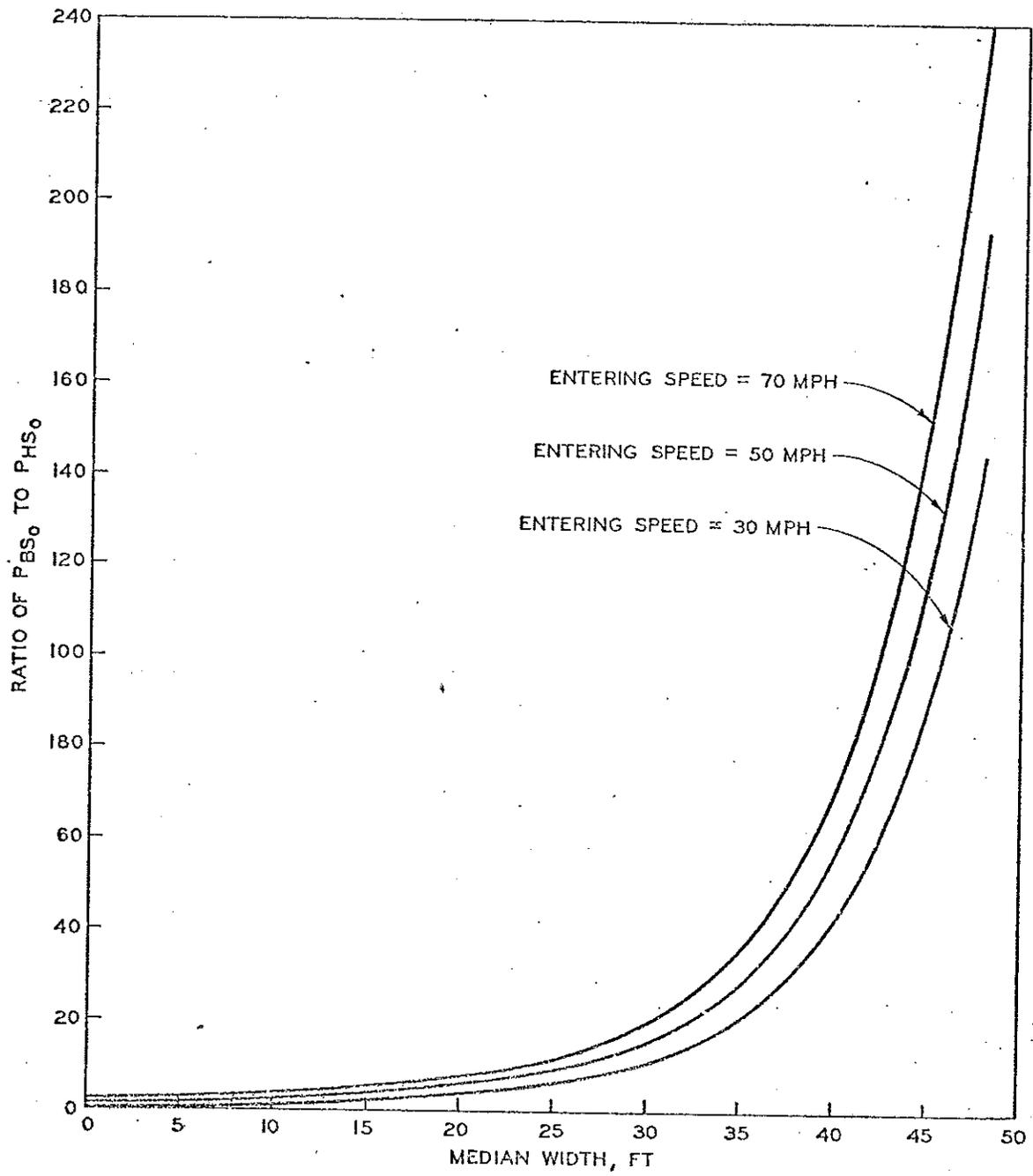


Figure 11. Ratio of P_B to P_H .

g) Once two vehicles are on a collision course defined by the Poisson process, neither driver is able to take evasive action.

h) No collision occurs at any time after the encroaching vehicle has reached the recovery point. At this point, the driver of the encroaching vehicle is assumed to be in control and evasive action by all parties is possible.

i) If the barrier is present, it is installed in the center of the median and is assumed to fully contain the encroaching vehicle. Thus, no barrier vaulting or breakthrough are possible.

j) Every point along the roadway section of interest has an equal opportunity to serve as an encroaching point.

k) The median is essentially flat; i. e., has no appreciable ditch or slope.

If the median width varies the relative risk determination is more complex. Consider for example, a median 700 ft long which increases linearly from a width of 34 ft to 46 ft. By averaging we can approximate the barrier-no barrier relative risk ratio shown in Figure 12 for various encroachment speeds.

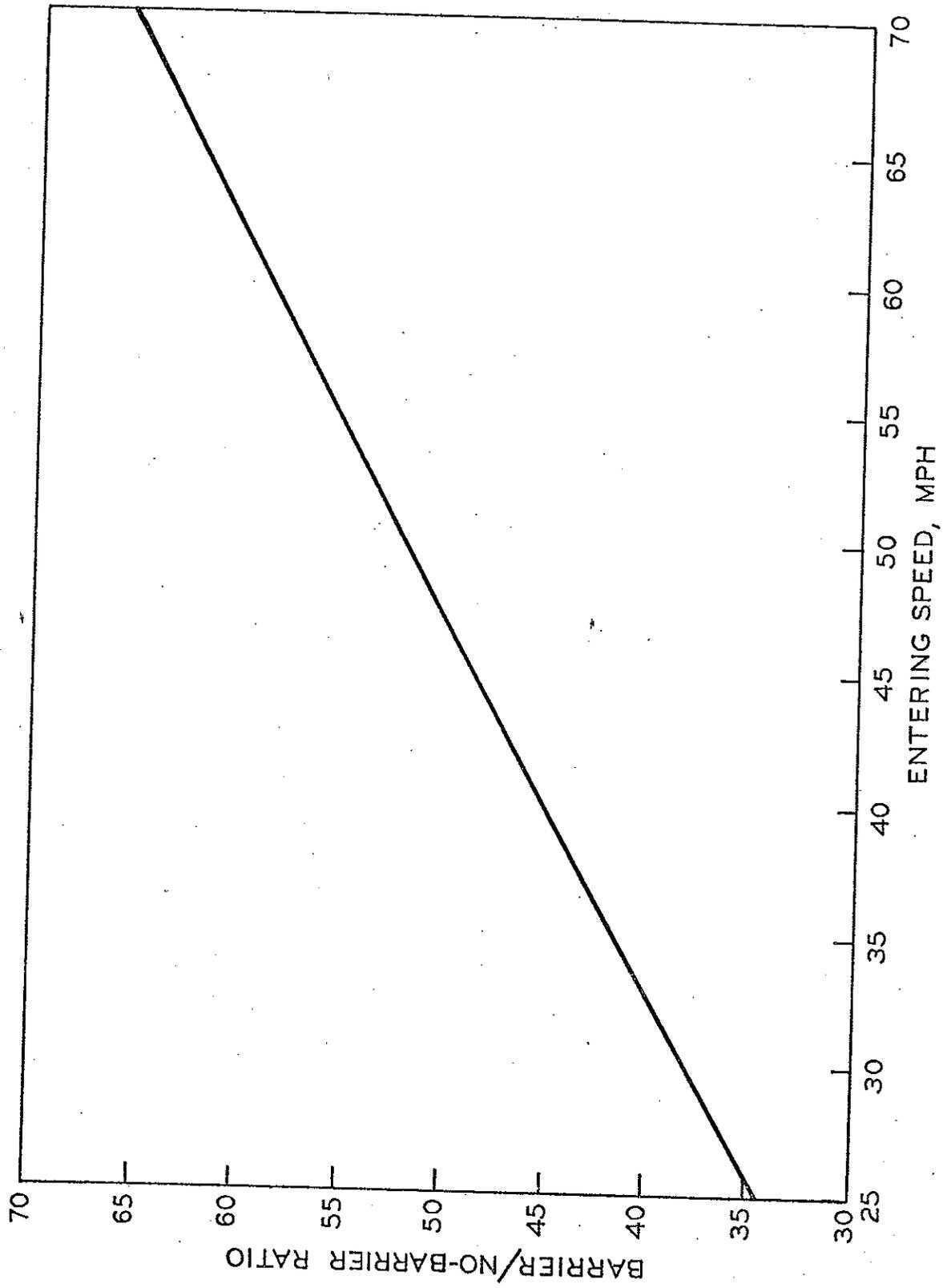


Figure 12. Estimated accident ratio for median encroachments.

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