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FREEWAY DESIGN AND CONTROL STRATEGIES AS AFFECTED BY TRUCKS AND TRAFFIC REGULATIONS

Vol. 1 Technical Report

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16. Abstract

A detailed simulation of multilane highway flows on grades was developed under Contract No. CPR-11-5093. Using data collected on mountain grades, the simulation is improved and further validated. The simulation model is applied to flows of mixed commercial and passenger vehicles on grades and level terrain. The results are codified and presented as design guides for two and three lanes (one-way) upgrade roadways.

This volume contains a description of the simulation model, all the validation results, all the field data collected for validation, and the complete set of design guides.

This is one of two volumes. They are:

Volume No.	FHWA No.	Short Title
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PREFACE

This report was prepared under Contract No. DOT-FH-11-7739 for the Department of Transportation, Federal Highway Administration. The research was conducted in the Engineering Sciences Division under the direction of Dr. Michael C. Noland, Director, and Dr. William Glauz. Mr. A. D. St. John was project leader.

The report was written by Mr. A. D. St. John, Mr. Donald Kobett, Dr. William Glauz, Mr. Duncan Sommerville, and Mr. Douglas Harwood. The writers acknowledge the assistance and suggestions provided by Mr. Justin True, Mr. Charles Stockfisch, Mr. Barry Benioff, and Dr. Guido Radelat of the Federal Highway Administration. We also acknowledge the considerable assistance by the California Division of Highways in selecting and inspecting data sites, in particular Mr. Karl Moskowitz, Mr. Fred Rooney, Mr. Norman Wingerd, Mr. Clarence Nevis, and Mr. Leonard Newman.

The report covers the period from 24 May 1971 through 31 January 1975.

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SUMMARY

A detailed simulation model of multilane highway flow was developed and applied in another project under Contract No. CPR-11-5093. The simulation has been improved in a series of adjustments so that it duplicates the flow characteristics of mixed flows in level terrain and on grades. After validation, the simulation was applied to flows of a mixture of commercial and passenger vehicles on grades and level terrain. The results have been codified and presented in the form of design guides.

The simulation model was adjusted and then validated by comparison with data collected on grades in California. Comparisons of traffic distribution to lane, lane changing rates and passenger car average speeds were made. Simulation results duplicate the important influences of grade, vehicle population and flow rate.

Both the field observations and the simulation results indicate distinctive characteristics of flows on sustained grades. After entering the foot of a grade, a mixed flow of commercial and passenger vehicles undergoes a transition of speeds and lane occupancies. After the transition, the flow remains irregular, and the operating speed versus capacity relations have the same characteristic shape as observed for level terrain flows. The on-grade, operating speed versus capacity relations derived from the simulation results have been used to construct design guides which indicate on-grade service levels for roadways with two and three lanes one-way, and various vehicle mixes.

The on-grade service levels provide the same combinations of operating speed and volume-to-capacity ratio as are employed for level terrain. The on-grade service levels differ, however, in that they involve higher risk exposure and driver work loads than the equivalent level terrain conditions. Consequently, on-grade service levels are identified with primed letters.

In the foot and crest transition regions the risk exposure and driver work loads tend to be as high as in the on-grade flows. A procedure is provided to estimate operating speeds in these regions based on the local speed of trucks. The same procedure should be applicable to flows in rolling terrains and to flows with distinctly different commercial vehicle populations.

Simulation results for AASHO design capacities are presented for both two and three lanes upgrade. The AASHO recommendations for consideration of a climbing (third upgrade) lane appear to be well founded.

Both field data and the simulation model indicate that 2 or 3 min is an appropriate period for relating the car speeds (operating or average) to total flow rate and truck flow rate on a short section of a sustained grade. Also, the car speeds will depend on the performance (or speed) of the trucks present during the short time period. Short period service levels on grades are thus more variable than in level terrain since they are sensitive to the number and character of trucks present. The design charts could be employed to evaluate the variability of speeds during a design hour. The recommended procedure would employ truck samples which are selected by a combination of probablistic and stochastic logic. The procedure should be computerized.

I. INTRODUCTION

On long upgrades commercial vehicles with large weight-to-power ratios climb at low speeds and impede the flow of traffic. Previous studies of these effects have been conducted by the Bureau of Public Roads, the Highway Research Board, State Highway Departments, and by foreign governments. These studies arrive at estimates of the reduced capacities and levels of service and recommendations for the addition of truck climbing lanes. Previous studies have emphasized the calculation or measurement of commercial vehicle performance and have then depended on brief analyses and experimental observations or intuitive ideas to estimate the resulting traffic interactions and characteristics.

A previous project (Contract No. CPR-11-5093) developed a detailed simulation model applicable to four-lane, divided highways in mountainous terrain. Capabilities for representing a truck climbing lane were included. An initial stage of validation was completed and a method was developed for codifying the results of a few simulation runs.

In project Tasks A and B, additional validation was accomplished. Numerous simulation runs were made and the codified results are presented in the form of design guides. Task C included a more thorough application of statistical techniques. The model was adjusted in the light of the new information and the validation efforts were expanded. Also, the simulation was applied for a greater variety of driver populations and the design guides were converted to concise forms which have extensive application.

II. EXPERIMENTAL PROGRAM

Data were collected to validate the simulation logic and guide the evaluation of model parameters. The data were obtained on the ground using simple, manual procedures. This method was chosen because it provides valuable data at minimum expense.

In the previous project* data were obtained on four-lane divided highways with 6% and 4% grades. The flow rates during data collection were low. It was desired to obtain data at higher flow rates on a 4 to 6% grade. In addition, the simulation had indicated that flows on a 2% grade were considerably different (due to the higher truck speeds) and data were sought on a 2% grade.

The data needed included flow rates, distribution to lane by vehicle type, spot speeds, lane changing frequencies, vehicle population and overall travel speeds. There was also a lack of information on traffic behavior at the initiation and drop of a climbing lane. These data were also sought.

A. Data Collection Sites

The characteristics desired for data collection sites are shown in Table I. This information was transmitted to FHWA Regional Offices by the Contract Monitor. The same information was sent directly to the Traffic Engineering Department of the California Division of Highways.

Potential sites were suggested by the highway departments in California, Colorado, Ohio, Pennsylvania, and West Virginia. The California sites appeared the most attractive for their characteristics and geographical proximity. They were visited in the company of an engineer from the Division of Highways. Four sites were selected, one each for the 2% and 6% grade, and two with climbing lanes on grades of about 5%.

At all four sites the road is four-lane, divided interstate highway. Horizontal curvature is moderate. Data were collected on days of the week and during hours when State Highway Department measurements indicated that flows would rise to maximum recorded levels.

* Contract CPR-11-5093.

TABLE I

SUMMARY OF CHARACTERISTICS DESIRED AT THREE DATA COLLECTION SITES

	Site No. 1	Site No. 2	Site No. 3
Average Grade	$\approx$ 2%	4 to 6%	4 to 6%
Grade Length	> 3/2 miles (2.4 km)	$\geq$ 3/2 miles (2.4 km)	$\geq$ 3/2 miles (2.4 km)
Lanes (preferably divided) Total	4	4	4 w/climbing lane (5th) added on upgrade
Upgrade peak hour flow*	$\geq$ 2,500	$\geq$ 1,800 on 4% $\geq$ 1,000 on 6%	$\geq$ 2,600 on 4% $\geq$ 2,000 on 6%
Traffic Composition	← 3 to 15% commercial including heavy trucks →		
Roadside Development	← None or minimum →		
Access	Preferably no access near or on grade, or a few private drives and low-volume service roads		
Design Speed**	← $\geq$ 60 mph (97 km/h) →		
Speed Limit**	← $\geq$ 60 mph (97 km/h) →		
Vantage Points (for data collectors)	Accessible positions to the side and preferably above the highway at the following locations: (1) near the foot, (2) on the grade more than 4,000 ft from the foot, (3) near the crest, (4) and for the climbing lane site points with views of the lane initiation and the lane drop.		

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* A wide range of flows during the daylight hours would be desirable.

** A short section of lower design speed and speed limit would not eliminate an otherwise desirable site.

The first grade, of 2 to 3%, is located on I-580 east of Hayward, California. The general character of the grade and some identifying landmarks are shown in Figure 1. Data were collected from eastbound traffic at three stations on this grade on Friday, 20 August 1971, between 1:00 PM and 5:30 PM. The weather was bright and clear. Details of the data collection courses are shown in Figures 2 through 4. The data types and amounts are summarized in Table II.

The 6% grade is located on I-680 north of San Jose, California. The general character of the grade and some identifying landmarks are shown in Figure 5. Data were collected from southbound* traffic at four stations on this grade on Sunday, 22 August 1971, between noon and 4:00 PM. During the first hour the sky was partly cloudy; afterward the weather was bright and clear. Details of the data collection courses are shown in Figures 6 through 9. The data types and amounts are summarized in Table III.

One of the climbing lane sites is located on I-80 between Emigrant Gap and the Yuba Gap overcrossing. The general character of the grade is shown in Figure 10. There was a 55 mph speed limit on the climbing lane. Data were collected from eastbound traffic at five stations on this grade on Friday and Saturday, 27-28 August 1971. Data were collected downstream of the climbing lane drop on Friday between 2:30 PM and 3:30 PM, and at the other four stations on Saturday between 11:00 AM and 4:00 PM. The weather was bright and clear on both days. Details of the data collection courses are shown in Figures 11 through 15. The data types and amounts are summarized in Table IV.

The other climbing lane site is located on I-80 between the Donner Lake road undercrossing and the Donner Summit. The general character of the grade is shown in Figure 16. There was a 55 mph speed limit on the climbing lane. Vantage points at the climbing lane drop were not too good and vehicle maneuvers could be observed only to within 600 ft (183 m) of the end of the climbing lane terminating taper. Data were collected from westbound traffic at three stations on this grade on Sunday, 29 August 1971, between noon and 4:00 PM. The weather was bright and clear. Details of the data collection courses are shown in Figures 17 through 19. The data types and amounts are summarized in Table V.

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* I-680 is a nominally north-south highway. At the data site its direction is almost due east-west and the observed traffic was moving westward.

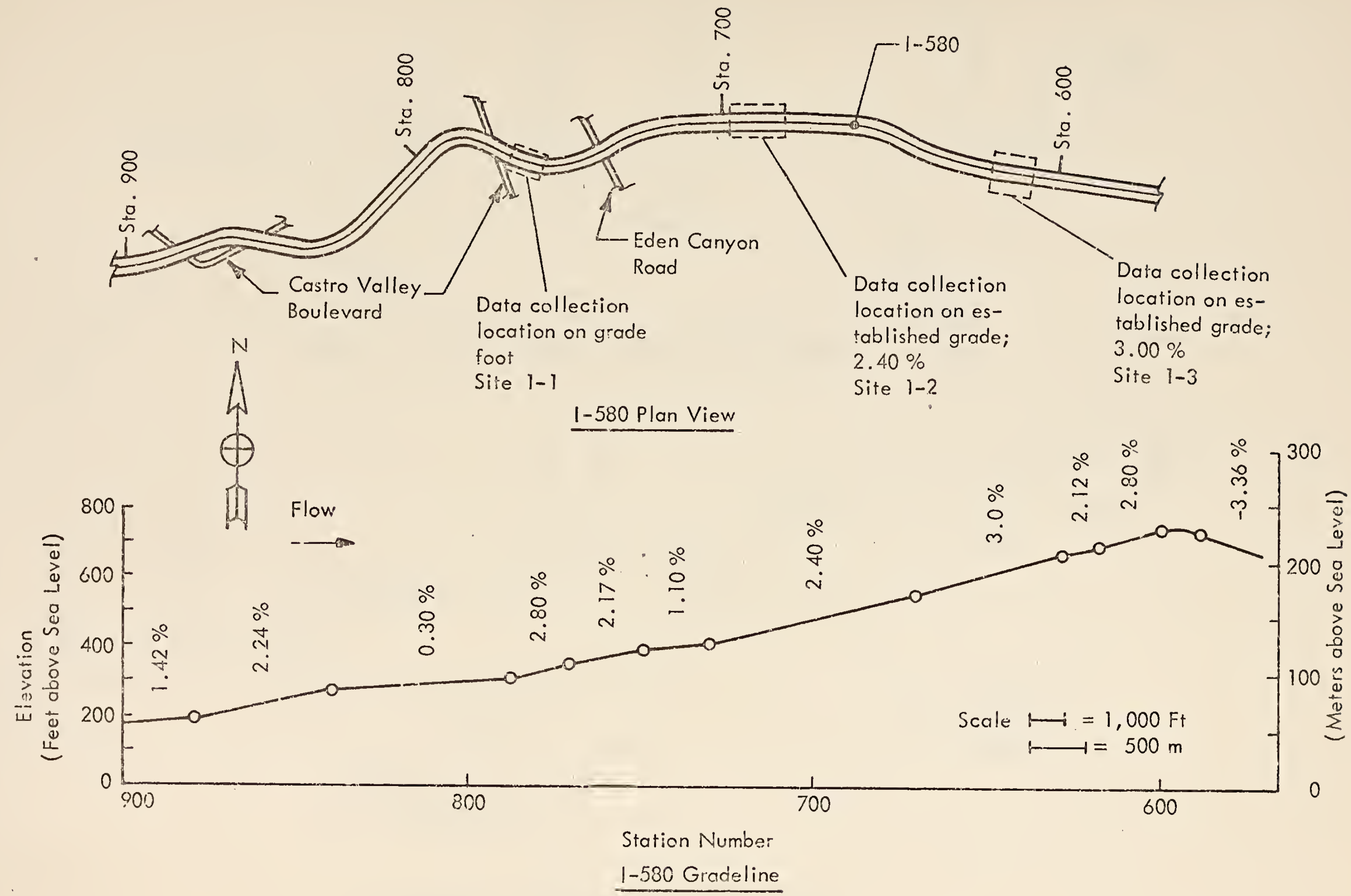
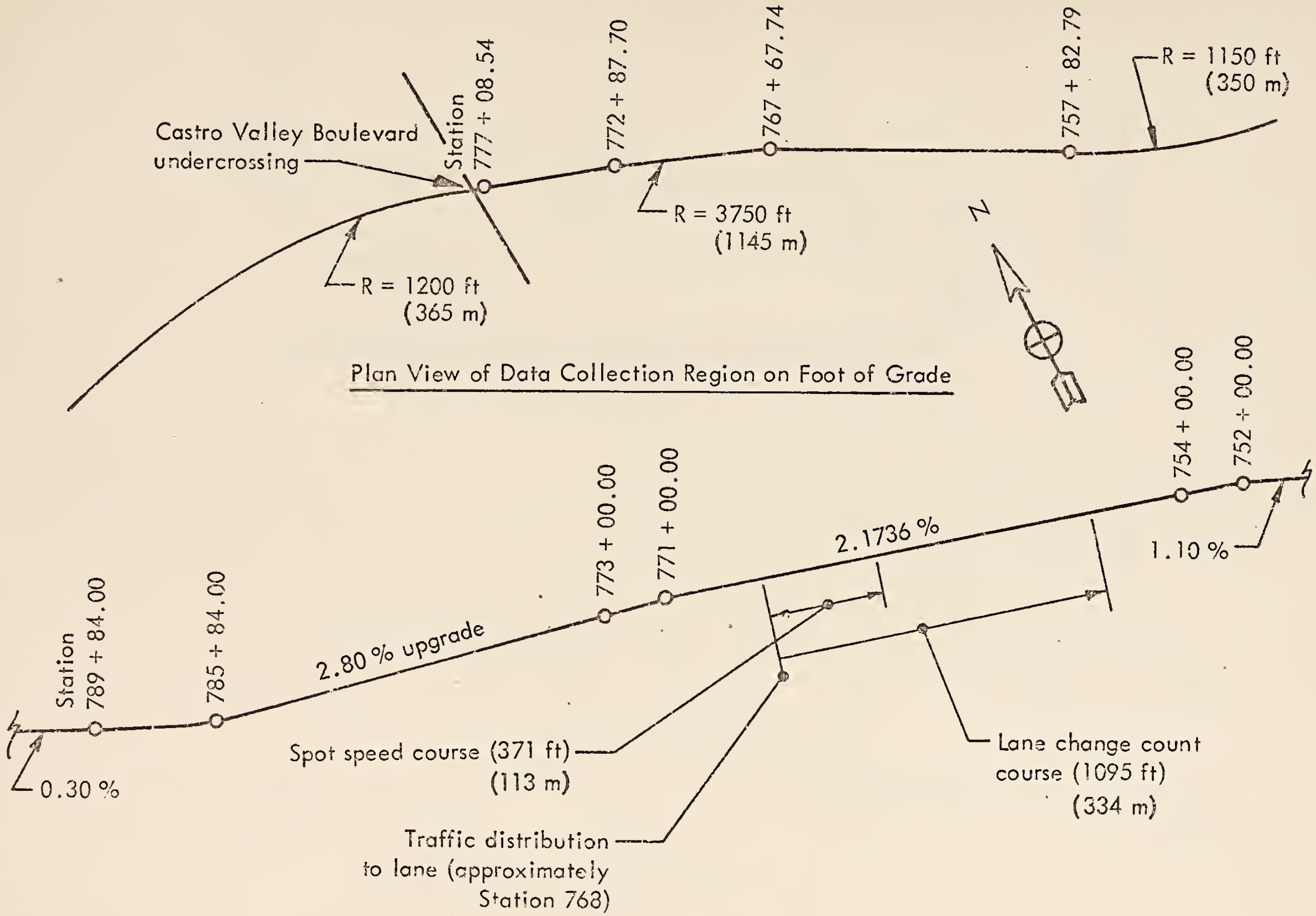


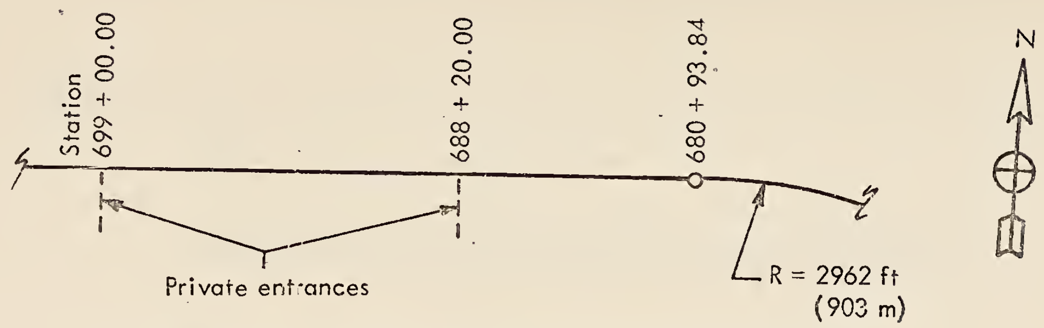
Figure 1 - Data Collection Sites on I-580



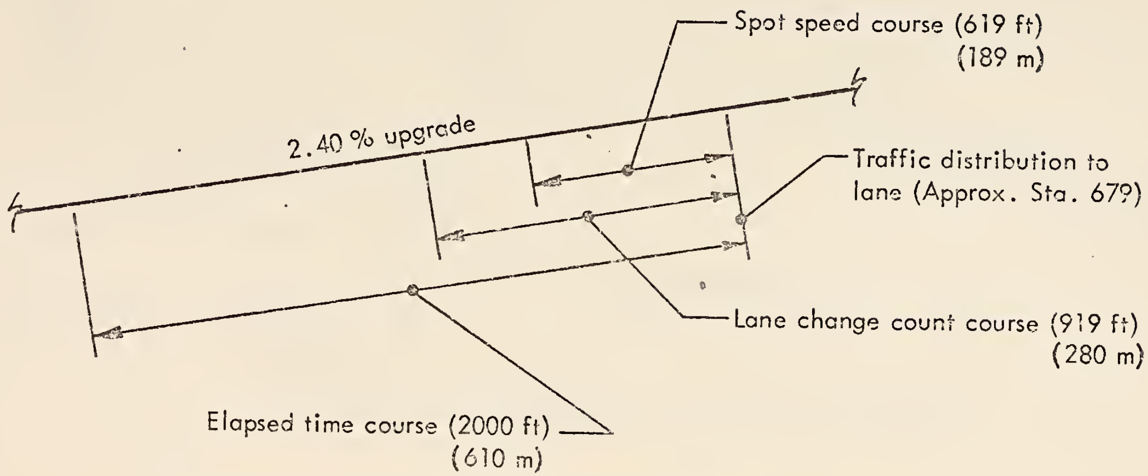
Plan View of Data Collection Region on Foot of Grade

Gradeline and Locations of Data Collection Areas

Figure 2 - I-580 Data Collection Location on Grade Foot, Site 1-1

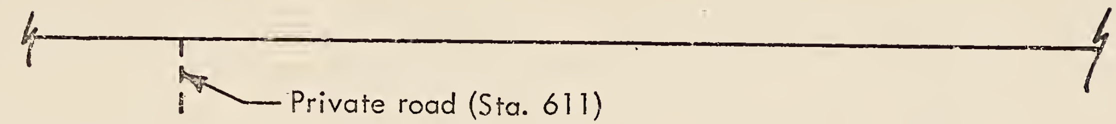


Plan View of Data Collection Region on Established Grade

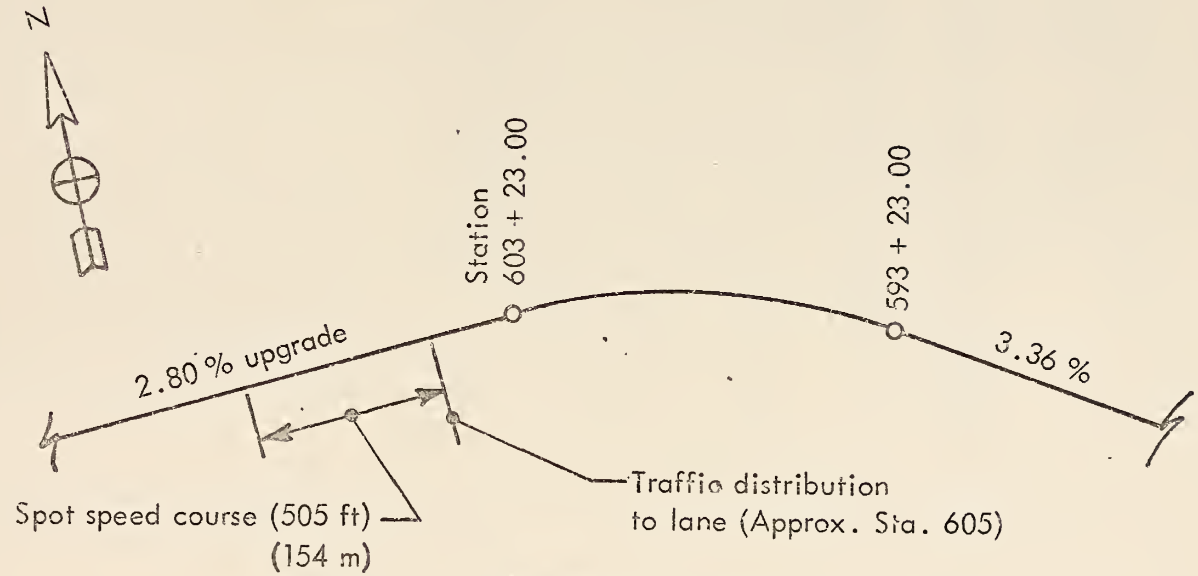


Gradeline and Locations of Data Collection Areas

Figure 3 - I-580 Data Collection Location on Established Grade, Site 1-2



Plan View of Data Collection Region at Grade Crest



Gradeline and Locations of Data Collection Areas

Figure 4 - I-580 Data Collection Location at Grade Crest, Site 1-3

TABLE II

DATA COLLECTED ON I-580

On Grade Foot, Site 1-1

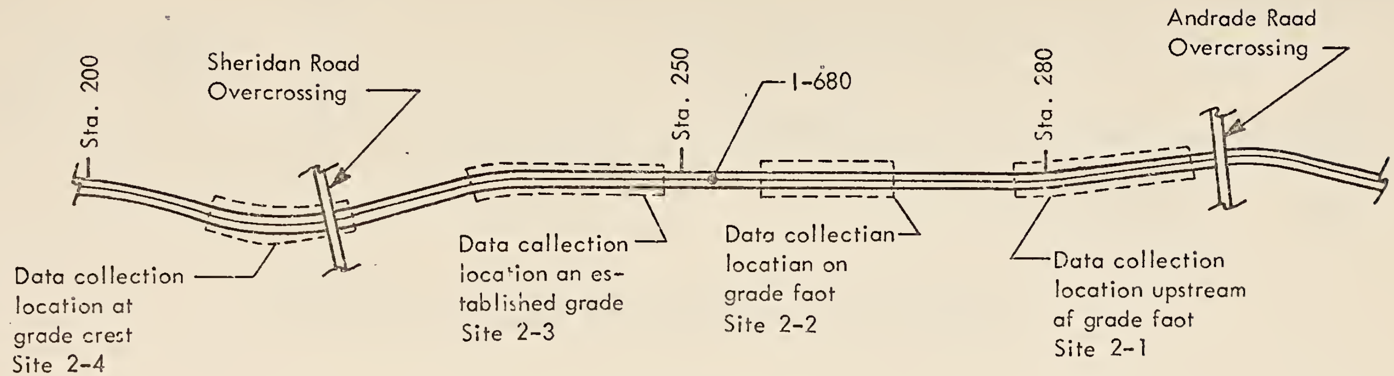
Distribution to lane - 90 min
Lane change count - 39 min
Spot speeds - 45 min
(Sample size - 124)

On Established Grade (2.4%), Site 1-2

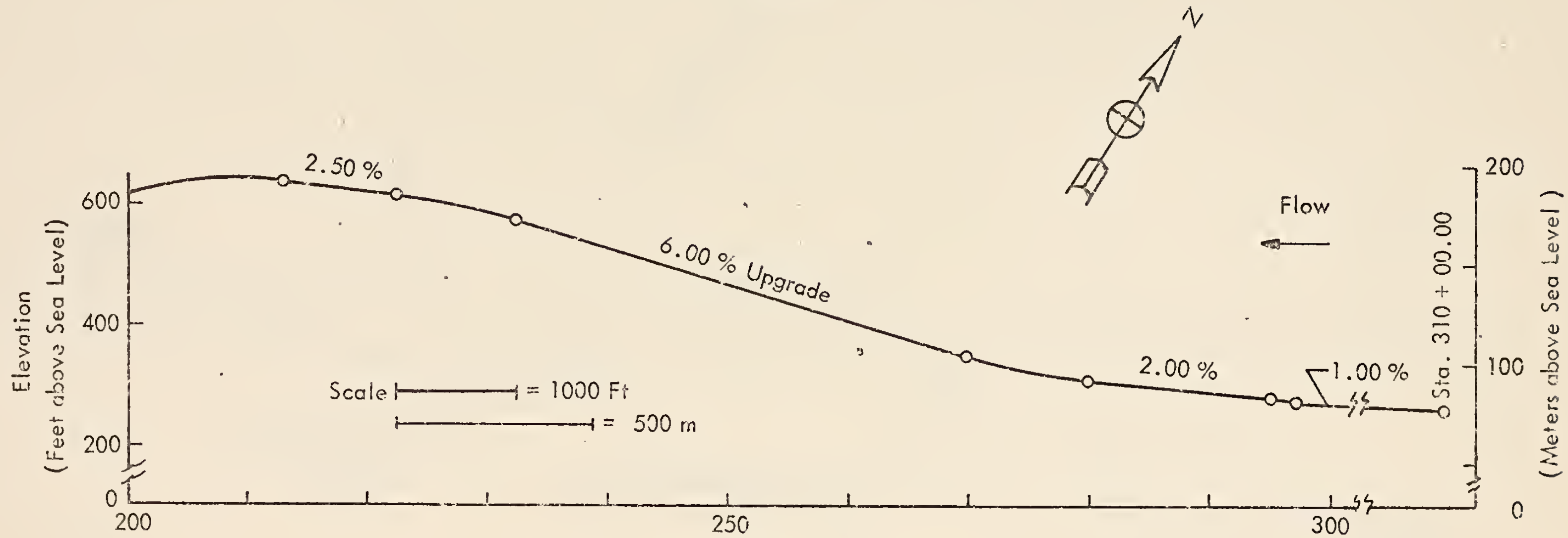
Distribution to lane - 225 min
Lane change count - 113 min
Spot speeds - 190 min
(Sample size - 127)
Elapsed time - 452 min (2 persons)
(Sample size - 448)

On Established 3% Grade, Site 1-3

Distribution to lane - 63 min
Lane change count - 0 min
Spot speeds - 63 min
(Sample size - 134)



I-680 Plan View



I-680 Gradeline

Figure 5 - Data Collection Sites on I-680

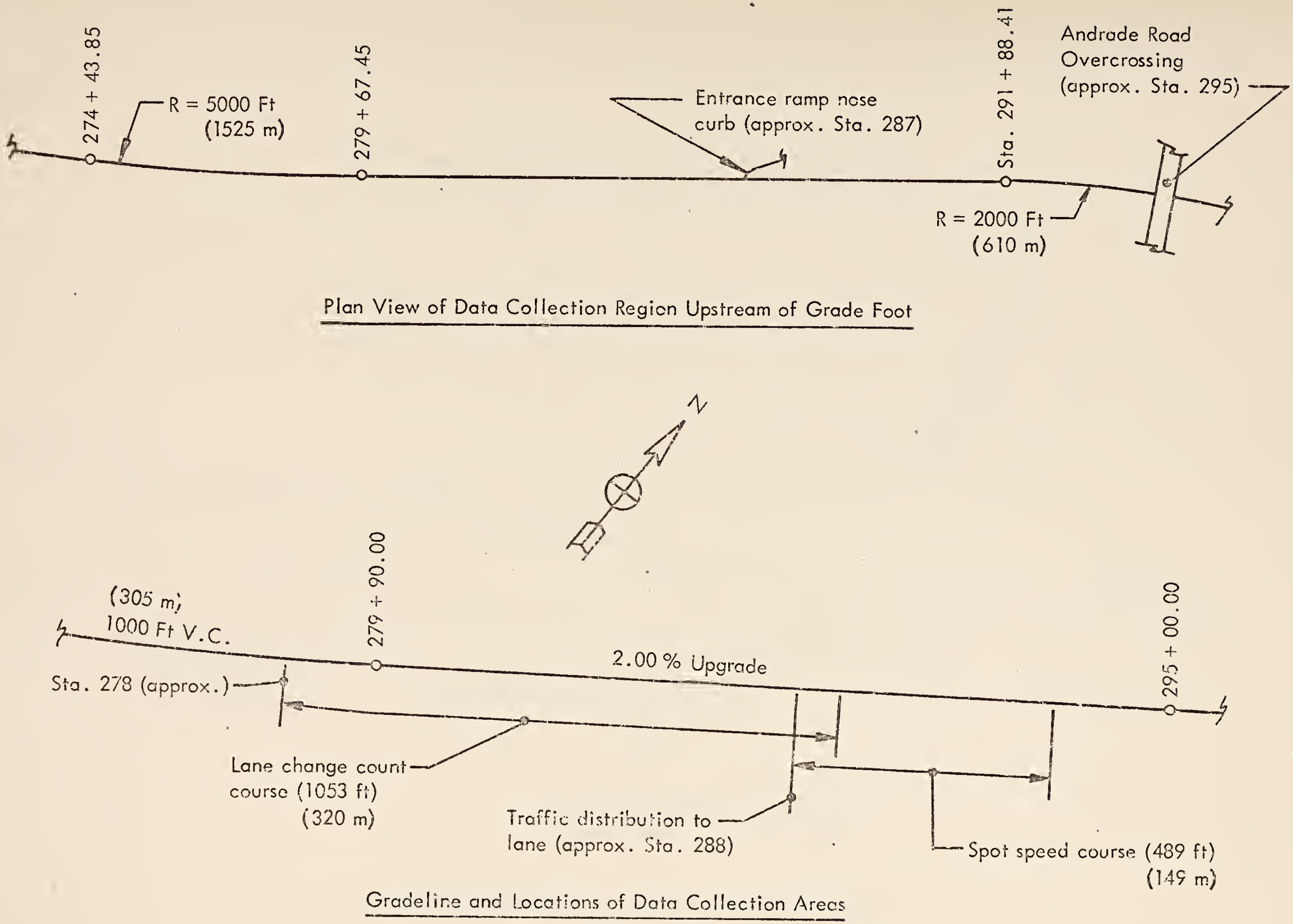
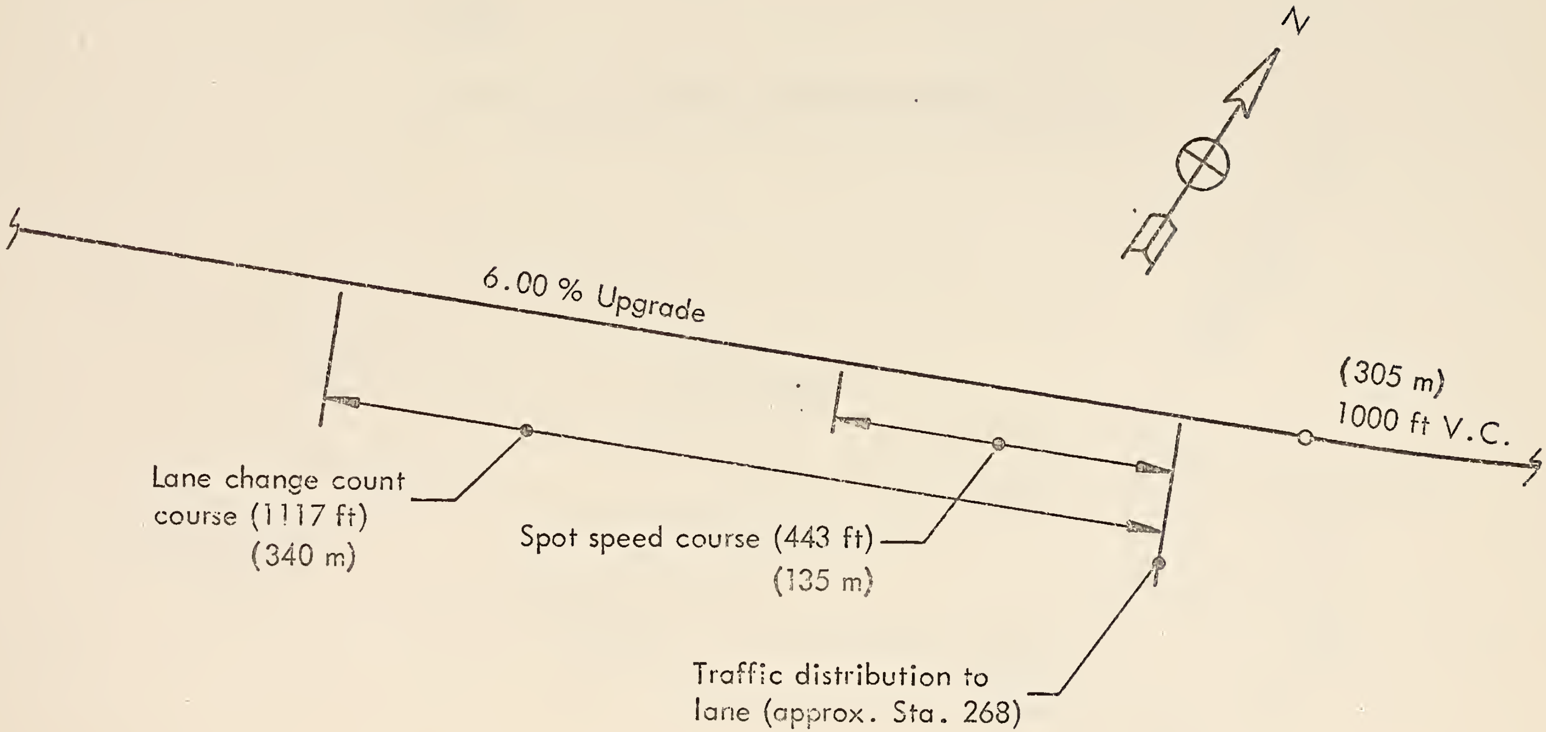


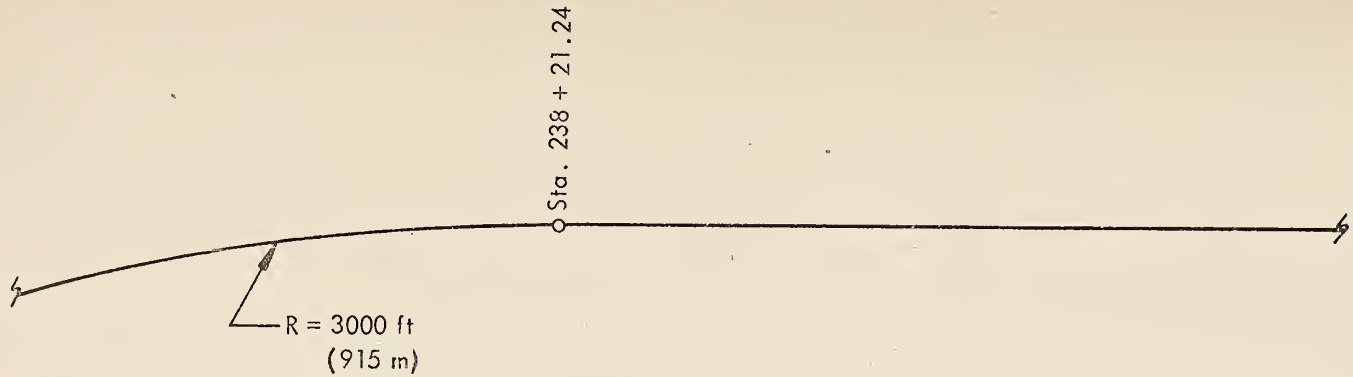
Figure 6 - I-680 Data Collection Location Upstream of Grade Foot, Site 2-1

Plan View of Data Collection Region on Grade Foot

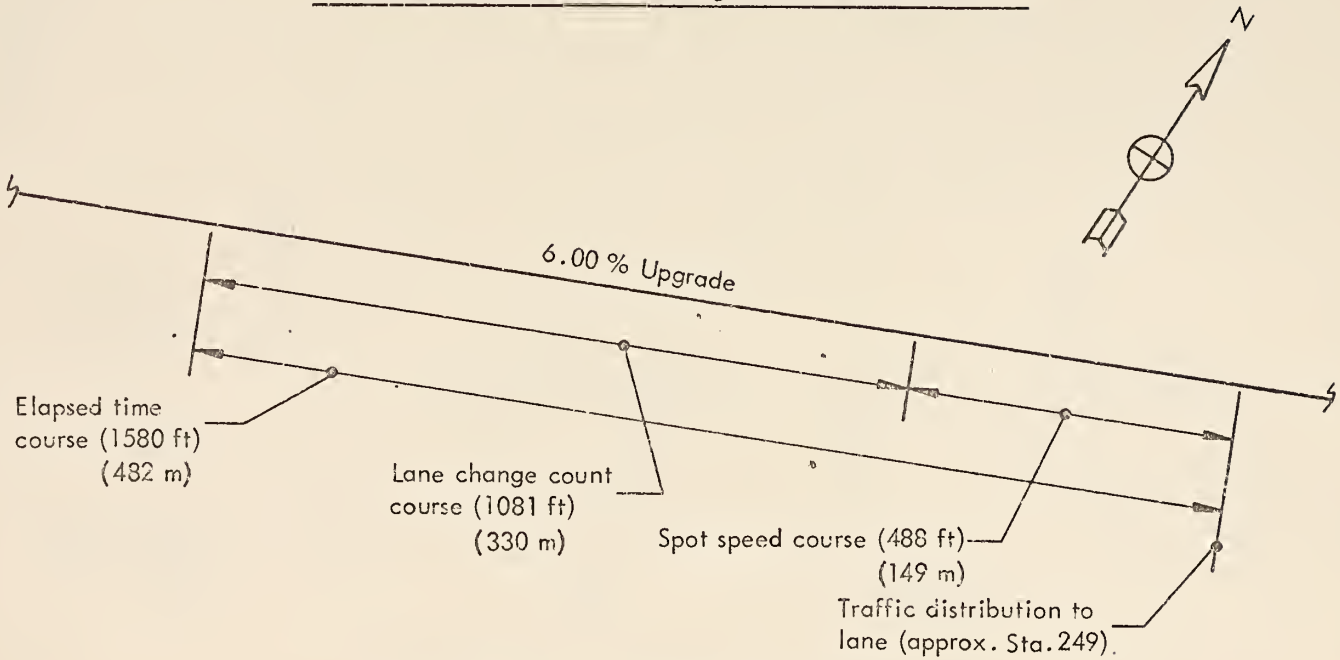


Gradeline and Locations of Data Collection Areas

Figure 7 - I-680 Data Collection Location on Grade Foot, Site 2-2

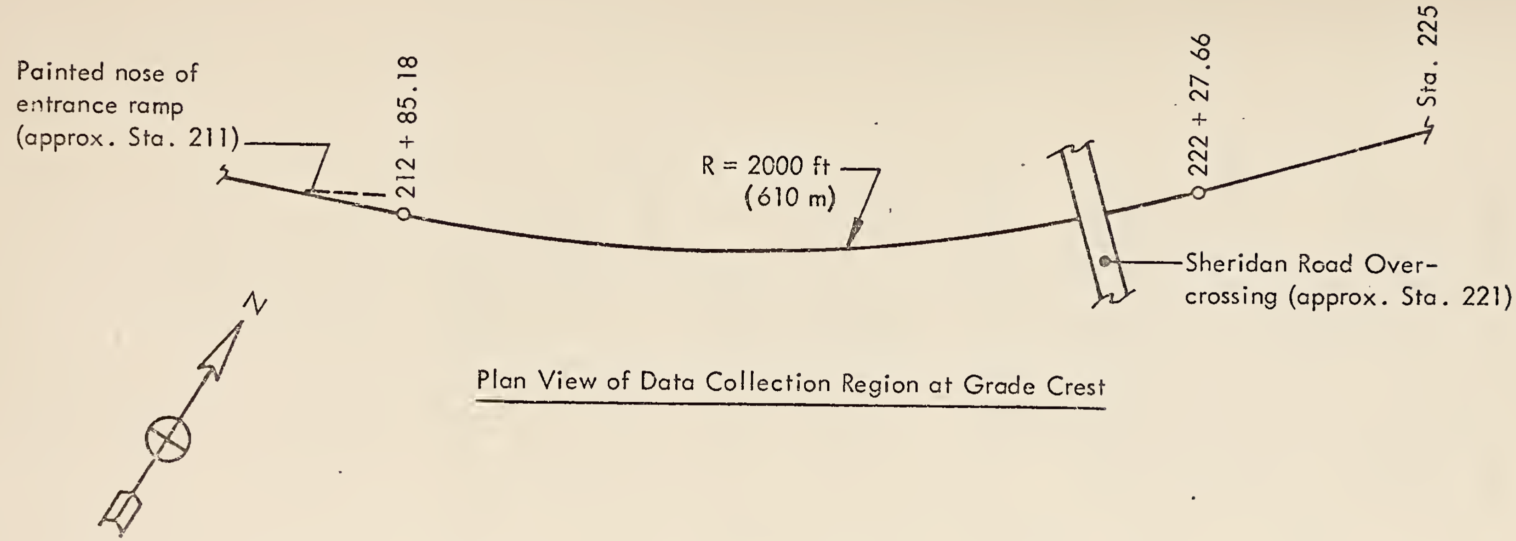


Plan View of Data Collection Region on Established Grade

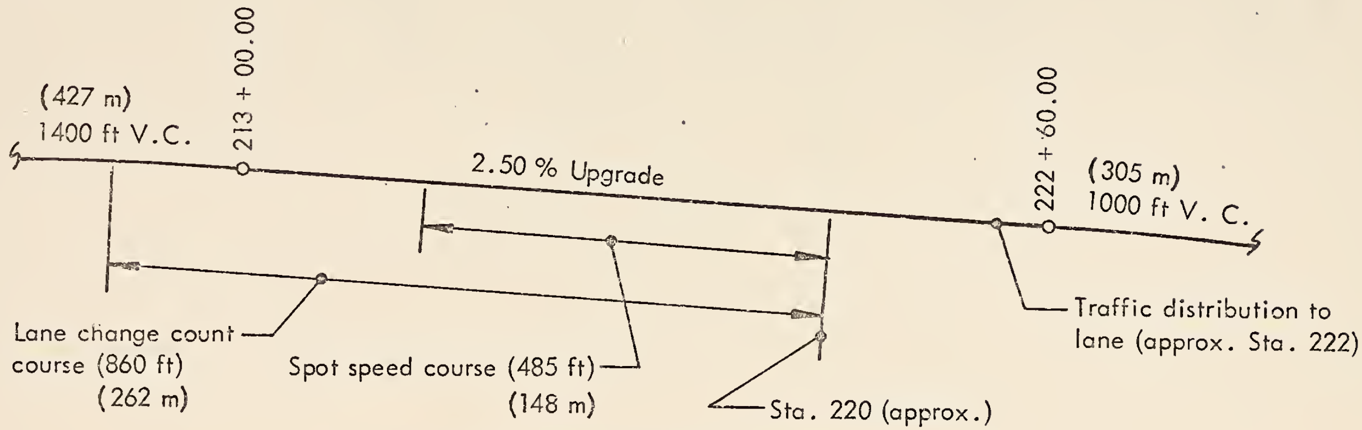


Gradeline and Locations of Data Collection Areas

Figure 8 - I-680 Data Collection Location on Established Grade, Site 2-3



Plan View of Data Collection Region at Grade Crest



Gradeline and Locations of Data Collection Areas

Figure 9 - I-680 Data Collection Location at Grade Crest, Site 2-4

TABLE III

DATA COLLECTED ON I-680

Upstream of Grade Foot, Site 2-1

Distribution to lane - 147 min
Lane change count - 75 min
Spot speeds - 75 min
(Sample size - 150)

On Grade Foot, Site 2-2

Distribution to lane - 49 min
Lane change count - 47 min
Spot speeds - 47 min
(Sample size - 109)

On Established Grade (6.0%), Site 2-3

Distribution to lane - 248 min
Lane change count - 109 min
Spot speeds - 133 min
(Sample size - 132)
Elapsed time - 400 min (2 persons)
(Sample size - 571)

At Grade Crest, Site 2-4

Distribution to lane - 76 min
Lane change count - 38 min
Spot speeds - 40 min
(Sample size - 82)

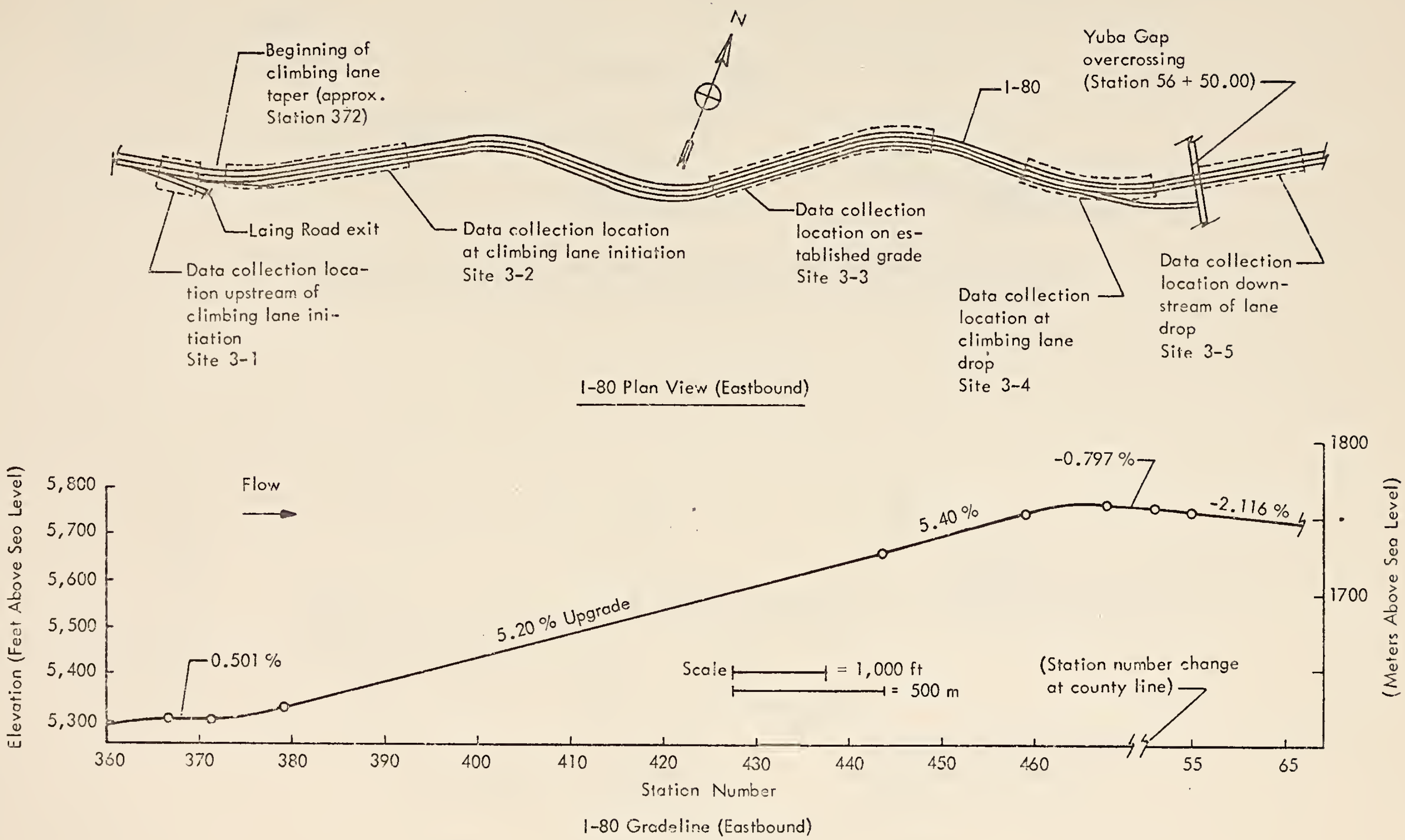
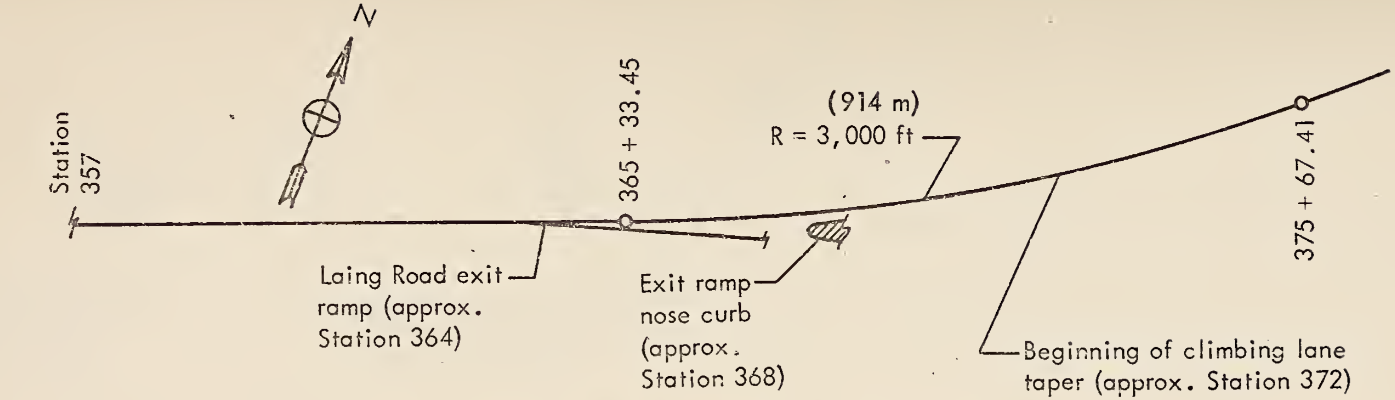
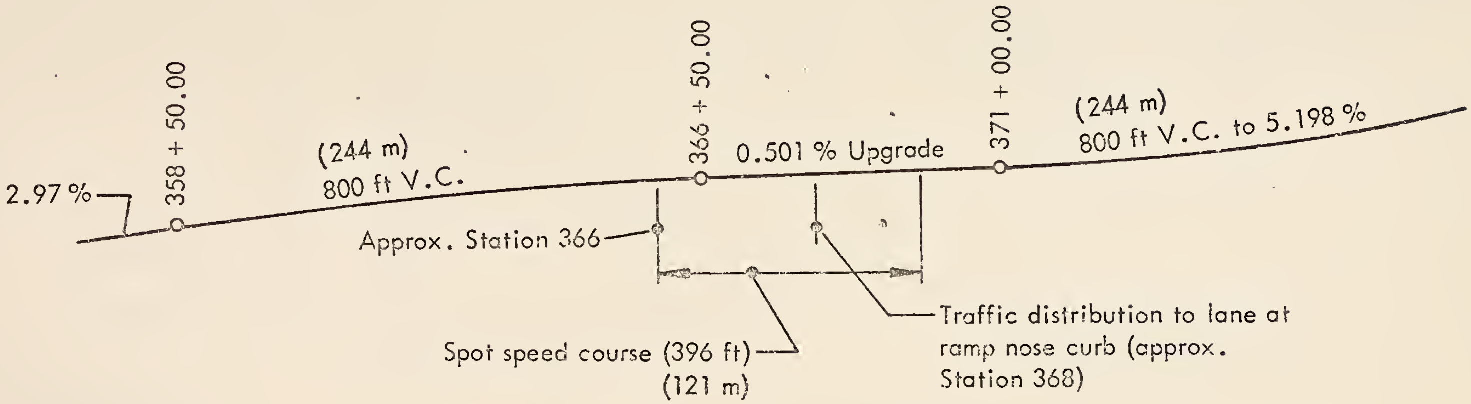


Figure 10 - Data Collection Sites on Eastbound I-80

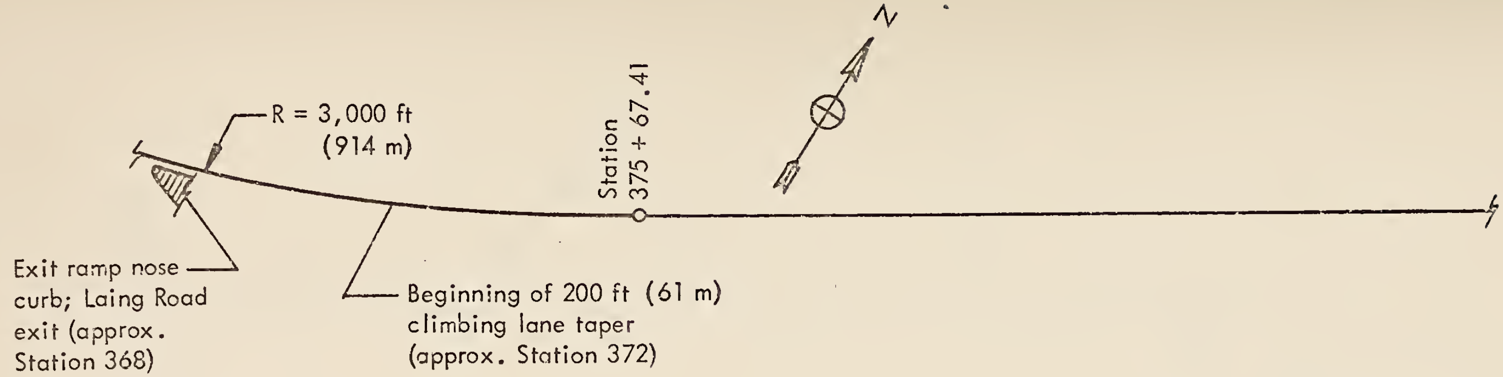


Plan View of Data Collection Region Upstream of Climbing Lane Initiation

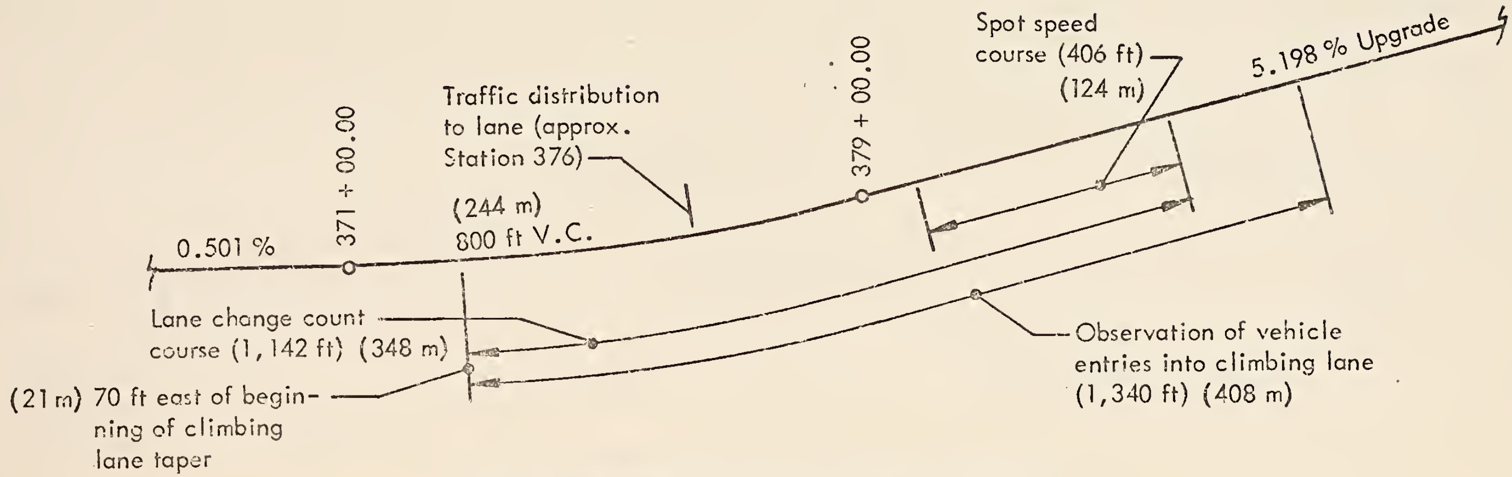


Gradeline and Locations of Data Collection Areas

Figure 11 - I-80 (Eastbound) Data Collection Location Upstream of Climbing Lane Initiation, Site 3-1

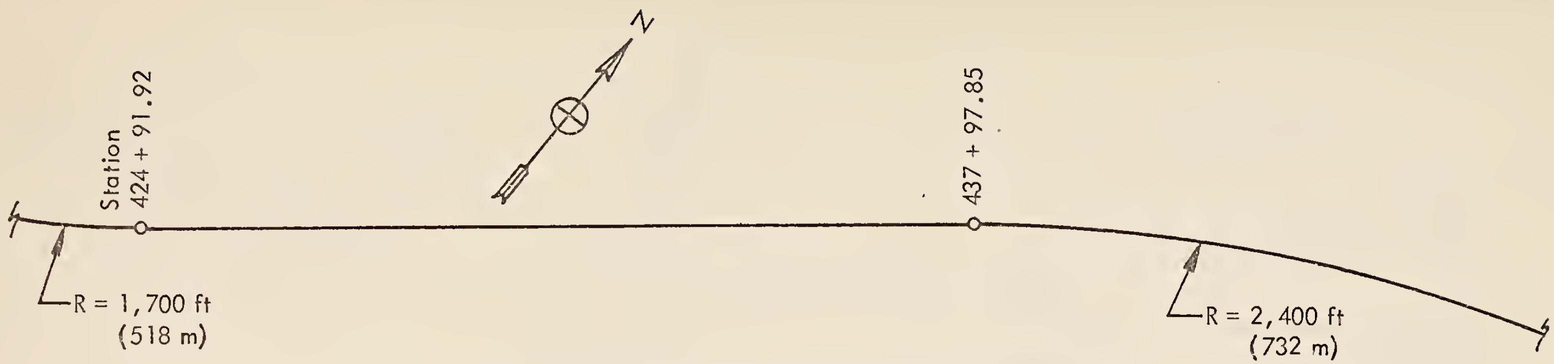


Plan View of Data Collection Region at Climbing Lane Initiation

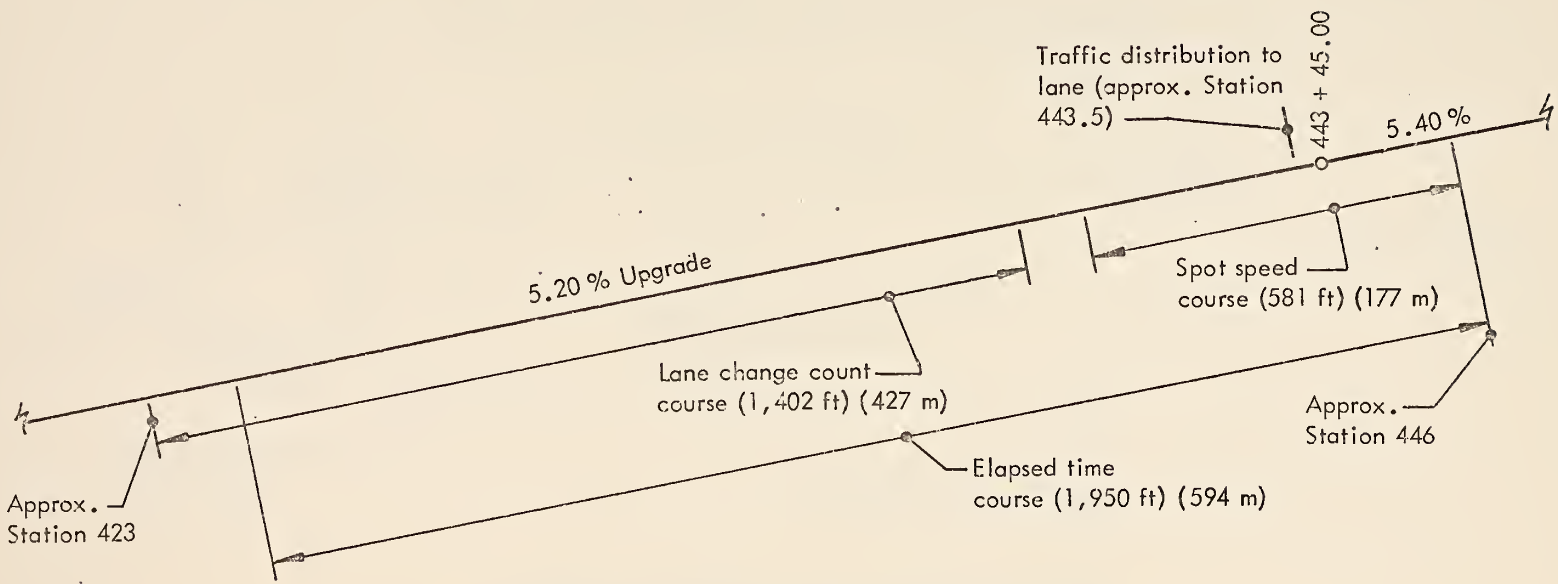


Gradeline and Locations of Data Collection Areas

Figure 12 - I-80 (Eastbound) Data Collection Location at Climbing Lane Initiation, Site 3-2

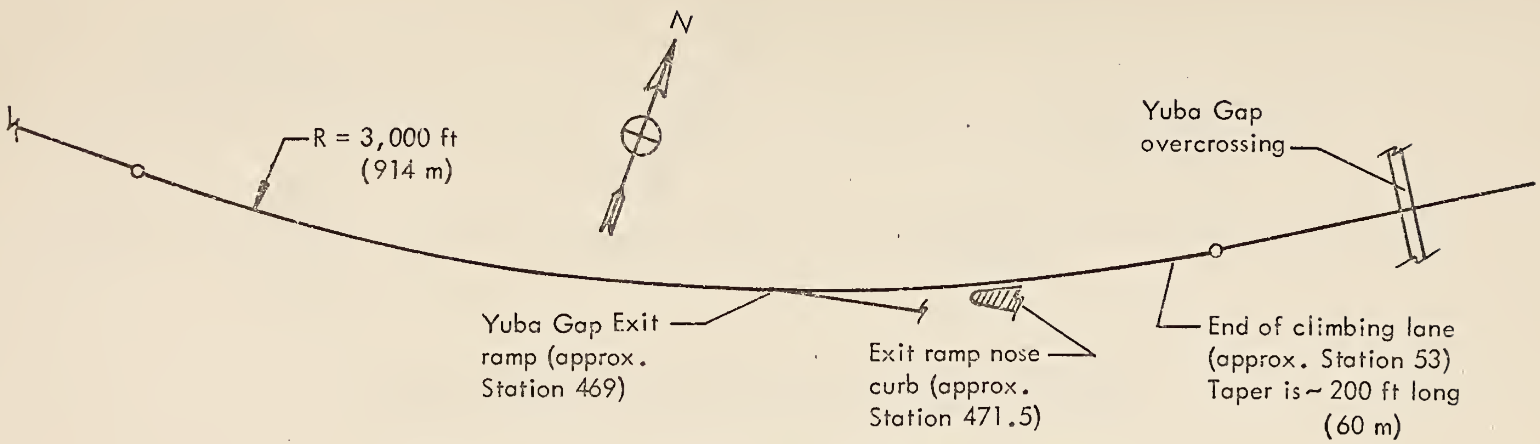


Plan View of Data Collection Region on Established Grade

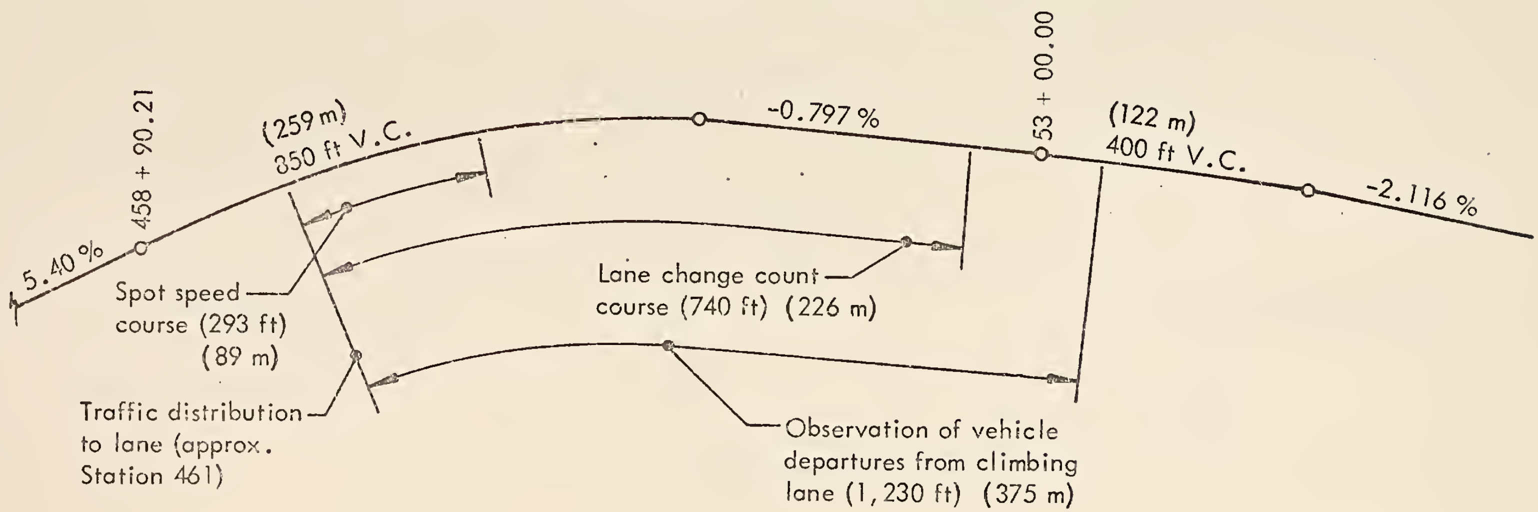


Gradeline and Locations of Data Collections Areas

Figure 13 - I-80 (Eastbound) Data Collection Location on Established Grade, Site 3-3

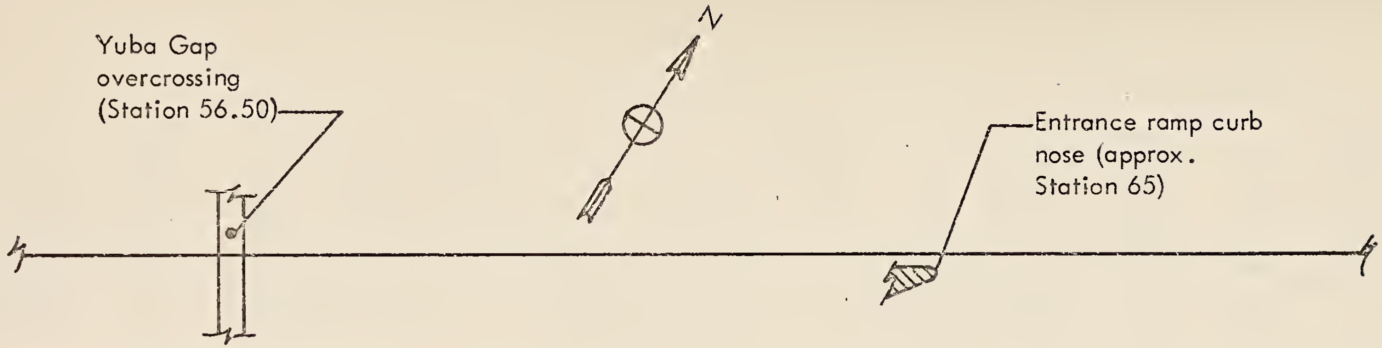


Plan View of Data Collection Region of Climbing Lane Drop

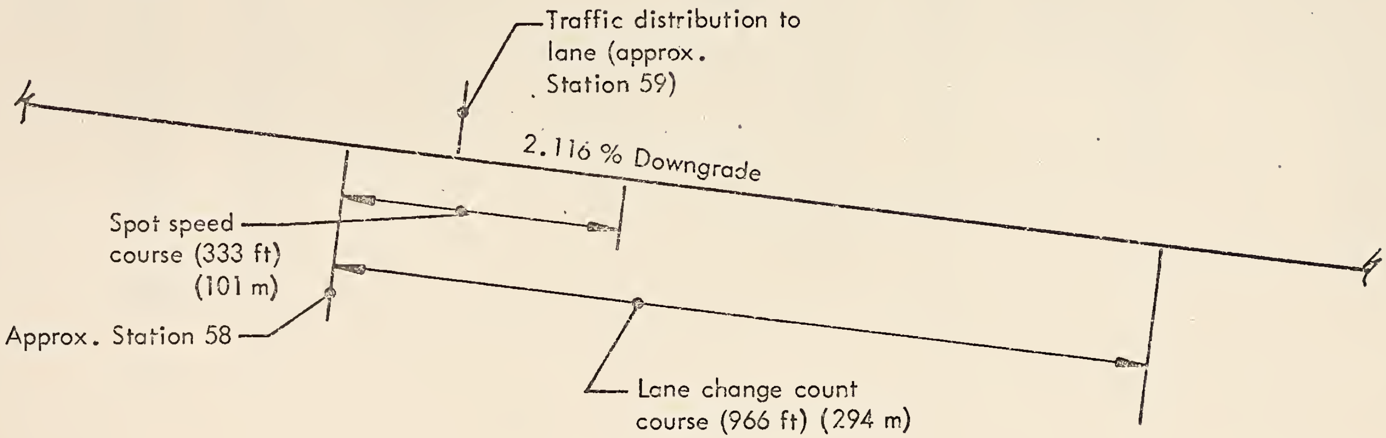


Gradeline and Locations of Data Collection Areas

Figure 14 - I-80 (Eastbound) Data Collection Location at Climbing Lane Drop, Site 3-4



Plan View of Data Collection Region Downstream of Lane Drop



Gradeline and Locations of Data Collection Areas

Figure 15 - I-80 (Eastbound) Data Collection Location Downstream of Lane Drop, Site 3-5

TABLE IV

DATA COLLECTED ON EASTBOUND I-80

Upstream of Climbing Lane Initiation, Site 3-1

Distribution to lane - 97 min
Spot speeds - 97 min
(Sample size 87)

At Climbing Lane Initiation, Site 3-2

Distribution to lane - 174 min
Lane change count - 82 min
Spot speeds - 82 min
(Sample size 66)
Vehicle maneuvers at climbing lane initiation - 157 min
(Sample size 101)

On Established Grade (5.2% to 5.4%), Site 3-3

Distribution to lane - 130 min
Lane change count - 61 min
Spot speeds - 59 min
(Sample size 138)
Elapsed time - 460 min (2 persons)
(Sample size 490)

At Climbing Lane Drop, Site 3-4

Distribution to lane - 242 min
Lane change count - 201 min
Spot speeds - 184 min
(Sample size 188)
Vehicle maneuvers at climbing lane drop - 134 min
(Sample size - 75)

Downstream of Crest and Climbing Lane Drop, Site 3-5

Distribution to lane - 20 min
Lane change count - 18 min
Spot speeds - 9 min
(Sample size - 11)

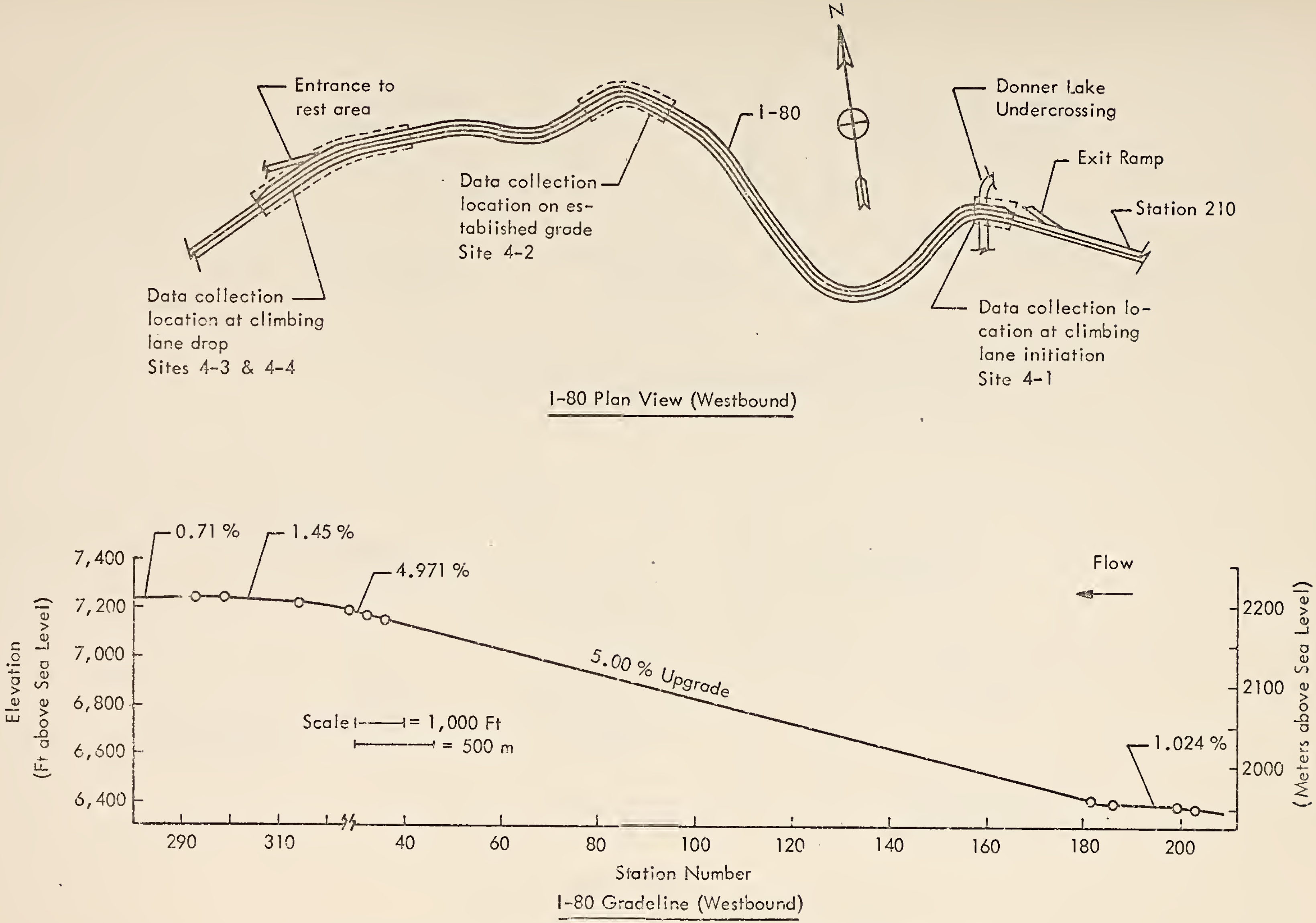
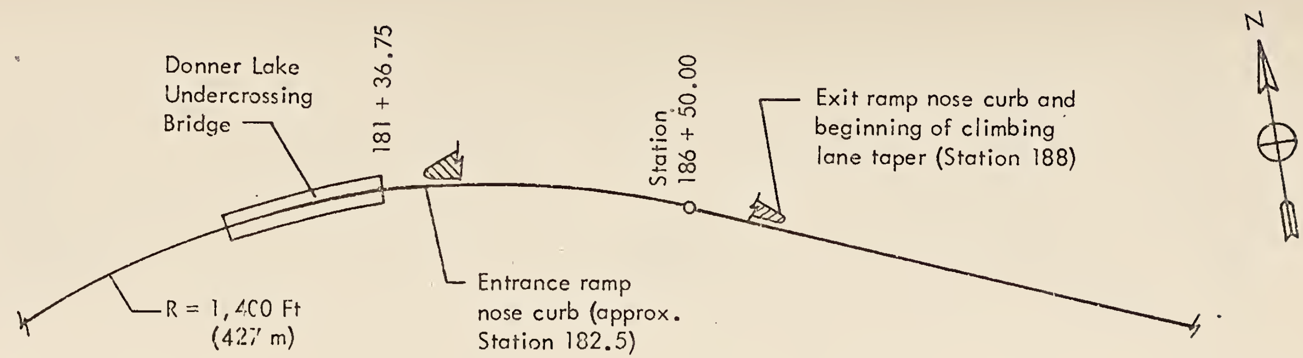
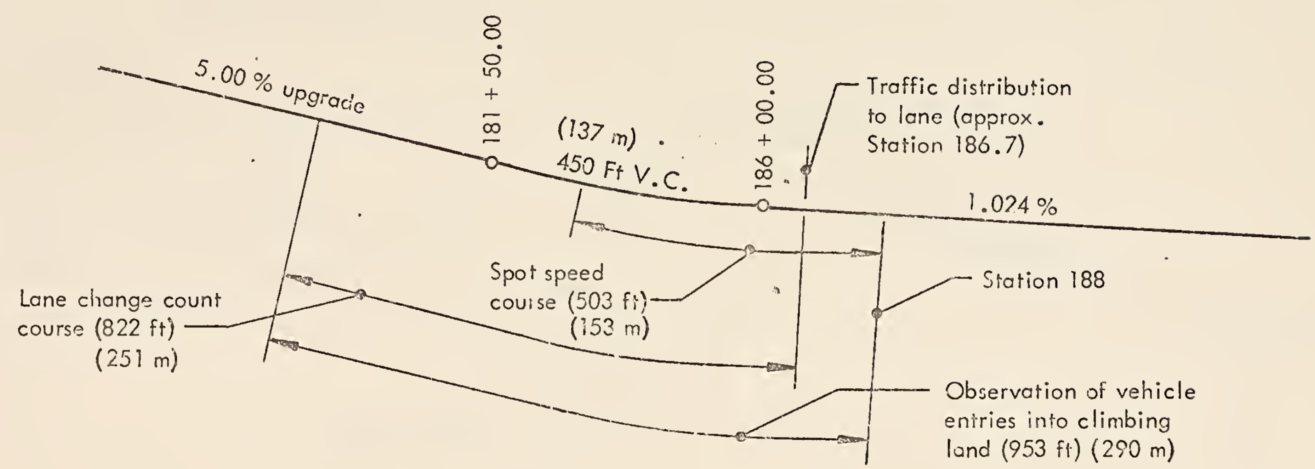


Figure 16 - Data Collection Sites on Westbound I-80



Plan View of Data Collection Region at Climbing Lane Initiation



Gradeline and Locations of Data Collection Areas

Figure 17 - I-80 (Westbound) Data Collection Location at Climbing Lane Initiation, Site 4-1

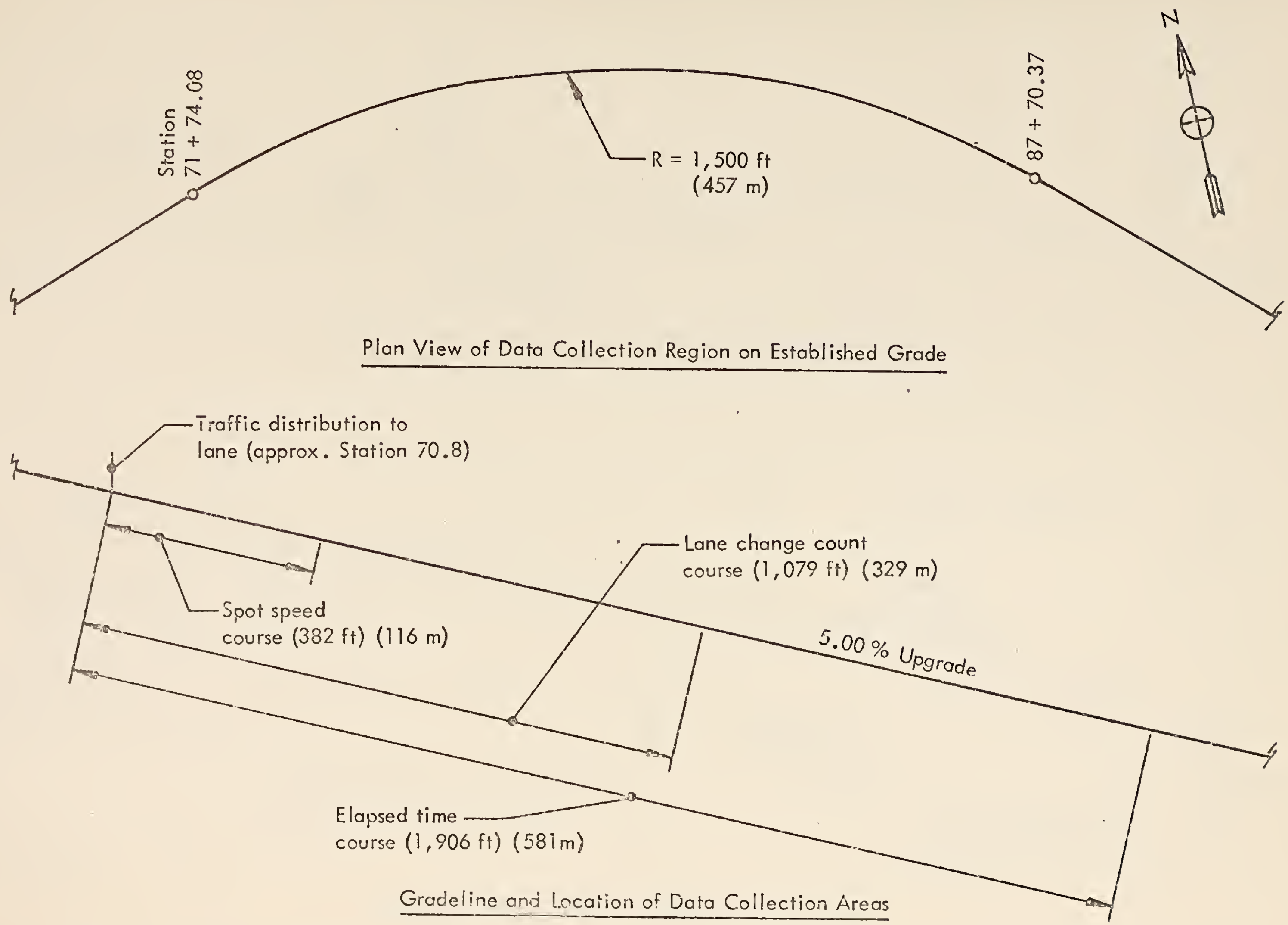
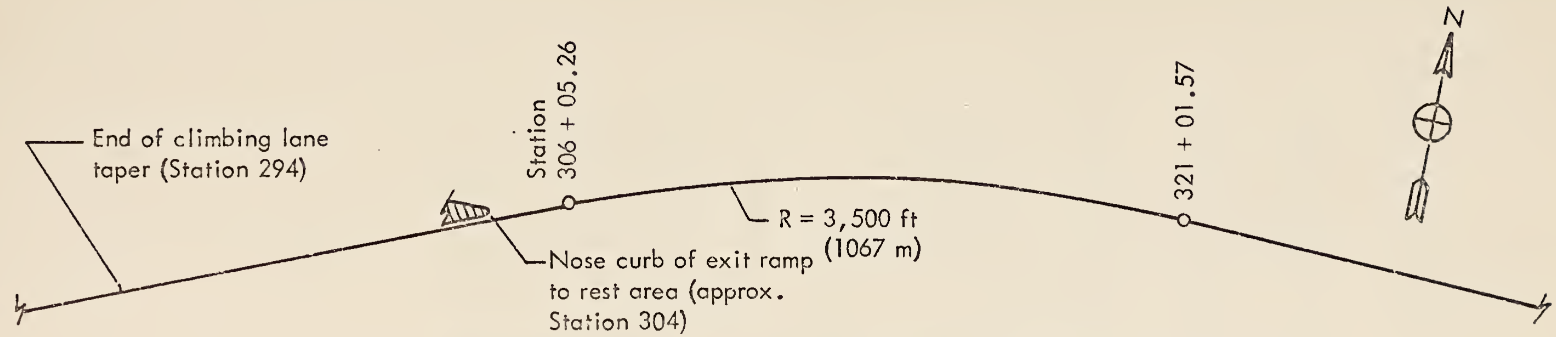
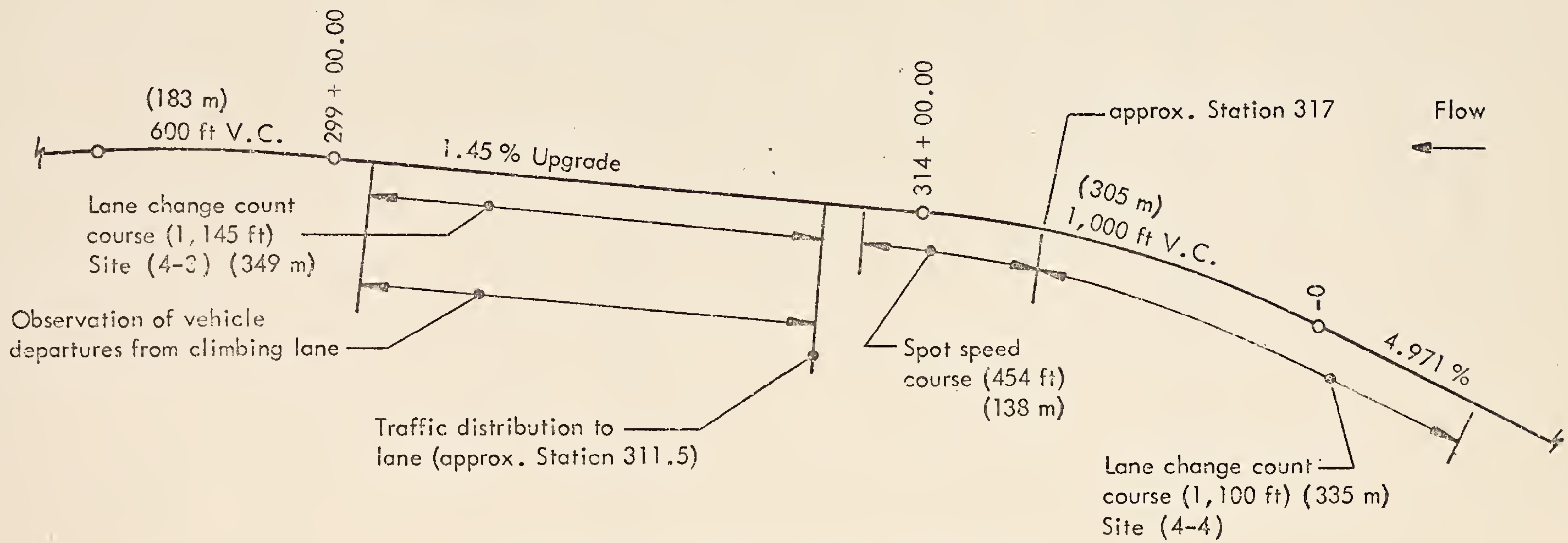


Figure 18 - I-80 (Westbound) Data Collection Location on Established Grade, Site 4-2



Plan View of Data Collection Region at Climbing Lane Drop



Gradeline and Locations of Data Collection Areas

Figure 19 - I-80 (Westbound) Data Collection Location at Climbing Lane Drop, Sites 4-3 and 4-4

TABLE V

DATA COLLECTED ON WESTBOUND I-80

At Climbing Lane Initiation, Site 4-1

Distribution to lane - 200 min
Lane change count - 150 min
Spot speeds - 200 min
(Sample size - 137)
Vehicle maneuvers at climbing lane initiation - 200 min
(Sample size - 113)

On Established Grade (5%), Site 4-2

Distribution to lane - 200 min
Lane change count - 98 min
Spot speeds - 102 min
(Sample size - 275)
Elapsed time - 400 min (2 persons)
(Sample size - 531)

At Climbing Lane Drop, Sites 4-3 and 4-4

Distribution to lane - 150 min
Lane change count upstream of observation post - 50 min
Lane change count downstream of observation post - 128 min
Spot speeds - 122 min
(Sample size - 122)
Vehicle maneuvers at climbing lane drop - 142 min
(Sample size - 95)

B. Data Collection Procedures

The data were collected manually by temporary employees (obtained through Kelly Services, Inc.) under the supervision of MRI personnel. Simple procedures were employed. The only equipment and materials required were stopwatches, hand tally counters, data forms and clipboards.

1. Traffic counts (for lane distribution): These data included 1-min counts of traffic, distinguishing both vehicle type and lane occupied. The vehicle types distinguished were:

Passenger cars and two-axle pickup trucks
Truck with unknown number of axles
Truck with two axles
Truck with three axles
Truck with four axles
Truck with five or more axles
Camper
Travel trailer
Utility trailer
Boat on trailer
Bus (commercial and school)
House trailer

Counts were made for 50 min followed by a 10-min break. Two observers were required. At the beginning of a 50-min period, a clipboard-mounted stopwatch was started and allowed to run uninterrupted. One observer monitored the watch, called out 1-min intervals and counted traffic in the leftmost lane. Passenger vehicles were tallied on a hand counter and other vehicles were noted on special data forms.* The hand counter reading was recorded at the end of each minute. The other observer counted traffic in the remaining lane (or lanes) by noting the passage of vehicles by type on the data forms.

2. Spot speeds: These data included the time for vehicles to traverse a 300- to 500-ft (90-150 m) course, and also an estimate of the number of passenger and nonpassenger type vehicles in platoon behind the subject vehicle. The traverse times were obtained by an observer with a stopwatch. The speed course was generally delineated by available features such as paddle markers, guard rail ends, etc. Occasionally, it was necessary to install markers in which case 3 ft by 6 ft white canvas panels were used, staked to the ground at the edge of the shoulder.

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* Code symbols were assigned to each vehicle type to facilitate the recording.

Each clock minute was not noted on the data sheets; rather, the observer noted the time at frequent intervals, usually 3 to 5 min.* (In analyzing the data, the speed measurements were assigned to specific minutes, subjectively, using the general criterion that the measurements were made uniformly in time.) Observers taking spot speeds were instructed to give priority to trucks, buses, campers and trailers. The vehicle types distinguished in the traffic counts were also identified in the spot speed data.

The spot speed observers also made the lane change counts since sufficiently large samples could be obtained by a single observer. The normal procedure was to alternate between spot speeds and lane changing at 10-min intervals.

3. Lane change counts: Lane change counts were made by one observer over roadway sections approximately 1,000 ft (300 m) long. The counts were made over 1-min intervals, the lane vacated and lane entered were identified, and two general vehicle classes were distinguished--trucks and nontrucks.

The procedure was entirely manual, i.e., observed lane changes were recorded on specially prepared data forms. The lane change courses were delineated by available features whenever possible; occasionally it was necessary to install canvas panel markers. Course lengths of 1,000 to 1,200 ft (300-360 m) were selected after experience showed that one observer could not reliably monitor longer courses. In some cases vantage point deficiencies forced the use of courses shorter than 1,000 ft (300 m).

As noted earlier, the lane change counts were made alternately with spot speed measurements by a single observer.

4. Elapsed times or travel times: These data are similar to the spot speed data except the vehicles were timed over a longer course--in the neighborhood of 2,000 ft (600 m). Also, elapsed times were measured only on the established grade, whereas spot speeds were measured on the foot and crest as well. Vehicle platooning was estimated as in the case of spot speeds.

* The spot speed observer was usually close enough to the traffic counters to obtain time references. In one or two cases he had to keep time independently.

Two observers were used to measure elapsed times on each grade to insure adequate sample sizes. The observers were instructed to give priority to passenger vehicles, then campers and trailers, and last trucks.

5. <u>Vehicle maneuvers at climbing lane initiation</u>: Travel paths of vehicles in the lane adjacent to the climbing lane at its point of initiation were observed. Attention was almost exclusively focused on nonpassenger class vehicles. The following quantities were obtained.

Speed (by timing over a marked course near the climbing lane initiation)

Vehicle type

Estimated location of lane change if one was made (either into or away from the climbing lane)

Estimated location of leader in the climbing lane if the subject vehicle entered the climbing lane

Time between passage of start of climbing lane and entry into climbing lane

Judgment of whether leader was being overtaken

Number of vehicles in the climbing lane passed by the subject vehicle (subdivided into passenger and nonpassenger classes)

Unequally spaced, opportunely located natural markers were used for measuring speed and estimating locations. The most upstream marker was chosen at or very near the climbing lane initiation and identified as number 0. Subsequent upstream markers were numbered in increasing order.

Speed was measured by timing between marker zero and a marker 500 to 700 ft (150-200 m) downstream. Location estimates were noted on data forms by entering the last marker passed, interpolating when possible. A typical entry might be 3-1/2 indicating an estimated location halfway between markers 3 and 4.

On eastbound I-80, seven markers were in usable view, which encompassed a course 1,340 ft (408 m) long. On westbound I-80, eight markers were in view and the corresponding course length was 953 ft (290 m).

6. <u>Vehicle maneuvers at climbing lane drop</u>: Travel paths were observed of vehicles which were in the climbing lane as they entered the vicinity of the lane termination. Unequally spaced, opportunely located reference markers were again used for measuring speed and estimating locations. The course was selected to provide a reasonably long observation span upstream of the lane drop, commensurate with the view afforded by local vantage points.

On eastbound I-80 the course started 1,345 ft (410 m) upstream of the lane drop and extended to within 115 ft (35 m) of the end of the climbing lane termination taper, providing a course length of 1,230 ft (375 m). Ten reference markers were available to delineate this course, numbered 0 through 9 progressing downstream. On westbound I-80 the view was not as good and the course extended from 1,745 ft (532 m) upstream to 600 ft (183 m) upstream of the end of the climbing lane terminating taper. This provided a course length of 1,145 ft (349 m). Five delineating markers were available, in this case numbered 1 through 5 progressing downstream.

The vehicles observed were randomly selected from those which were in the climbing lane at the upstream course boundary. The following quantities were obtained:

Speed (by timing over a span at the upstream end of the observation course)

Vehicle type

Estimated location where vehicle leaves climbing lane

Number of vehicles in adjacent lane which passed subject vehicle while it was still in the climbing lane (passers subdivided into passenger and nonpassenger classes)

Number of vehicles in climbing lane passed by subject vehicle after it left the climbing lane (passed vehicles subdivided into passenger and nonpassenger classes)

Time between passage of upstream course boundary and exit from climbing lane

C. Analysis Techniques

1. Data encoding: The experimental data obtained from the four grades in California were punched on IBM cards; the complete file includes slightly over 6,000 cards. Various types of codes were developed and will be used subsequently in this report for ease of identification. These codes are described below.

The four grades on which data were collected are coded as follows:

Grade Code	Description
1	I-580 East of Hayward, California
2	I-680 North of San Jose, California
3	I-80 (Eastbound) between Emigrant Gap and the Yuba Gap overcrossing
4	I-80 (Westbound) between the Donner Lake road undercrossing and the Donner Summit

Data were collected at several positions on each grade. The positions were coded in increasing numerical order beginning with the most upstream position, which results in the following:

Grade	Position Code	Description of Location
I-580	1	On grade foot
I-580	2	On 2.4% established grade
I-580	3	On 3.0% established grade
I-680	1	Upstream of grade foot
I-680	2	On grade foot
I-680	3	On 6% established grade
I-680	4	At grade crest
I-80 (Eastbound)	1	Upstream of climbing lane initiation
I-80 (Eastbound)	2	At climbing lane initiation
I-80 (Eastbound)	3	On established grade
I-80 (Eastbound)	4	At climbing lane drop
I-80 (Eastbound)	5	Downstream of climbing lane drop

Grade	Position Code	Description of Location
I-80 (Westbound)	1	At climbing lane initiation
I-80 (Westbound)	2	On established grade
I-80 (Westbound)	3	At climbing lane drop
I-80 (Westbound)	4	At climbing lane drop

Some of the data collection positions had two lanes (in one direction) and some three. The lanes were numbered in increasing order from right to left, i.e., for a two-lane section the right lane is No. 1 and the left No. 2. On three lanes the right, middle and left lanes are, respectively, 1, 2, and 3.

Numerical codes were assigned to data type as shown below:

Data Type Code	Description
1	Traffic counts for distribution to lane
2	Spot speeds
3	Lane change counts
4	Elapsed times
5	Vehicle maneuvers at climbing lane initiation
6	Vehicle maneuvers at climbing lane drop
7	Lane change counts at the upstream course on I-80 (Westbound) at the climbing lane drop

Each data card contains the raw data of one of the seven types which were gathered over a 1-min interval. In other words, there is a card for every minute of each type of data gathered.

2. Preliminary analysis: A magnetic tape was prepared containing the raw data, in a rearranged format, together with a large amount of derived data. This tape contains over 900 records of 710 words each. Each record contains all of the data for a 1-min period at all locations on one grade. The data will be described in a general fashion here. A detailed description of the tape format and a copy of the tape can be obtained by interested parties by contacting the authors.

The major subdivision of the tape is by grades; within grades, the data are arranged chronologically. Each minute's data (a 710 word record) is arranged in the following fashion: elapsed times; vehicle maneuvers at climbing lane initiation; vehicle maneuvers at climbing lane drop; and, for each position code, the traffic counts, spot speeds, and lane changes.

The elapsed times refer to the travel times of vehicles on the established grade. Up to five vehicles were timed in each minute and their travel times and derived average speeds are on the tape. Also, the average speeds for all vehicles by lane and for all lanes are given.

The vehicle maneuvers of interest are lane changing of vehicles near the initiation or drop of the climbing lane. In addition to the location of the lane change, the speed of the vehicle, its type, the location of a new leader, number of passed vehicles, elapsed time from beginning (or end) of climbing lane and other data are recorded. The maneuvers of as many as three vehicles may be recorded each minute at the climbing lane initiation and at the drop.

The traffic counts are arranged by lane and for each lane by vehicle classification. Twelve vehicle classes were identified. Fifteen different subtotals and totals are also calculated and recorded for ease of subsequent analysis.

Spot speeds were determined by timing vehicles over measured sections of roadway. As many as five vehicles were timed at each position on the grade during each minute. The times, speeds, lane occupied and information descriptive of platoons are entered on the tape for each of these five vehicles.

Lane changes during each minute are recorded according to lanes involved and broadly by vehicle classification (truck or nontruck). Also included are totals and derived quantities such as lane changes per vehicle-mile.

3. <u>Stepwise multiple regression analysis</u>: The principal analytical tool used in the analysis of the experimental data was a stepwise multiple regression analysis. A "packaged" computer program was used for these analyses.

To use the program we selected from the tape a dependent variable and a sequence (usually 2 to 10) of candidate independent variables. The data corresponding to these variables were extracted from the tape and placed into arrays for subsequent analysis.

The analysis proceeded as follows:

1. The computer program performed a linear regression analysis of the dependent variable with each of the independent variables, one at a time. The independent variable which reduced the largest proportion of the total sum of squares of the dependent variable was then chosen as the most significant; this variable was retained for further analysis.

2. A multiple regression analysis treating the dependent variable, the independent variable just identified, and each of the remaining independent variables, one at a time, was performed. The independent variable which further reduced the total sum of squares by the largest proportion was then retained as the second most significant.

3. The process of step two was repeated one or more times, each time adding one more independent variable to the multiple regression analysis.

4. The above process was terminated when no additional independent variable could further reduce the total sum of squares by more than a predetermined proportion (we used 1% as the criteria).

At each step of the process--that is, as each new independent variable was retained for further analysis--a tabulation of pertinent statistical parameters was printed. This tabulation consisted of the total sum of squares, the amount and proportion by which this total was reduced, both in this step and cumulatively; the F- statistic, which may be used for tests of significance; the standard error of the estimate; the regression coefficients; the standard errors of the regression coefficients; the t-statistic for each regression coefficient; and the intercept of the regression. Also printed were the mean and standard deviation of each variable, a correlation matrix, and at termination of the analysis, a table of residuals.

It is important that one properly interpret the results of a multiple regression analysis. To this end the t-statistic offers a means of estimating the validity of each term in the regression. For convenience a very brief tabulation of the t-distribution is given in Table VI.

TABLE VI

PERCENTAGE POINTS OF THE t DISTRIBUTION

Degrees of Freedom, f	Confidence (%) 90	95	99
15	1.75	2.13	2.95
20	1.725	2.09	2.845
25	1.71	2.06	2.79
30	1.70	2.04	2.75
40	1.68	2.02	2.70
60	1.67	2.00	2.66
120	1.66	1.98	2.62
∞	1.65	1.96	2.58

The number of degrees of freedom, f, is equal to the sample size, n, less the number of terms in the regression equation (including the intercept). If the magnitude of t derived from the regression exceeds the value given in the 90% column of the table for the corresponding sample size, we can be 90% confident that the relationship is meaningful. Higher confidence is associated with t-values exceeding those given in the other columns. For convenience we shall henceforth refer to the 99% confidence level as "highly significant," the 95% level as "significant" and the 90% level as "barely significant."

For each dependent variable a variety of independent variables were selected as candidates in the stepwise regression analyses. All such variables used and included in this report are displayed in Table VII. The independent variables are identified in the sections which follow.

Additional tests were performed on the field data and regression results. Tests were made to determine if traffic characteristics measured at different grades or at different sites on the same grade were distinct in a statistical sense. Also, some results were tested for the importance of nonlinearities. These tests and results are presented for individual characteristics in the sections of the report which follow.

TABLE VII

CANDIDATE INDEPENDENT VARIABLES

X_1 - total flow (vehicles/min)

X_2 - Percent trucks and buses

X_3 - Percent campers

X_4 - Percent trailers

X_5 - Number of trucks in preceding minute

X_6 - Number of trucks in following minute

X_7 - Number of campers in preceding minute

X_8 - Number of campers in following minute

X_9 - Number of trailers in preceding minute

X_{10} - Number of trailers in following minute

X_{11} - Total flow (100 vehicles/hr)

X_{12} - Flow rate of buses and small trucks (two or three axles) (100 vehicles/hr)

X_{13} - Flow rate of large trucks (four or five axles) (100 vehicles/hr)

X_{14} - Flow rate of buses and small trucks for previous minute (100 vehicles/hr)

X_{15} - Flow rate of large trucks for previous minute (100 vehicles/hr)

X_{16} - Average of X_{11} in the current and previous minutes

X_{17} - Average of X_{12} and X_{14}

X_{18} - Average of X_{13} and X_{15}

X_{19} - Total truck flow rate (100 vehicles/hr, $X_{12} + X_{13}$)

X_{20} - $(X_{11})^2$

X_{21} - $(X_{11})\ (X_{19})$

X_{22} - Camper and trailer flow rate (100 vehicles/hr)

X_{23} - Truck and bus flow rate previous minute (100 vehicles/hr, $X_{14} + X_{15}$)

X_{24} - Truck and bus flow rate following minute (100 vehicles/hr)

D. On-Grade Speed Data

1. Two lanes, one-way, 6% grade: Grade 2, on I-680, is a 6% grade with two lanes each way; data were recorded for the upgrade flow. Speeds of passenger vehicles were obtained over a 4-hr period, starting at noon on a Sunday. During this period, the mean flow rate was 1,600 vehicles/hr with 10-min flows varying from about 1,400 vehicles/hr early in the period to 2,100 vehicles/hr later in the afternoon. Trucks and buses made up an average of 2.1% of the vehicles. There were 5.6% campers and 4.1% trailers. The average passenger vehicle speeds were 72.3 ft/sec (49.3 mph or 79.4 kmph) in the right-hand lane and 86.2 ft/sec (58.8 mph or 94.7 km/h) in the median lane.

The passenger vehicle speed (ft/sec) was used as the dependent variable in a multiple regression analysis. The candidate independent variables were X_1 through X_{10} of Table VII.

The result for passenger vehicles in the right-hand lane is shown in equation (1).

$$\begin{array}{llllll} V_1 = 93.78 & - 0.543X_1 & - 1.120X_2 & - 4.051X_5 & - 0.622X_4 & \\ & & & & & (1) \\ t: & 3.32 & 2.82 & 2.46 & 2.24 & \end{array}$$

Fraction of variance reduced = 0.201.*
Standard error of estimate = 13.67 ft/sec.**

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* The variance of the entire field sample is given by

$$s^2 = \sum_{i=1}^{n} (V_{1i} - \overline{V}_1)^2/(n-1)$$

where the V_{1i} are the n individual data values and $\overline{V}_1$ is the mean of the entire set. After a relation such as equation (1) is obtained by regression the variance is recalculated with $\overline{V}_1$ replaced by the right side of equation (1), i.e., by V_1. This provides the sample variance from the "curve fit," which is less than the original s^2. The fractional reduction in variance estimates how much of the original variance is explained by accounting for the effect of the variables on the right side of equation (1).

** The standard error of estimate is based on the variance which remains around the curve fit. If additional field samples are obtained under the same conditions, two-thirds of them should have V_1 values in the range, $V_1 \pm$ one standard error of estimate.

The terms are given in the order they were accepted into the stepwise multiple regression. The t-values are also given with the equation. The passenger vehicle speeds in the right-hand lane decrease with increases in the total flow, the percent trucks and buses, the number of trucks in the preceding minute, and the percent trailers. The last two terms are significantly related to the passenger vehicle speeds while the other two are highly significant.

The speeds in the median lane are related to the independent variables as shown in equation (2).

$$V_2 = 107.39 - 0.679X_1 - 0.806X_2 - 2.140X_5 \qquad (2)$$

$$t: \quad 4.61 \quad 2.43 \quad 1.72$$

Fraction of variance reduced = 0.215.
Standard error of estimate = 11.76 ft/sec.

In this instance, the number of trucks in the previous minute is only barely significant (the sample size was 135).

To further discriminate the significant variables, a second stepwise multiple regression was run. In this instance the independent variables were X_{11} through X_{15} (see Table VII).

In this instance the right-hand lane passenger vehicle speeds are given by equation (3).

$$V_1 = 90.71 - 0.961X_{11} - 8.386X_{13} - 6.561X_{15} \qquad (3)$$

$$t: \quad 3.36 \quad 2.66 \quad 1.99$$

Fraction of variance reduced = 0.172.
Standard error of estimate = 14.21 ft/sec.

Thus, these speeds are reduced (highly significant) by the presence of large trucks and significantly reduced by the presence of large trucks in the previous minute. Small trucks and buses do not significantly affect passenger vehicle speeds in the right-hand lane.

The results in the median lane are given in equation (4).

$$V_2 = 103.54 - 0.855X_{11} - 9.326X_{13} - 6.820X_{15} \tag{4}$$

$$t: \quad 3.28 \qquad 3.54 \qquad 2.55$$

Fraction of variance reduced = 0.236.
Standard error of estimate = 11.98 ft/sec.

Since the presence of large trucks in the previous minute was found to be nearly as important as the presence of large trucks in the near vicinity of the passenger vehicles, a final regression was performed using 2-min averages. The independent variables were X_{16} through X_{18} (see Table VII).

Equations (5) and (6) give the results of these analyses.

$$V_1 = 95.34 - 1.255X_{16} - 14.465X_{18} \tag{5}$$

$$t: \quad 3.19 \qquad 3.09$$

Fraction of variance reduced = 0.156.
Standard error of estimate = 14.24 ft/sec.

$$V_2 = 109.88 - 17.371X_{18} - 1.231X_{16} \tag{6}$$

$$t: \quad 4.43 \qquad 3.64$$

Fraction of variance reduced = 0.238.
Standard error of estimate = 11.88 ft/sec.

In appraising the regression results, it should be recognized that in each minute of data, one or occasionally two passenger car speeds were obtained in each lane. Thus, the individual speed values are essentially individual vehicle speeds. The standard errors of estimates probably consist largely of the vehicle-to-vehicle speed variance. Under these conditions it would be difficult to detect nonlinearities with regression variables selected according to their capability to reduce variance. The tests for nonlinearities were made using means from stratified data.

Figure 20 presents passenger vehicle speeds in the right and median lanes on the 6% grade as a function of flow rate. The symbols are means of speeds within flow rate strata. All values were calculated using the measurements of individual passenger vehicle speeds. The possibility of nonlinearity was evaluated by using orthogonal polynomials to extract polynomial components. The significance of the polynomial components was determined in a F-test which showed that polynomial regression would not improve the fit.

2. Two lanes, one-way, 2.4% grade: This grade was a 2.4% grade with two lanes each way on Interstate 580. Downstream of the 2.4% grade was a 3% grade which may have influenced the upstream traffic as discussed subsequently.

Data were collected over a 4-1/2 hr period starting at 1:00 PM on a Friday. Ten-minute flow rates ranged from approximately 1,700 vehicles/hr to 3,000 vehicles/hr with an overall average of about 2,315 vehicles/hr. The traffic consisted of 7.1% trucks, 3.1% campers, and 1.3% trailers. The average passenger vehicle speed in the right-hand lane was 80.1 ft/sec (54.6 mph or 87.9 km/h) and 85.9 ft/sec (58.5 mph or 94.2 km/h) in the median lane.

A stepwise multiple regression analysis was performed using independent variables X_1 through X_{10}. Passenger vehicle speeds in the right-hand lane are given in equation (7).

$$\begin{array}{llll} V_1 = 102.73 & - 0.637X_1 & + 0.626X_3 & \\ t: & 7.20 & 1.69 & \end{array} \qquad (7)$$

Fraction variance reduced = 0.314.
Standard error of estimate = 11.76 ft/sec.

The relationship with X_3 is just barely significant and, judging by the sign, may be spurious.

Passenger vehicle speeds in the median lane are given by

$$\begin{array}{lll} V_2 = 121.98 & - 0.871X_1 & - 2.286X_8 \\ t: & 7.78 & 2.30 \end{array} \qquad (8)$$

Fraction of variance reduced = 0.371.
Standard error of estimate = 13.34 ft/sec.

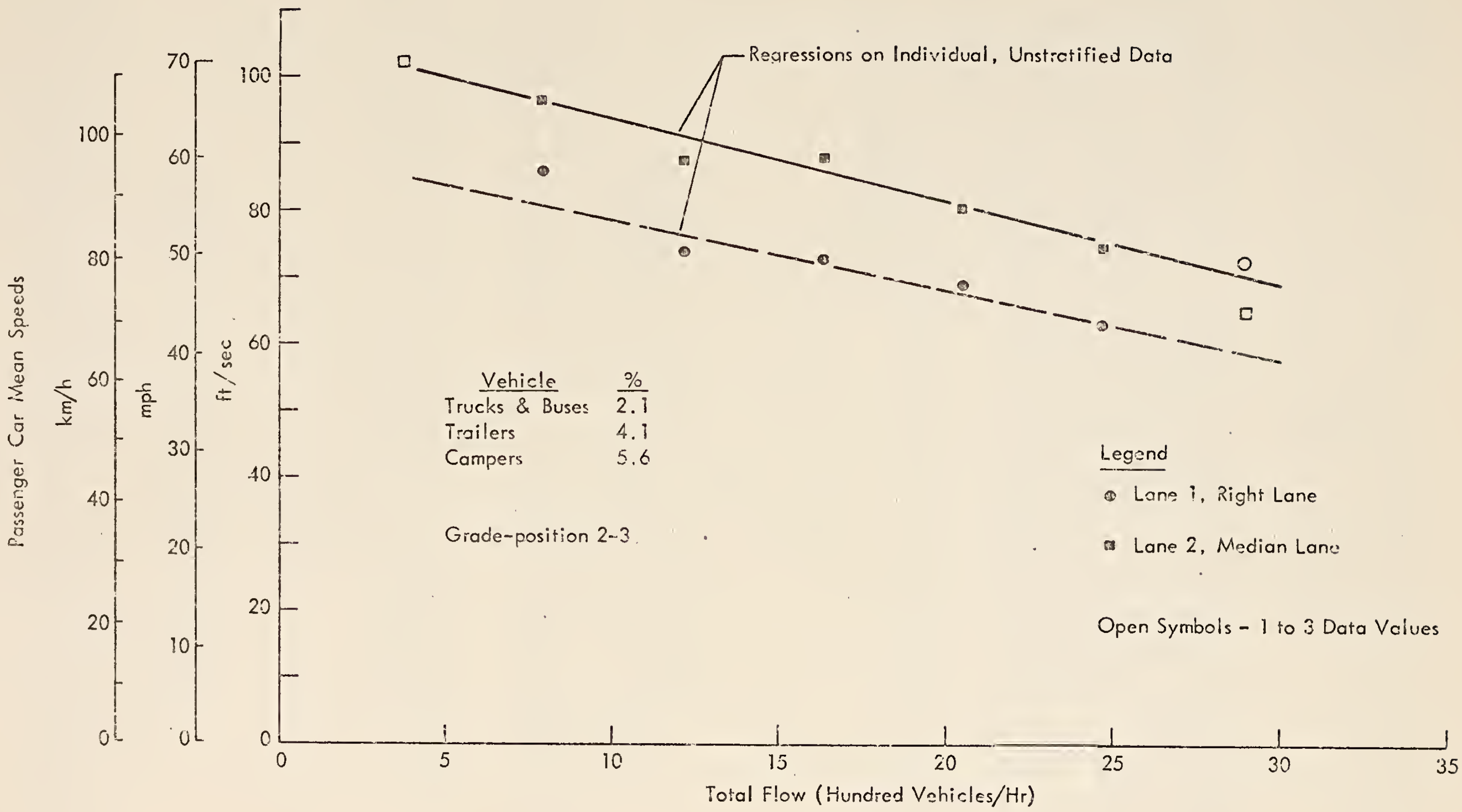

Figure 20 - Passenger Vehicle Speeds on 6% Grade, Data Stratified on Flow

The relationship with X_8, the number of campers in the following minute, is significant. Campers may force slower passenger cars to use the median lane; however, a similar influence from trucks should be obtained. The sample size was 128 individual minute intervals.

The range of flow rates observed extends close to 4,000 vehicles/hr. Since these higher flow rates are near capacity, the passenger car speeds may be expected to exhibit a nonlinear trend with flow rate; that is, the speed should be nonlinear with flow rate for high flows, although at low flow rates (say, below 3,000 vehicles/hr) it should be linear. Therefore, further analysis was undertaken, splitting the data into high and low flow rates. For these analyses, X_{11}, X_{19}, X_{20}, and X_{21} were used as candidate independent variables. X_{20} and X_{21} were used only for high flow rates, where a nonlinear trend was expected.

For flow rates under 3,000 vehicles/hr, passenger vehicles in the right-hand lane are given by:

$$\begin{aligned} V_1 &= 96.549 - 0.660X_{11} \\ t&: \qquad\quad 2.84 \end{aligned} \tag{9}$$

Fraction of variance reduced = 0.073.
Standard error of estimate = 12.22 ft/sec.

which is highly significant. However, no independent variable was significantly related to the passenger vehicle speeds in the median lane, so no equation is given.

For higher flow rates (greater than 3,000 vehicles/hr) the passenger vehicle speeds in the right-hand lane are given by:

$$\begin{aligned} V_1 &= 114.93 - 1.392X_{11} \\ t&: \qquad\quad 1.73 \end{aligned} \tag{10}$$

Fraction of variance reduced = 0.090.
Standard error of estimate = 11.69 ft/sec.

The nonlinear terms were not significant. Here again, none of the four independent variables were significantly related to the passenger vehicle speeds in the median lane, so no equation is given.

In view of the failure of the analysis to elicit the anticipated results, the data were examined in a slightly different way. Three-minute averages rather than 1-min averages were used. Because of the longer time period, the division between high and low flow rates was lowered, for the analysis, from 3,000 to 2,700 vehicles/hr.

The results for low flow rates were nearly identical with those given above, so will not be repeated here. However, at high flow rates, passenger vehicle speeds were determined to follow equations (11) and (12).

$$V_1 = 109.51 - 1.268X_{11} \qquad (11)$$

$$t: \qquad 2.77$$

Fraction of variance reduced = 0.180.
Standard error of estimate = 11.93 ft/sec.

$$V_2 = 102.21 - 0.034X_{20} \qquad (12)$$

$$t: \qquad 3.33$$

Fraction of variance reduced = 0.235.
Standard error of estimate = 14.21 ft/sec.

Both results are highly significant (n = 37). The passenger vehicle speeds in the median lane do appear to be quadratic rather than linear with flow.

The remarks made about the 6% grade data also apply here. That is, the standard error of estimate is due largely to the speed variance between individual passenger vehicles. This variance reduces the ability of the stepwise regression to select nonlinear independent variables. Consequently, the speed data from individual vehicle measurements were stratified in minute flow rates. In Figure 21 the symbols are mean speeds within speed strata. Tests confirmed the importance of nonlinear terms, and regression on the mean speeds provided the forms shown. The expressions for mean passenger car speeds in the right and median lanes are:

$$V_1 = 83.30 + 0.820\ X_{11} - 0.037\ X_{11}^2 \qquad (13)$$

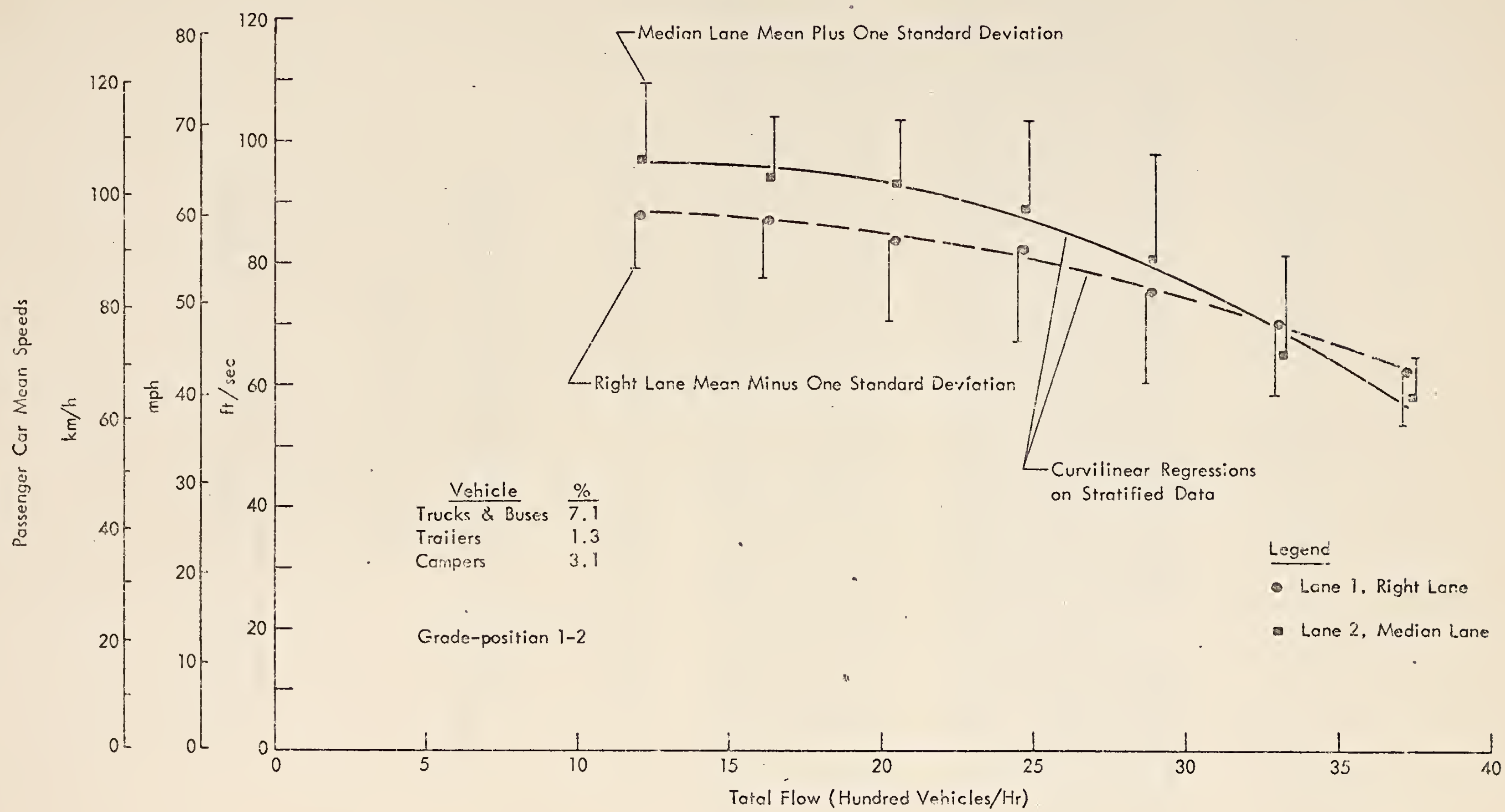

Figure 21 - Passenger Vehicle Speeds on 2.4% Grade, Data Stratified on Flow

and

$$V_2 = 83.75 + 1.870\ X_{11} - 0.070\ X_{11}^2 \tag{14}$$

where the V's have units of ft/sec and X_{11} is the total mixed flow (both lanes) in hundreds of vehicles per hour ($10 \leq X_{11} \leq 38$). In the derivations of equations 13 and 14 equal weights were given to each of the points shown in Figure 21.

3. <u>Three lanes, one-way, 5.2-5.4% grade</u>: Eastbound Interstate 80 between Emigrant Gap and Yuba Gap contains an added climbing lane and is on a 5.2-5.4% grade. The flow rate averaged 945 vehicles/hr with relatively little variation over the period of observation. The average speeds for passenger vehicles were 66.9, 83.8, and 91.1 ft/sec (45.6, 57.1 and 62.1 mph or 73.4, 91.9, and 100.0 km/h) in the right-hand, center, and median lane, respectively. The flow contained approximately 2.7% trucks, 3.3% campers, and 2.8% trailers.

Perhaps due to the relatively narrow range of flows observed (800 to 1,100 vehicles/hr from 10-min counts) little relationship was found between passenger vehicle speeds and flow rate. Using variables X_1 through X_{10} as candidate independent variables, the passenger vehicle speeds in the right-hand, center, and median lanes, respectively, were found to be as represented in equations (15) through (17).

$$\begin{array}{llll} V_1 = 78.77 + & 8.135X_9 & - 8.159X_5 & - 0.822X_1 \\ t: & 2.97 & 2.21 & 1.79 \end{array} \tag{15}$$

Fraction of variance reduced = 0.291.
Standard error of estimate = 9.75 ft/sec.

$$\begin{array}{ll} V_2 = 82.73 + & 2.581X_6 \\ t: & 1.95 \end{array} \tag{16}$$

Fraction of variance reduced = 0.043.
Standard error of estimate = 9.07 ft/sec.

$$V_3 = 85.51 + 0.439X_1 - 2.398X_8 \tag{17}$$

$$t: \quad 2.34 \quad 1.95$$

Fraction of variance reduced = 0.137.
Standard error of estimate = 6.79 ft/sec.

The sample sizes (n) were 28, 86 and 57, respectively.

In no instance was the relationship between passenger speeds and total flow rate highly significant. A significance was found however, between median lane passenger vehicle speeds and flow rate but with a positive rather than negative correlation, indicating that vehicle speeds increased with increased flow. For the low flow rates observed this may be, in fact, what occurred. It appears that low speed passenger vehicles may use the median lane at extremely low flow rates, but as the flow rate increases somewhat they tend to move out of the median lane to the right.

Further analysis was done with these data. Variables X_{11}, X_{19}, and X_{22} were used, with each one measured as a 3-min average.

Passenger car speeds in the right-hand and median lanes were not found significantly related to any of these three variables. In the center lane equation (18) holds

$$V_2 = 81.92 - 7.730X_{19} \tag{18}$$

$$t: \quad 1.84$$

Fraction of variance reduced = 0.039.
Standard error of estimate = 9.09 ft/sec.

which is only marginally significant.

It was obvious from the range and character of data that nonlinear terms would not be important.

4. Three lanes, one-way, 5.0% grade: The fourth grade on which experimental data were collected was on westbound Interstate 80 towards Donner Pass where there was a 5% grade with climbing lane. Four hours of data were collected on this grade starting at noon on a Sunday. Hourly flow rates, based on 10-min counts, ranged from 1,300 vehicles/hr early in the period to 1,650 vehicles/hr at the end of the period, with an average of 1,435 vehicles/hr. Average speeds were 67.86, 79.56 and 89.46 ft/sec (46.3,

54.3 and 61.0 mph or 74.6, 87.4, and 98.2 km/h) in the right-hand, center, and median lane, respectively. The traffic was composed of 2.5% trucks, 4.2% campers and 4.4% trailers.

Equations (19), (20), and (21) contain the results of multiple regression for the passenger vehicle speeds in each of the three lanes, using X_1 through X_{10} as candidate independent variables.

$$V_1 = 71.12 - 0.799X_3 \qquad (19)$$

t: 2.24

Fraction of variance reduced = 0.081.
Standard error of estimate = 10.57 ft/sec.

$$V_2 = 81.00 - 1.370X_8 \qquad (20)$$

t: 2.11

Fraction of variance reduced = 0.031.
Standard error of estimate = 7.60 ft/sec.

$$V_3 = 90.18 - 0.702X_9 \qquad (21)$$

t: 1.61 (not significant)

Fraction of variance reduced = 0.021.
Standard error of estimate = 5.21 ft/sec.

As was the case with the eastbound Interstate-80 grade, just discussed, total flow rate had little influence on vehicle speeds, at least over the small range of flow rates observed.

Using 3-min averages and X_{11}, X_{19}, and X_{22} as candidate independent variables, passenger vehicle speeds in the right-hand and center lanes were found to satisfy equations (20) and (21).

$$V_1 = 97.17 - 2.093X_{11} \qquad (22)$$

t: 3.26

Fraction of variance reduced = 0.157.
Standard error of estimate = 10.13 ft/sec.

$$V_2 = 82.97 - 2.749X_{22} \tag{23}$$

$$t: \qquad 2.14$$

Fraction of variance reduced = 0.032.
Standard error of estimate = 7.62 ft/sec.

No significant relationships could be found for the median lane. It is noted, however, that the speeds in the right-hand lane, using 3-min averages, are highly significantly related to total flow rate.

Data collection sites 3-3 and 4-2 are very similar. Both have the third climbing lane and grades from 5.0 to 5.4%. Tests were made on the regression results for individual lanes at the two sites. Between sites, the slopes of the speed versus flow relations were statistically indistinguishable. The intercepts for the right lanes and for the median lanes were indistinguishable between sites. The middle lane intercepts were barely distinguishable. However, when data from the two sites were combined, the standard errors of estimate were not worsened. The results from the combined data are shown in Figure 22 and presented in equations (24) through (26).

$$V_1 = 75.21 - 0.617\, X_{11} \tag{24}$$

Standard error of estimate = 10.64 ft/sec.

$$V_2 = 88.96 - 0.631\, X_{11} \tag{25}$$

Standard error of estimate = 8.32 ft/sec.

$$V_3 = 91.91 - 0.149\, X_{11} \tag{26}$$

Standard error of estimate = 5.92 ft/sec.

where V_1 , V_2 and V_3 are passenger car mean speeds (ft/sec) in the right, middle, and median lanes. X_{11} is the total mixed flow rates, 100 vehicles/hr ($9 \le X_{11} \le 18$).

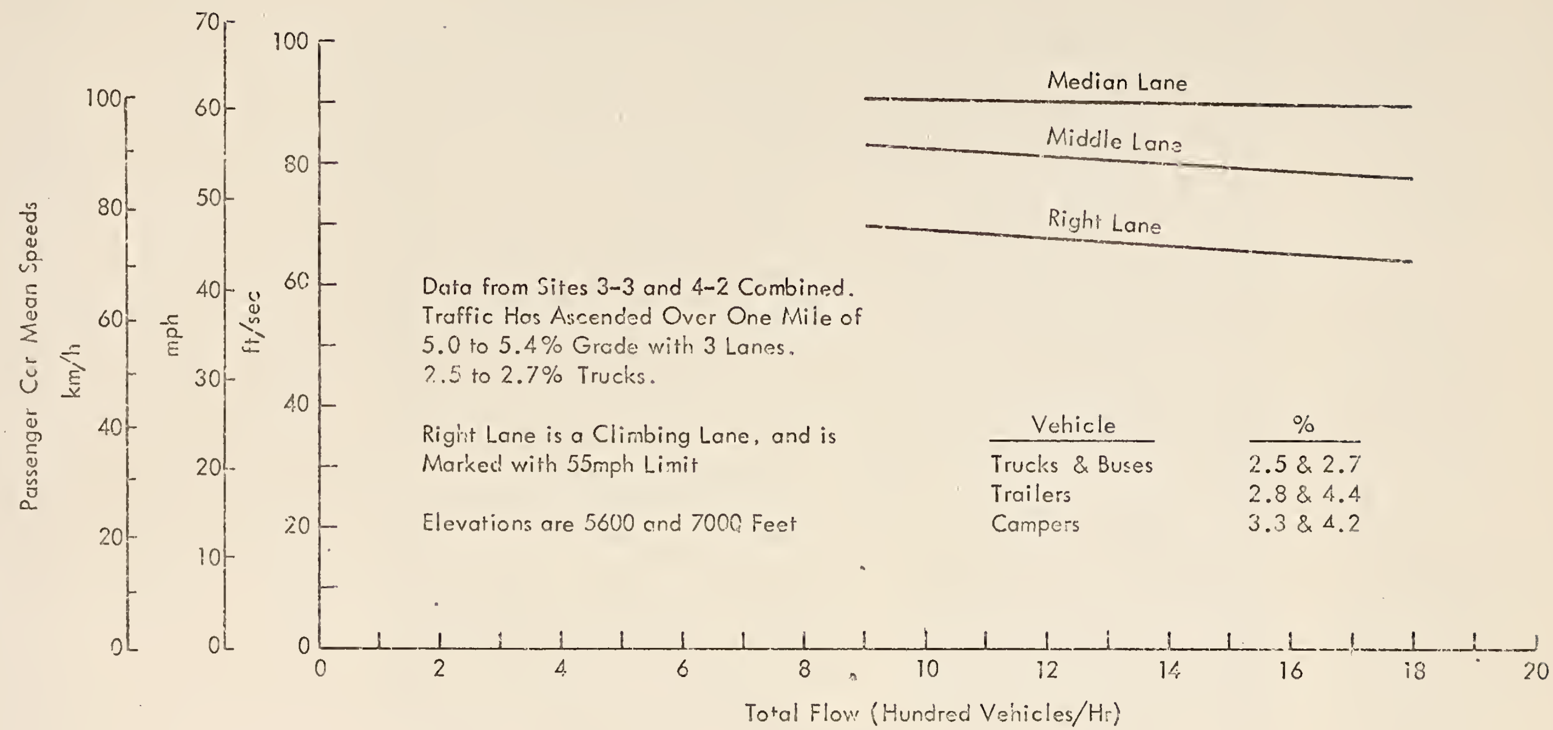

Figure 22 - Passenger Car Mean Speeds on a 5.0 to 5.4% Grade

E. Distribution to Lane

The traffic counts, by lane and by vehicle type, were analyzed for dependence on other measured quantities. For the first analyses, X_1 through X_{10} (see Table VII) were used as candidate independent variables. The results of the stepwise multiple regression analyses are shown in Tables VIII through X.

Table VIII contains the percentage of vehicles other than trucks in the right-hand lane where there were only two lanes available. The vehicles included passenger cars, two-axle pickup trucks, cars or pickups with trailers, and buses. It seems that almost without exception, the total flow and the percentage of trucks and buses are significant. On Grade 2, the importance of both the percentage of trucks and buses and the total flow are greater on the grade and at the grade crest than they are prior to the grade. Further examination of Table VIII indicates that the fraction of nontrucks in the right-hand lane decreases as the percentage of trucks and buses increases. This fraction also decreases with increases in the total flow,* except at the foot of grade 1.

The independent variables X_7 through X_{10} are not significantly related to the distribution to lane for two-lane flow. Likewise, generally speaking, X_3 through X_6 do not play a strong role. Of the exceptions, the percent of campers (X_3) appears only in one of the analyses, one in which there were only 16 data points. The percent of trailers (X_4) appears in two analyses, in one of which it was the third variable entered, and the other of which it was the first variable entered, but with strange results. The latter case occurred at the foot of grade 2. Although X_4 was the first variable entered in the regression, two other variables, X_1 and X_2, were subsequently entered. The addition of X_2 decreased the significance of X_4 in the regression analysis to a nonsignificant status. Further examination showed that at this data collection site, X_2 and X_4 were correlated with a correlation coefficient of 0.262.

* The number of significant digits corresponding to X_1 was small in some of the initial analyses due to an unfortunate program limitation in print format which was overcome in subsequent runs by suitable normalization.

TABLE VIII

PERCENTAGE OF NONTRUCKS IN RIGHT-HAND LANE OF TWO LANES, ONE-WAY*

Independent Variables	Grade 1 (I-580)			Grade 2 (I-680)				Grade 3 (I-80, Eastbound)	
	Grade Foot (1-1)	2.4% Grade (1-2)	3% Grade (1-3)	Upstream of Foot (2-1)	Grade Foot (2-2)	6% Grade (2-3)	Grade Crest (2-4)	Upstream of Lane Addition (3-1)	Downstream of Lane Drop (3-5)
X_1 -- Total Flow (veh/min)	0.30 4.26 (2)		-0.42 2.10 (3)	-0.54 5.34 (1)	-0.36 2.14 (2)	-0.510 6.26 (2)	-0.634 4.54 (2)	-0.895 4.77 (1)	-1.737 2.81 (2)
X_2 -- % Trucks & Buses	-0.807 4.89 (1)	-0.956 8.93 (1)	-0.602 3.01 (1)	-0.634 4.53 (2)	-0.490 1.78 (3)	-1.608 8.98 (1)	-1.695 6.46 (1)	-0.849 2.99 (2)	
X_3 -- % Campers									1.051 3.10 (1)
X_4 -- % Trailers					-0.370 1.44 (1)		0.506 2.03 (3)		
X_5 -- No. Trucks in Preceding Minute	-0.828 2.40 (3)		-1.735 2.33 (2)						
X_6 -- No. Trucks in Following Minute	-0.658 1.74 (4)								
Intercept	25.6	35.7	50.6	54.9	46.4	46.6	55.3	65.0	70.7
n	84	206	51	138	76	238	72	84	16
Fraction of Variance Reduced	0.466	0.281	0.302	0.306	0.170	0.354	0.592	0.303	0.735
Standard Error of Estimate	5.0	7.4	9.6	6.9	8.7	9.1	7.8	10.7	9.6

* Each entry consists of the regression coefficient followed by the t-statistic and, in parenthesis, the order in which the term was selected.

TABLE IX

PERCENTAGE OF NONTRUCKS IN EACH OF THREE LANES ON GRADE 3 (I-80 EASTBOUND)*

Independent Variables	Position 2 400 ft Downstream from Beginning of Climbing Lane Taper			Position 3 on 5.2% Grade 6,300 ft from Foot			Position 4 Near End of 5.4% Grade and About 1,000 ft Upstream of Lane Drop		
	Right	Center	Median	Right	Center	Median	Right	Center	Median
X_1 -- Total Flow (veh/min)		-0.969 6.99 (1)	1.030 7.72 (1)	-0.446 2.45 (4)	-0.934 3.55 (1)	1.377 5.87 (1)	-0.206 1.99 (3)	-0.677 4.55 (1)	0.931 6.08 (1)
X_2 -- % Trucks & Buses		-0.518 3.45 (2)	0.569 3.96 (2)	-0.638 3.28 (2)		0.644 2.58 (2)	-0.464 4.50 (1)		0.413 2.70 (2)
X_3 -- % Campers	0.290 2.98 (2)		-0.292 2.12 (3)	0.309 1.66 (5)					
X_4 -- % Trailers	0.697 5.56 (1)	-0.556 3.01 (3)		0.611 3.13 (1)	-0.673 2.40 (2)		0.525 4.10 (2)	-0.440 2.40 (2)	
X_5 -- No. Trucks in Preceding Minute	-1.377 2.07 (3)								
X_6 -- No. Trucks in Following Minute								-2.228 1.93 (3)	
X_7 -- No. Campers in Preceding Minute				-3.310 2.56 (3)	3.505 1.87 (3)				
X_8 -- No. Campers in Following Minute									
X_9 -- No. Trailers in Preceding Minute	-1.539 1.92 (4)								
X_{10} -- No. Trailers in Following Minute									
Intercept	5.94	62.29	31.62	23.43	66.54	9.15	14.85	60.31	25.21
n	208	208	208	121	121	121	229	229	229
Fraction of Variance Reduced	0.189	0.235	0.276	0.265	0.163	0.249	0.155	0.123	0.153
Standard Error of Estimate	7.6	11.0	10.6	10.1	14.5	13.0	8.8	12.6	13.0

* Each entry consists of the regression coefficient followed by the t-statistic and, in parenthesis, the order in which the term was selected.

TABLE X

PERCENTAGE OF NONTRUCKS IN EACH OF THREE LANES ON GRADE 4 (I-80 WESTBOUND)*

Independent Variables	Position 1 About 100 ft Past Beginning of Lane Addition Taper			Position 2 on 5% Gradt at End of 1,500 ft Radius Curve			Position 3 on 1.4% Grade, 1,000 ft After 5% Grade and 1700 ft from Lane Drop			Position 4 on 5% Grade Near Crest VC. 3,400 ft From Lane Drop		
	Right	Center	Median	Right	Center	Median	Right	Center	Median	Right	Center	Median
X_1 -- Total Flow (veh/min)		-0.730 7.76 (1)	0.708 7.43 (1)	-0.233 2.54 (3)	-0.396 3.60 (1)	0.620 5.59 (1)		-0.479 3.34 (1)	0.603 4.00 (1)		-0.411 1.90 (2)	
X_2 -- % Trucks & Buses		-0.821 5.66 (2)	0.795 5.41 (2)	-0.399 2.61 (2)		0.519 2.82 (3)						
X_3 -- % Campers	NO SIGNIFICANT VARIABLES						0.266 1.79 (3)	-0.446 2.12 (2)			-0.763 2.51 (1)	
X_4 -- % Trailers				0.519 4.56 (1)	-0.258 1.90 (2)	-0.275 2.00 (4)	0.308 2.13 (1)					
X_5 -- No. Trucks in Preceding Min												
X_6 -- No. Trucks in Following Min		-1.405 2.32 (3)	1.469 2.40 (3)	-1.140 1.66 (6)		2.081 2.53 (2)	-1.242 1.92 (2)			-2.805 2.12 (1)		3.268 2.00 (1)
X_7 -- No. Campers in Preceding Min				-1.161 2.04 (4)								
X_8 -- No. Campers in Following Min												
X_9 -- No. Trailers in Preceding Min				-1.027 2.00 (5)								
X_{10} -- No. Trailers in Following Min		-0.981 1.72 (4)				1.080 1.76 (5)						
Intercept		60.43	40.42	22.35	52.31	25.83	14.57	55.00	27.99	19.72	53.61	38.15
n	191	191	191	191	191	191	144	144	144	48	48	48
Fraction of Variance Reduced		0.365	0.340	0.223	0.074	0.236	0.092	0.100	0.101	0.089	0.177	0.080
Standard Error of Estimate		8.0	8.1	7.7	9.1	9.3	7.5	10 7	11.2	8.3	9.3	10.3

* Each entry consists of the regression coefficient followed by the t-statistic and, in parenthesis, the order in which the term was selected.

The observed simple correlation coefficient between percent trucks and percent trailers* at grade position 2-2 (r_{TT}, say) is of statistically significant magnitude.** A true association between these two variables was not expected to exist. However, the high correlation coefficient raised the possibility that the sequences of vehicle arrivals by type <u>might</u> be the result of traffic interactions. A thorough investigation, described below, showed that the correlation was due to chance; however, the correlation was still disruptive to the regression process.

The most straightforward way to examine the association is to compute the partial correlation coefficient, r_{TT}. Such a coefficient is often described as "the TT correlation holding everything else constant." Technically, the procedure is to compute the correlation coefficient between T and T from the covariance matrix of the conditional (bivariate) distribution of T and T given everything else (whereas, of course, the simple correlation r_{TT} is extracted from the joint distribution of all the variables). Partial correlation coefficients are interpreted and manipulated in exactly the same way as simple correlation coefficients.***

The computer partial correlation coefficient between percent trucks and percent trailers is $r_{TT} = + 0.1709$, which is not statistically significant.

Although the measures, percent trucks and percent trailers, are quantitative and therefore technically subject to correlation analysis, in fact they appear as units in the 1-min counts at the observation site. Therefore, another way of examining the association is to describe the sequence of trucks and trailers observed, that is, to test the truck-trailer sequence against randomness. This is done by a so-called runs test. The runs test is logically more desirable than a correlation coefficient because it does not depend on linearity; i.e., it is completely general in detecting departures from randomness in the truck-trailer sequence.

The raw data sheets enable the truck-trailer sequence to be conducted by lane. When both trucks and trailers occur in the same minute in different (or both) lanes, however, the order of their appearance is not retrievable from the raw data sheets. Such ambiguous minutes are rare; also,

* "Trailer" signifies a vehicle pulling a trailer.

** Significant with 95% confidence. The minimum detectable magnitude for r_{TT} at 95% confidence at location 2-2 is 0.225.

*** Except that the sample size N in the simple case becomes n-p+2 for the partial case, where p = number of variables in the whole set.

only three trucks were observed in the center lane. Therefore, the runs test was applied to, respectively: (1) the right lane only, and (2) all data with ambiguous minutes deleted. In neither case was the hypothesis of randomness rejected; i.e., in neither case was a statistically significant association between trucks and trailers detected.* However, the observed number of runs was high; i.e., consistent with a positive correlation; and the test statistic was "almost rejectable" (92% confidence).

Finally, the result of $r_{TT} = 0.262$ at location 2-2 was considered as one of the 11 r_{TT} results obtained and examined as a candidate for outlier status. The value of $r_{TT} = 0.262$ at 2-2 cannot be considered extreme when regarded as the maximum reading from a sample of size 11 from a normal distribution with mean zero and standard deviation estimated from the sample. In other words, it is not unreasonable to get one correlation coefficient (out of 11) as large as 0.262 even though the time correlation in question is zero.

Returning to the distributions to lane, Figure 23 shows a graphical representation of the distribution versus total flow rate. The curves were taken from the regression analyses by assuming, arbitrarily, a uniform traffic mix composed of 5% trucks, no campers, and no trailers. Each curve is drawn over the approximate range of flows observed. The figure clearly shows the decreased fraction in the right-hand lane on grade 2 (6%) as one progresses farther up the grade, with the beginnings of a redistribution at the grade crest. The data for grade 3, position 1, could be considered as an extension of the data for grade 2 although the distribution on position 5 of grade 3 was undoubtedly influenced by the lane drop immediately upstream. Likewise, position 3 of grade 1--a 3% grade--appears to be an extension of the other results. Position 1-2 was apparently little affected by flow rate, but position 1-1, at the grade foot, exhibited an increasing trend due to the positive coefficient, as pointed out above.**

The initial regression results shown in Figure 23 raised questions concerning the distinguishability of the results obtained for individual grade-positions. Statistical tests on the slopes and intercepts indicated that the results for 1-3, 2-1, 2-2, and 2-4 were statistically indistinguishable. The combined data provided the regression result in equation (27).

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* $Z_{\text{right lane}} = 1.75$, $Z_{\text{all}} = 1.61$, where Z = standard normal variable.

** This phenomenon, an increase in the percentage of traffic in the right-hand lane as capacity is approached, was noted in some earlier simulation studies (Contract CPR-11-5093, Final Report, Vol. II, pp. 49-50, 1970).

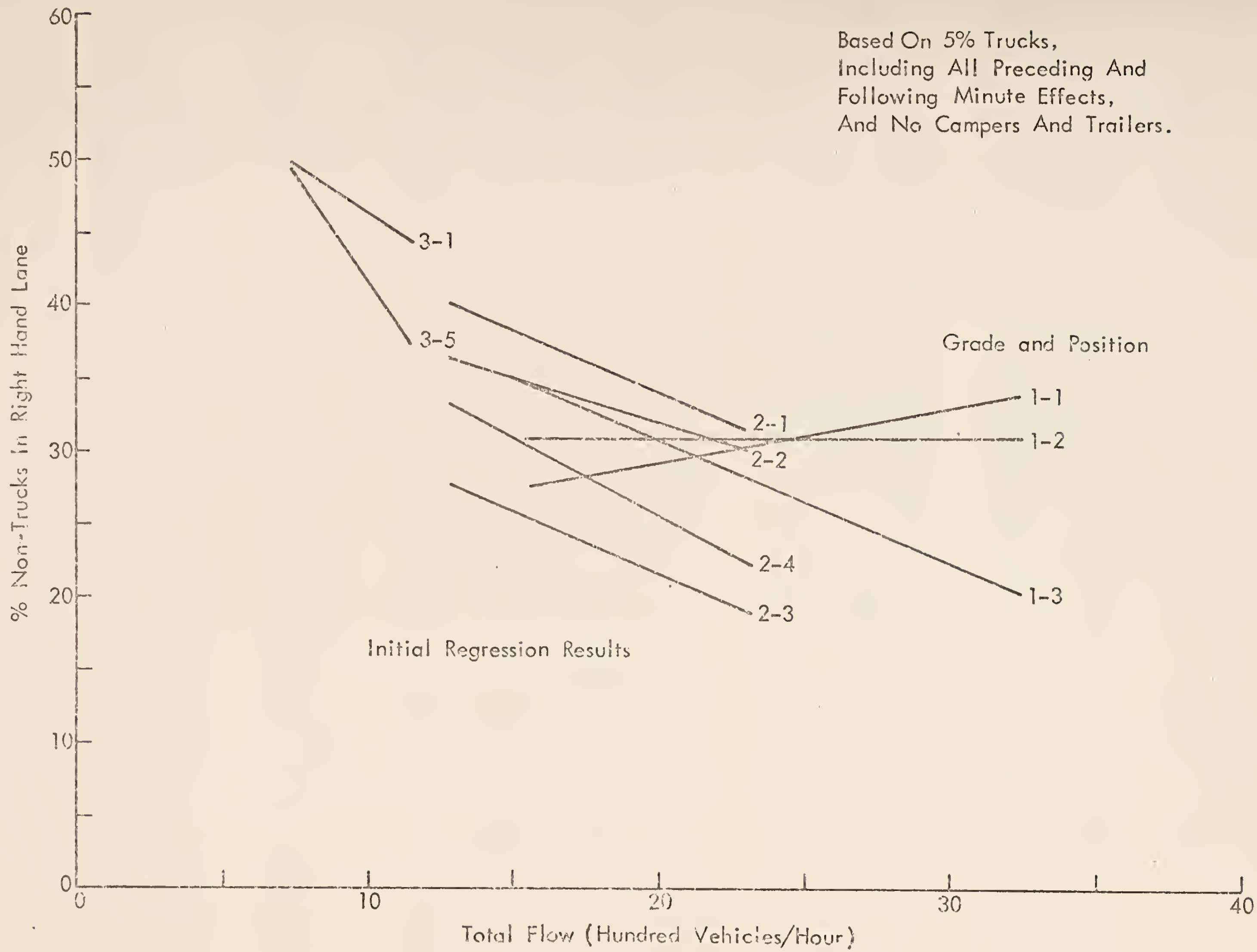

Figure 23 - Distribution to Lane for Two-Lane, One-Way Flow on Grade

$$Y = 45.98 - 0.712 X_{11} \quad (27)$$

Standard error of estimate = 8.65 ft/sec.

where Y = percent nontrucks in right lane of two lanes.

X_{11} = total mixed flow, 100 vehicles/hr, $12 \leq X_{11} \leq 33$.

The final results are shown in Figure 24. Notice that the distribution at 2-3, on the 6% grade, was found to be distinguishable from the values at the foot and crest locations. The low values at 2-3 indicate the extent to which nontrucks vacate the right lane with a small percent of slow trucks.

Table IX shows the distribution to lane of nontrucks on grade 3, which has a climbing lane. It should be noted that the sum of the intercepts for the three lanes is approximately 100%, and the sum of the coefficients of each X is approximately zero, but the sums are not exact. This is because the selections of terms for the regressions were not identical in each lane.

Variables X_5 through X_{10} play only a subsidiary role in these regressions, and X_1, X_2 and X_4 are the most important. The X_1 coefficients indicate that with increased flow, the median lane percentage increases with a corresponding decrease in the center lane percentage and to some extent in the right-hand lane percentage. The median lane flow also increases as the percentage of trucks increases. At position 2, at the climbing lane initiation where there is relatively little traffic in the right-hand lane, the nontruck traffic tends to shift from the center lane to the median lane as the truck percentage increases. Further up the grade, more nontrucks are found in the right-hand lane, but these tend to move out of that lane as the truck percentage increases.

Trailers and campers are both included as nontrucks. The influence of X_3 and X_4 can probably be explained by the fact that campers and trailers often tend to use the right-hand lane.

Table X contains the results of stepwise regression analyses for grade 4. Many of the comments concerning Table IX apply here also. However, several additional observations may be made. First of all, there was almost no traffic in the right-hand lane at position 1, 400 ft after begin-

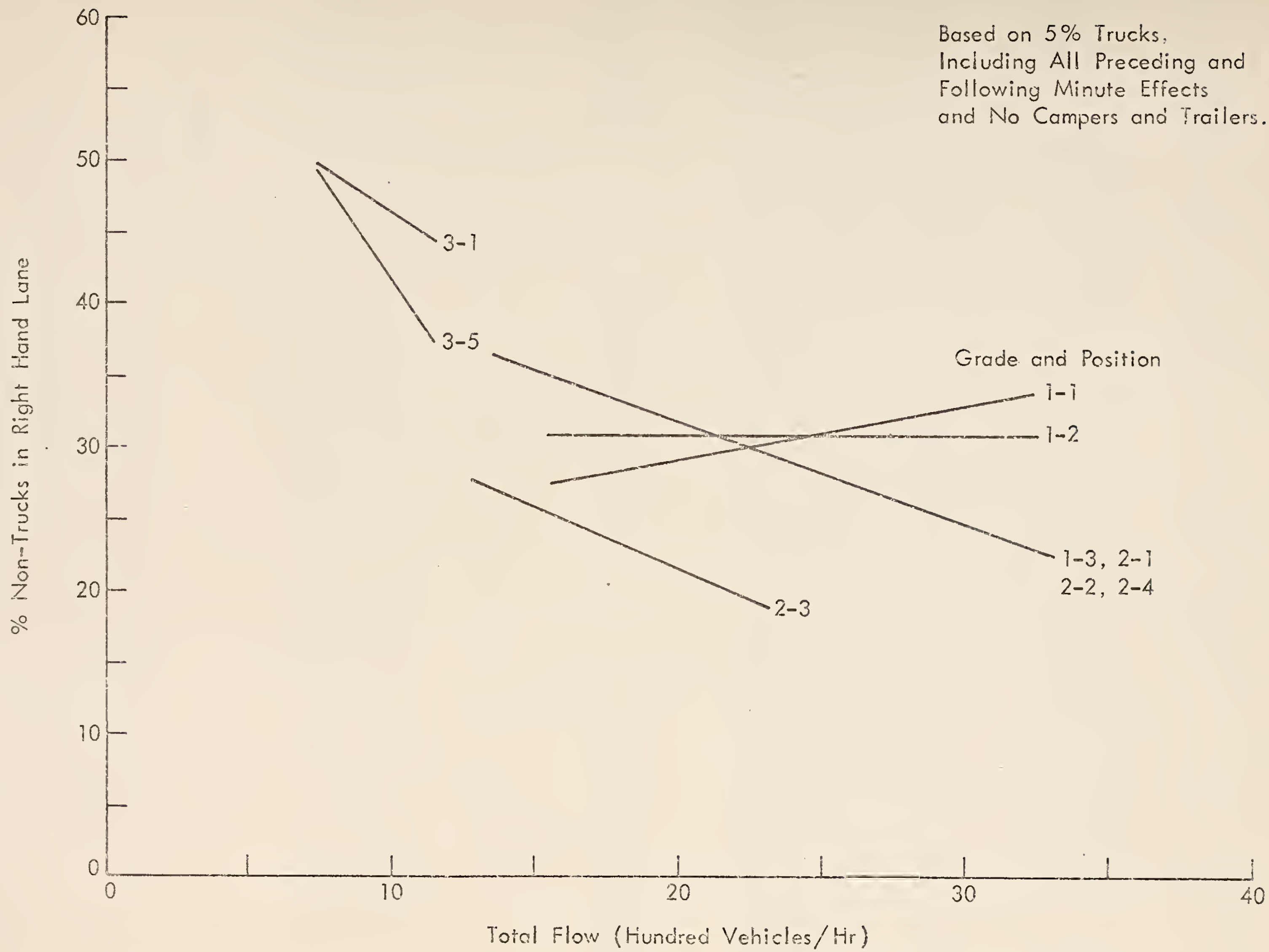

Figure 24 - Distribution to Lane for Two-Lane, One-Way Flow on Grade--Combined Data

ning of the climbing lane taper (the mean was 0.6%). This low volume explains the failure of a significant analysis. The percentage of trucks has no influence on the distribution to lane at positions 3 and 4. It should be recalled that these positions are near the end of the climbing lane.

Variable X_6, the number of trucks in the following minute, did have a significant effect on the distribution to lane. Its effect was to drive traffic out of the right-hand lane. Apparently, vehicles that have recently passed a truck are reluctant to reenter the right-hand lane.

The data in Tables VIII, IX, and X enabled the direct calculation of the percentage of nontrucks in each lane. For traffic engineers who wish to use these relationships, the terms involving campers and trailers may be a complicating factor. If the flow rates of these vehicles are known, of course, there is no complication, but this is not always the case. Rather than arbitrarily deleting these terms from the equations, it would be better to substitute the experimentally observed values on which the regression analyses were based. For reference they are repeated below:

Grade Code	Percentage Campers	Percentage Trailers
1	3.1	1.3
2	5.6	4.1
3	3.3	2.8
4	4.2	4.4

Terms in the equation, such as flow rate of trailers, can be converted to the product of percentage trailers and total flow rate where necessary. Finally, in using the regression for design purposes or comparison with other data, it is acceptable to replace quantities such as number of trucks in previous minute with the truck flow rate per minute.

F. Lane Changing Rates

Lane changing was examined from the viewpoint of the driver. The number of lane changes per vehicle-mile for nontrucks, a measure of driver activity, was used as the dependent variable. The independent variables were X_{11} (total flow rate, 100 vehicles/hr), X_{19} (truck and bus flow rate, 100 vehicles/hr), X_{23} (truck and bus flow rate preceding minute, 100 vehicles/hr), X_{24} (truck and bus flow rate following minute, 100 vehicles/hr).

At each grade position, the originating lane and direction of the lane change (alternatively, destination lane) were noted. Stepwise multiple regression analyses were then run for each lane pair as well as for the total of all lane changes.

Table XI shows the results on grade 1, the 2.4% grade. At position 2, on grade, the regressions had significance. The effect of increasing truck and bus flow is to increase the lane changing activity of nontrucks. However, the coefficient of X_{11} is negative, indicating that the lane change rate decreases with increased total flow. It must be remembered that the lane change rate can decrease if either the number of lane changes decreases or if the travel, in vehicle-miles, increases. In either case, however, the lane changing activity is decreased from the individual driver's viewpoint.

At position 1 on grade 1, most of the regressions were insignificant except that the lane change rate from the median to the right-hand lane was found to be weakly dependent (and with marginal significance) upon the truck and bus flow rate the preceding minute.

Figure 25 shows the total lane change rates vs. flow on grade 1. The curves are drawn over the approximate range of validity. The curve labelled 1-1 simply indicates the mean lane change rate observed, since no significant relationship to flow rate was found.

Statistical tests indicated that neither the slopes nor intercepts of the curves in Figure 25 were undistinguishable. The relations are statistically distinct.

The regression results for grade 2, the 6.0% grade, are displayed in Table XII. However, statistical tests on the total lane change rates indicated that the intercepts and slopes for the 2-1 and 2-3 grade positions were statistically indistinguishable. The combined results provide the relation given in equation (28).

$$R = 0.9856 - 0.0270\ X_{11} \qquad (28)$$

Standard error of estimate = 0.4379

where R = lane changes per vehicle-mile for nontrucks.

X_{11} = 100 vehicles/hr of total mixed flow, $9 \le X_{11} \le 25$.

TABLE XI

LANE CHANGES PER VEHICLE-MILE FOR NONTRUCKS ON GRADE 1 (I-580)*

Independent Variables	Position 1 2-Right	Position 1 1-Left	Position 1 All	Position 2 2-Right	Position 2 1-Left	Position 2 All
X_{11} -- Total Flow (100 veh/hr)		NOT SIGNIFICANT	NOT SIGNIFICANT		-0.00340 1.76 (1)	-0.00673 2.48 (2)
X_{19} -- Truck & Bus Flow (100 veh/hr)				0.0615 4.08 (1)		0.0644 3.42 (1)
X_{23} -- Truck & Bus Flow Preceding Minute (100 veh/hr)	0.0440 1.85 (1)					
X_{24} -- Truck & Bus Flow Following Minute (100 veh/hr)						
Intercept	0.0220			0.0368	0.1744	0.2656
n (No. of 1-min Samples)		32	32	110	110	110
Fraction of Variance Reduced	0.102			0.134	0.028	0.143
Standard Error of Estimate	0.122			0.149	0.132	0.187

* Each entry consists of the regression coefficient followed by the t-statistic and, in parenthesis, the order i order in which the term was selected. Lane change rates presented according to originating lane and direction of lane change. Lane 1 is the right-hand lane.

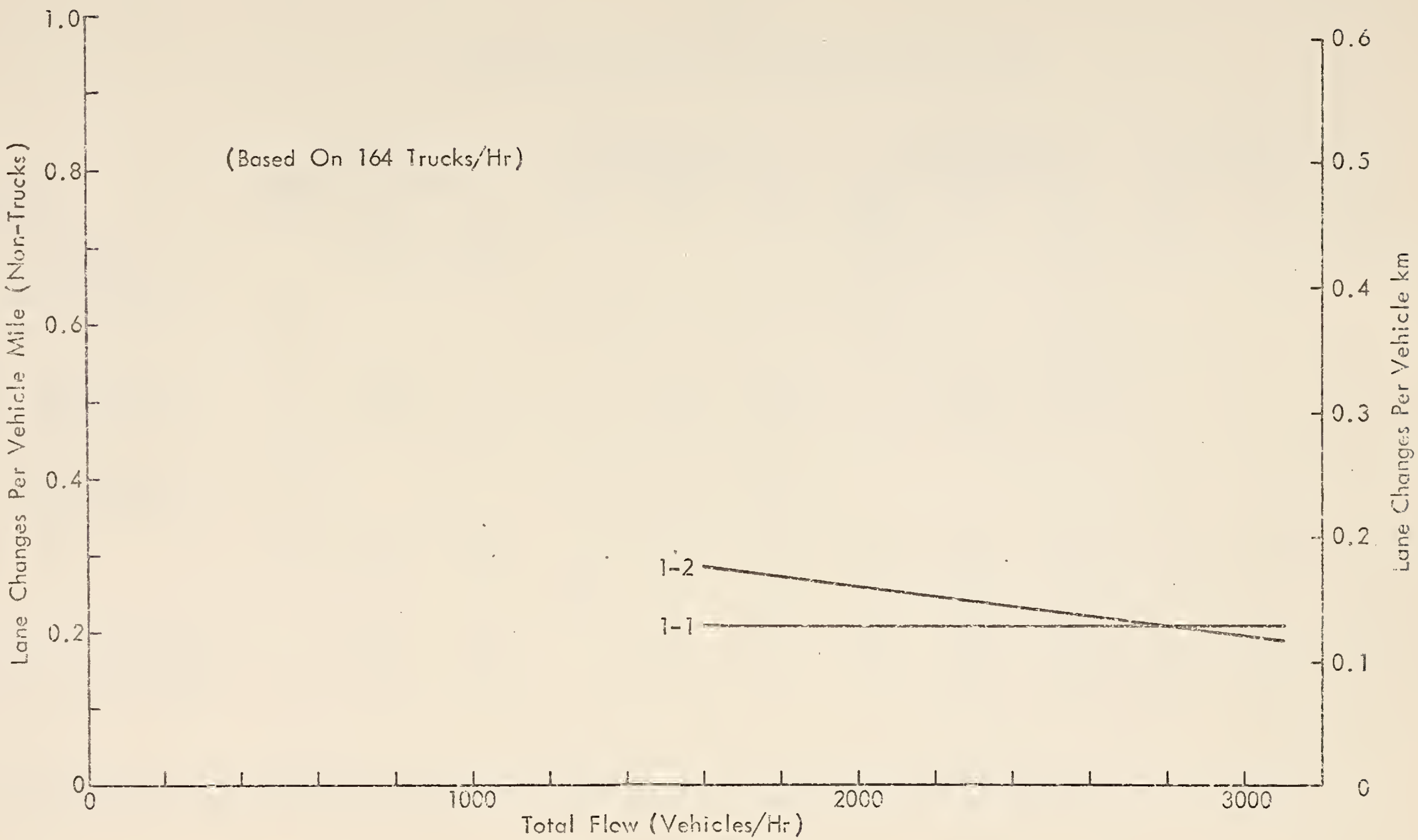

Figure 25 - Lane Changing on 2.4% Grade, Two Lanes Upgrade

TABLE XII

LANE CHANGES PER VEHICLE-MILE FOR NONTRUCKS ON GRADE 2 (I-680)*

Independent Variables	Position 1 Upstream of Grade Foot			Position 2 On Grade Foot, After VC to 6% Grade			Position 3 On 6% Grade About 3,000 ft From Foot			Position 4 Near Crest on 2.5% Grade		
	2-Right	1-Left	All	2-Right	1-Left	All	2-Right	1-Left	All	2-Right	1-Left	All
X_{11} -- Total Flow (100 veh/hr)	NOT SIGNIFICANT	-0.01667 2.14 (1)	-0.02240 2.03 (1)	NOT SIGNIFICANT			-0.01892 2.37 (2)		-0.02999 2.28 (2)	-0.03597 2.31 (1)	-0.08772 3.91 (1)	-0.12370 3.57 (1)
X_{19} -- Truck & Bus Flow (100 veh/hr)							0.1595 2.50 (1)		0.2494 2.47 (1)			
X_{23} -- Truck & Bus Flow Preceding Minute (100 veh/hr)		-0.0799 1.77 (2)			0.2055 3.02 (1)	0.2158 2.76 (2)		0.1495 2.33 (1)	0.1907 1.97 (3)			
X_{24} -- Truck & Bus Flow Following Minute (100 veh/hr)					-0.1754 2.58 (2)	-0.2206 2.83 (1)						
Intercept		0.7197	0.9346		0.3062	0.4401	0.5310	0.2243	0.8866	0.8793	2.1557	3.0350
n		67	67	35	35	35	104	104	104	34	34	34
Fraction of Variance Reduced		0.114	0.060		0.281	0.278	0.083	0.051	0.100	0.143	0.323	0.284
Standard Error of Estimate		0.248	0.349		0.292	0.335	0.306	0.333	0.489	0.428	0.618	0.955

* Each entry consists of the regression coefficient followed by the t-statistic and, in parenthesis, the order in which the term was selected. Lane change rates presented according to originating lane and direction of lane change. Lane 1 is the righthand lane.

The distinct regression results are plotted versus total flow in Figure 26. The total lane change rates at positions 2-1, 2-2, and 2-3 are all similar, averaging about 0.5 lane changes/vehicle-mile over the flow range of validity. At position 2-4, the grade crest, the lane change rate is significantly higher; it is also much more strongly dependent on total flow rate.

Lane changing rates on grades with climbing lanes are shown in Tables XIII and XIV and regression curves are plotted in Figure 27. It appears that the two grades do produce similar traffic flow, considering the range of flow rates observed. The horizontal lines in Figure 27 indicate average values--the regressions indicated the flow rate was not a significant parameter. With a constant truck flow rate of 25 trucks/hr on grade 3, the 3-2 and 3-4 results in Figure 27 are statistically indistinguishable. They are retained separately because of the difference in response to truck flow rate.

Finally, a remark is in order concerning the variability of lane change data. Lane changes are relatively rare events in that, in a 1-min time period only a few lane changes are observed over a short observation course. For example, a lane change rate of 0.5 per vehicle-mile would correspond to an average of four lane changes/min over a 1/5-mile (0.32 km) course at a flow rate of 2,400 vehicles/hr. Obviously, observed values fluctuate widely from this average. The observed standard deviation was of the same magnitude as the mean. This variation makes comparisons extremely difficult unless a very large amount of data is available.

G. Vehicle Maneuvers at Climbing Lane Drops

Data were collected at two climbing lane initiations and two drops. At the initiations it was apparent that most heavy commercial vehicles entered the climbing lane promptly. Campers, trailers and low performance passenger vehicles entered the climbing lane (if at all) after their speeds diminished on the upgrade.

At the climbing lane drops data were collected on the locations of merges from the climbing lane to the adjacent through lane. Figure 28 shows the results for the lane drop near the Yuba Gap overcrossing on I-80. At 1,345 ft (410 m) from the lane drop, a graphic sign indicates the drop. This is the second and last explicit warning sign. (A sign 1,945 ft (593 m) upstream displays "Through Traffic Merge Left.") The traffic control is complicated by an exit ramp to the overcrossing road. The painted nose for this ramp is 570 ft (174 m) upstream of the final lane drop; the nose curb is 314 ft (96 m) upstream.

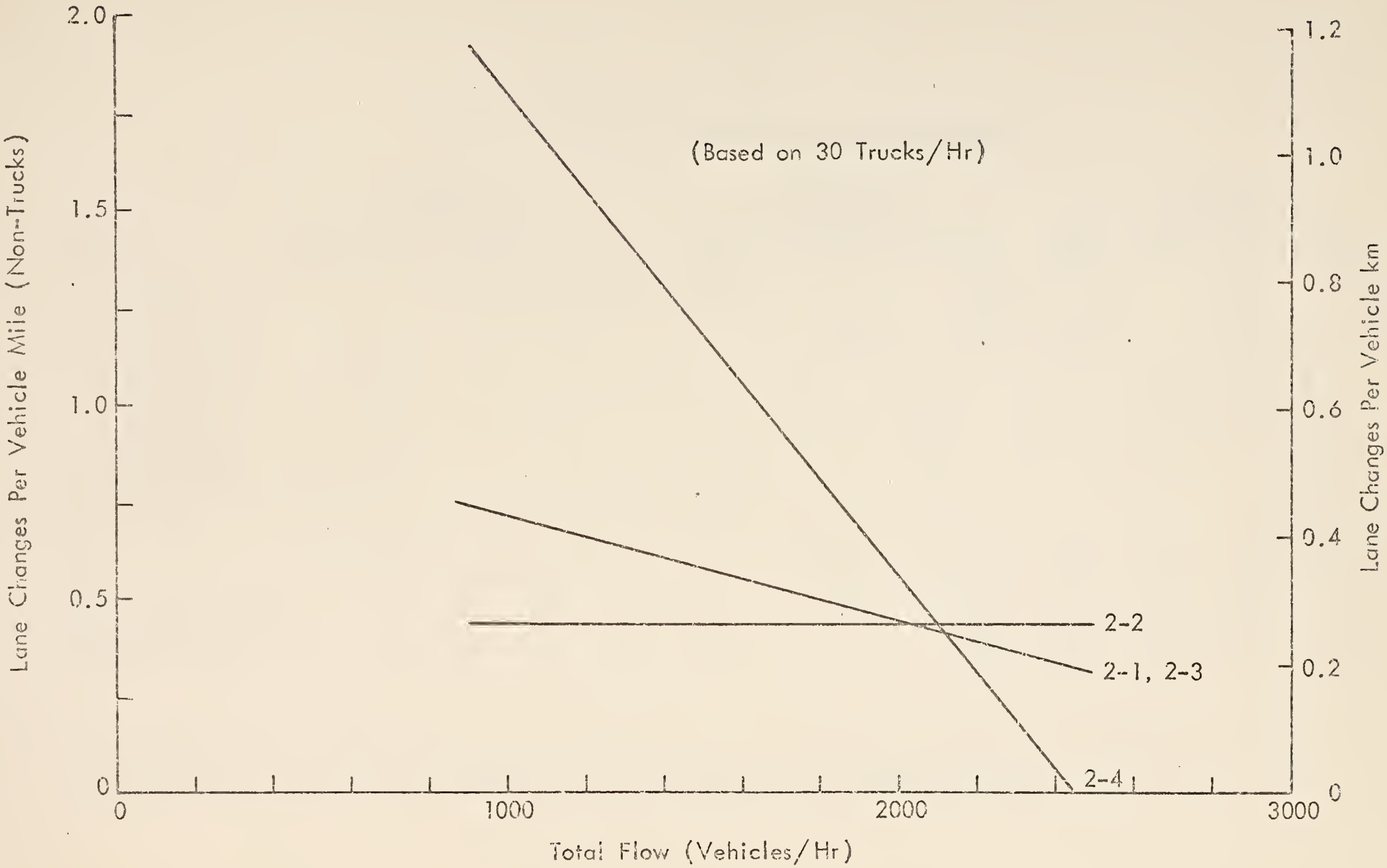

Figure 26 - Lane Changing on 6% Grade, Two Lanes Upgrade

TABLE XIII

LANE CHANGES PER VEHICLE-MILE FOR NONTRUCKS ON GRADE 3 (I-80 EASTBOUND)*

Independent Variables	Position 2 Just Downstream of Lane Addition					Position 3 On Target Section of 5.2% Grade					Position 4 At Crest Before Lane Drop				
	3-Right	2-Left	2-Right	1-Left	All	3-Right	2-Left	2-Right	1-Left	All	3-Right	2-Left	2-Right	1-Left	All
X_{11} -- Total Flow (100 veh/hr)			-0.02708 3.[illegible]3 (1)	-0.01686 2.10 (1)	-0.05816 3.50 (1)	-0.01843 1.99 (1)				-0.03681 2.13 (2)	-0.02283 2.20 (2)		-0.00958 2.19 (3)		-0.04550 3.01 (2)
X_{19} -- Truck & Bus Flow (100 veh/hr)	NOT SIGNIFICANT	NOT SIGNIFICANT					NOT SIGNIFICANT	0.1063 1.73 (1)	NOT SIGNIFICANT	0.3040 2.27 (1)	0.26758 3.46 (1)		0.10795 3.32 (1)	NOT SIGNIFICANT	0.38290 3.41 (1)
X_{23} -- Truck & Bus Flow Preceding Minute (100 veh/hr)												0.17267 2.67 (1)	0.07189 2.22 (2)		
X_{24} -- Truck & Bus Flow Following Minute (100 veh/hr)															
Intercept			0.4201	0.27162	1.1214	-0.3772		0.0993		0.8165	0.3203	0.1923	0.1068		1.0185
n			77	77	77	57		57		57	189	189	189	189	189
Fraction of Variance Reduced			0.116	0.055	0.141	0.067		0.052		0.148	0.072	0.037	0.089		0.085
Standard Error of Estimate			0.250	0.233	0.480	0.203		0.174		0.382	0.462	0.386	0.195		0.673

* Each entry consists of the regression coefficient followed by the t-statistic and, in parenthesis, the order in which the term was selected. Lane change rates presented according to originating lane and direction of lane change. Lane 1 is the righthand lane.

TABLE XIV

LANE CHANGES PER VEHICLE-MILE FOR NONTRUCKS ON GRADE 4 (I-80 WESTBOUND)*

Independent Variables	Position 2: In 1,500 ft Radius H. Curve on 5% Grade					Position 3: Near Crest, On 1.45% Grade, Ending About 700 ft From Lane Drop					Position 4: On Verticle Curve At End of 5% Grade, Ending 2,400 ft From Lane Drop. (Position 4 Is Upstream of Position 3)				
	3-Right	2-Left	2-Right	1-Left	All	3-Right	2-Left	2-Right	1-Left	All	3-Right	2-Left	2-Right	1-Left	All
X_{11} -- Total Flow (100 veh/hr)						NOT SIGNIFICANT	NOT SIGNIFICANT		NOT SIGNIFICANT	-0.02266 2.82 (1)	NOT SIGNIFICANT	NOT SIGNIFICANT	NOT SIGNIFICANT	NOT SIGNIFICANT	
X_{19} -- Truck & Bus Flow (100 veh/hr)			0.0486 1.76 (1)	0.1177 3.29 (1)	0.1465 2.26 (1)			0.0301 1.70 (1)							
X_{23} -- Truck & Bus Flow Preceding Minute (100 veh/hr)															
X_{24} -- Truck & Bus Flow Following Minute (100 veh/hr)	0.0520 1.98 (1)	-0.0525 2.11 (1)													0.2415 1.90 (1)
Intercept	0.0630	0.1066	0.0482	0.0371	0.2615			0.04634		0.7124					0.3378
n	93	93	93	93	93	123	123	123	123	123	48	48	48	48	48
Fraction of Variance Reduced	0.042	0.047	0.033	0.106	0.053			0.023		0.062					0.073
Standard Error of Estimate	0.124	0.118	0.123	0.159	0.288			0.115		0.335					0.473

* Each entry consists of the regression coefficient followed by the t-statistic and, in parenthesis, the order in which the term was selected. Lane change rates presented according to originating lane and direction of lane change. Lane 1 is the righthand lane.

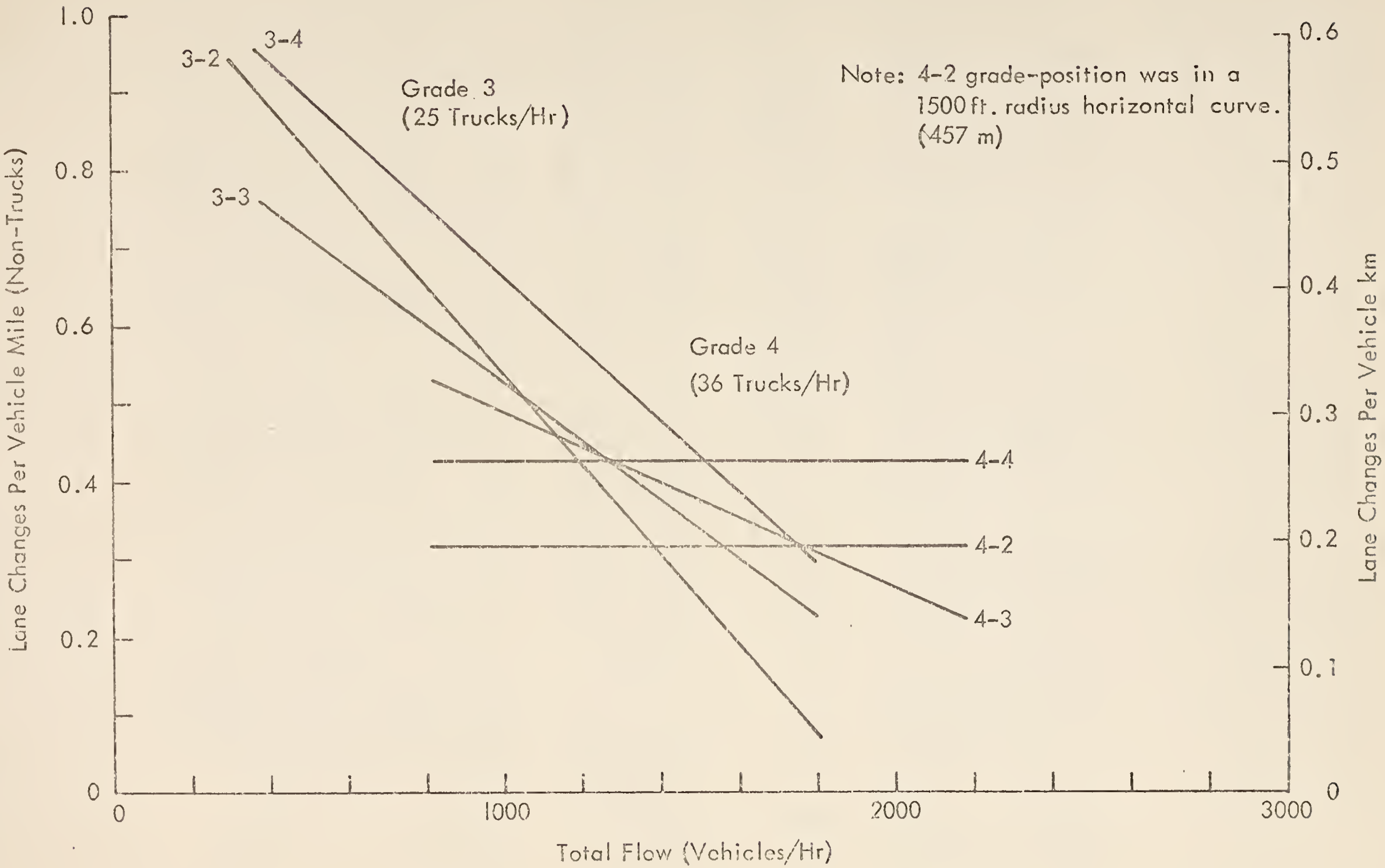

Figure 27 - Lane Changing on 5% Grade with Climbing Lane

Figure 28 shows that merge activity occurred in the vicinity of the warning signs; however, part of this activity may be normal lane changing. The minimum merge rate at around 1,150 ft (350 m) may be due to a combination of vertical and horizontal curvature which degrades the rear sight distance. Most merges are made in the final 1,000 ft (300 m) upstream of the drop. Trucks and buses appear to act somewhat earlier than passenger vehicles; however, a sizable number of trucks and buses went into the 185-ft (56 m) taper.

An attempt was made to collect data which would reflect the relation between local traffic conditions and the merge location. Specifically, a count was made of the center lane vehicles which passed the subject climbing lane vehicle between 1,345 ft (410 m) and the merge location. Even without extensive analysis, these data are considered insufficient. The problem involves all the considerations of relative speeds and spacings commonly found in merges from a long acceleration lane. Several subjective observations were made and recorded during or immediately after data collection.

Several early merges were made by trucks into a very large gap which was followed by a multilane platoon. These maneuvers appeared to constitute a defense against potential entrapment.

On numerous occasions, fast moving passenger vehicles in the middle lane moved to the median lane when overtaking a truck in the climbing lane within 1,200 ft (370 m) of the lane drop. The middle to median lane changes were made in the absence of impeding traffic in the middle lane. These maneuvers appeared to anticipate encroachment by the truck.

At the flow rates observed, the most serious impedance to merging vehicles (trucks, trailers, campers. and less often, passenger vehicles) was moderate speed vehicles in the middle. These vehicles were frequently low performance passenger cars, cars pulling trailers, campers, or cars being driven at moderate speeds. The middle lane vehicles frequently paced a truck which was accelerating and remained beside or just behind it. Judging by their speeds, the impeding vehicles would not choose to travel in the median lane and were reluctant to enter it even when the median lane was clear. On several occasions, the climbing lane vehicle made the merge near the lane drop and forced lane changes by the impeding vehicles. The brake lights of the middle lane vehicles were seen on two occasions.

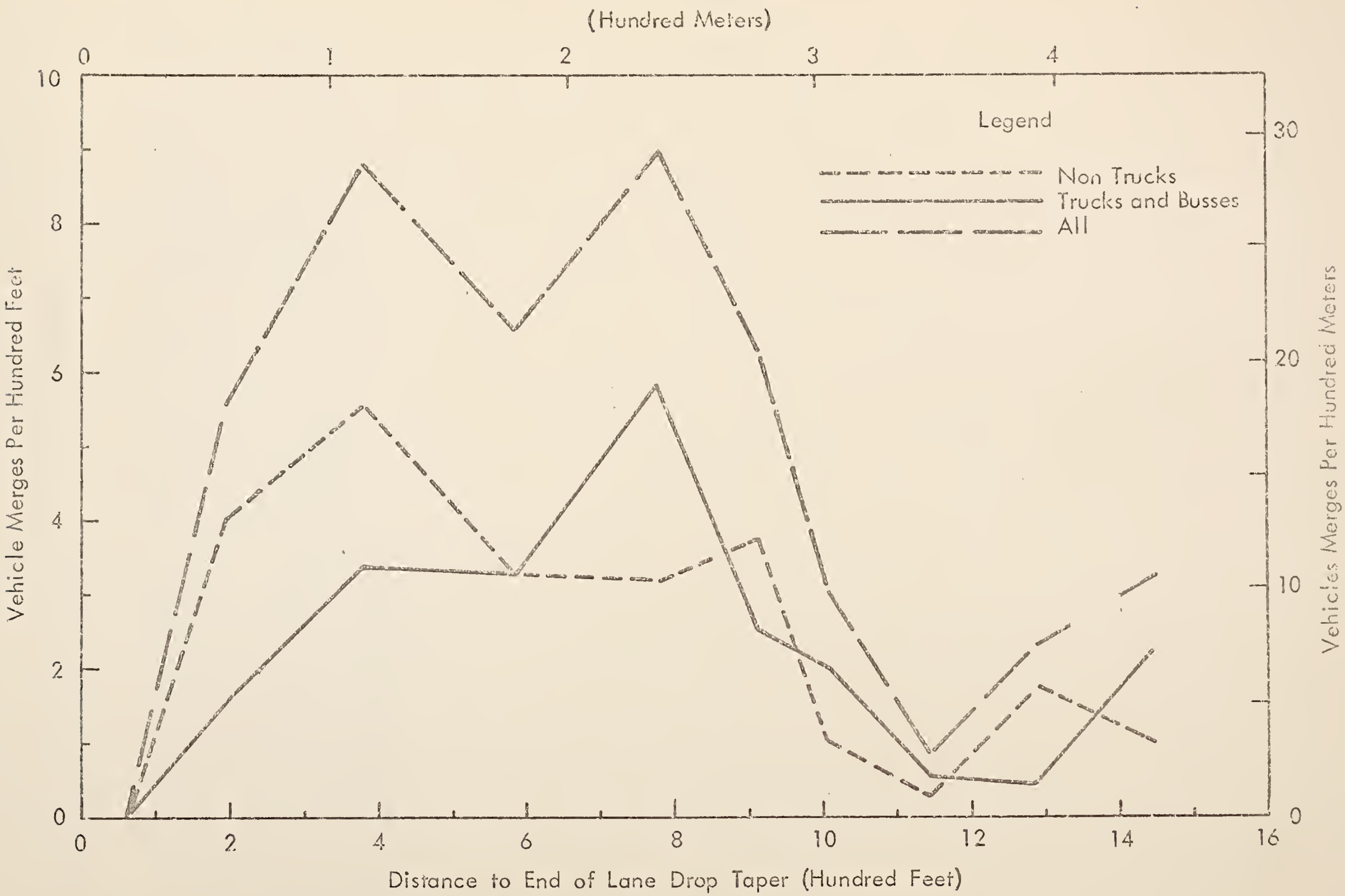

Figure 28 - Locations of Merges at Climbing Lane Drop Near Yuba Gap Overcrossing - Eastbound I-80

Figure 29 shows the results of merge activity at the second lane drop site. This site is located at the Donner Summit for westbound traffic on I-80. The observation position did not permit a good discrimination of merge positions close to the lane drop. Consequently, an average value is used for the last 600 ft (183 m).

It is clear that merges occurred closer to the drop at this location. There are two reasonable explanations. First, the shoulder is tapered off at a very slow rate where the lane drop occurs. Much of the climbing lane traffic (observed at close range) overruns the drop and uses the extension provided by the shoulder. Second, there are no explicit signs warning drivers of the lane drop. This handling of the drop is possible because there are no structures which limit pavement width near the drop. In distinction, the lane drop at the Yuba Gap overcrossing has the overcrossing structure immediately downstream.

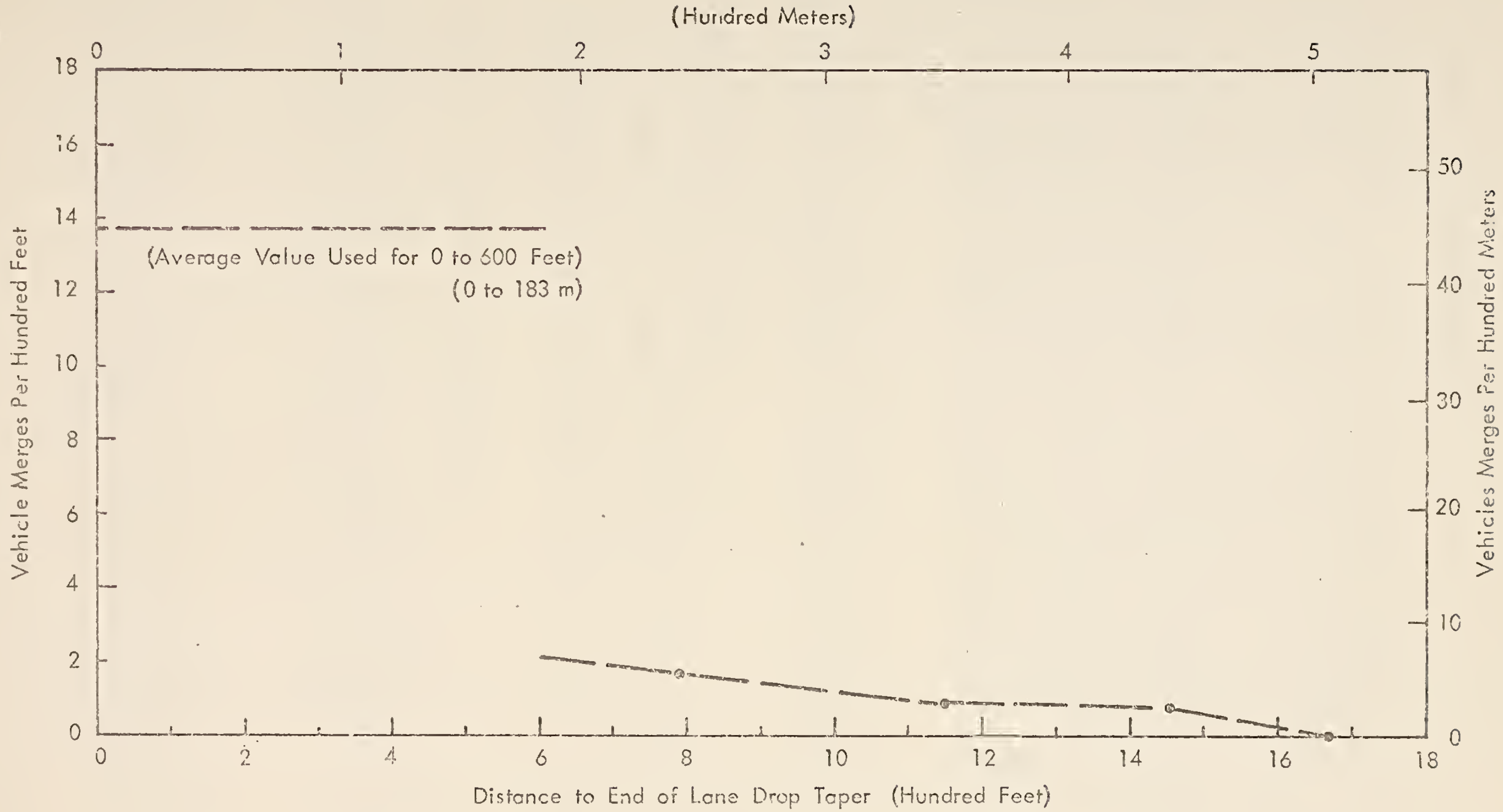

Figure 29 - Locations of Merges at Climbing Lane Drop
Donner Summit - Westbound I-80

III. SUMMARY OF SIMULATION FEATURES

A. General Nature of the Simulation

The simulation is microscopic in that vehicles retain their identities and their ongoing behavior is determined individually at relatively short time intervals. (One second was used in the simulation runs.*) Vehicles enter the simulated roadway in two ways. At simulation time zero vehicles are placed along the road at densities and speeds consistent with input flow rates and local grades. This process is denoted as "priming." Then, during the simulation vehicles enter at the upstream end of the roadway with stochastically determined time headways consistent with a truncated negative exponential distribution and the input flow rates. A warm-up time period is used to allow the initially inserted vehicles to establish speeds, platoons and lane locations consistent with the roadway and traffic characteristics. In addition, portions of road known as warm-up and cool-down lengths are used to isolate the studied road region from entrance and exit effects.

Each vehicle attempts to proceed at its desired speed, although performance limitations may prevent reaching or holding desired speeds. Lane changes are made (or sought) to:

Avoid a ramming accident,

Avoid the end of a terminating lane (on the right),

Move from behind a slow leader (before or after a delay is experienced), and

Satisfy a tendency to move right.

Vehicles temporarily accept short time headways precipitated by their own lane change or a lane change somewhere in front of them. A specified fraction of vehicles cooperate with lane changers by decelerating moderately to maintain or improve a gap in front of them.

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* The coefficients in overtaking and following equations provide marginal asymptotic stability for the one second review interval, in agreement with reported field observations. The one second interval is also sufficiently small for the timing of driver decisions.

The risk involved in vehicle interactions is quantified as the negative acceleration which the situation would normally elicit in the trailing vehicle. Risk is used as a measure in selecting lane changing opportunities so that following, overtaking, and lane changing have a common fundamental logic.

Vehicles wanting to change lanes become willing to accept greater risk and use more severe deceleration as time progresses and/or the situation worsens.

Two types of "accidents" are possible in the simulation. One of these types of accident is allowed to go to completion. This type involves vehicles which may be forced to abandon a lane change after they are committed to pass the end of the lane occupied. In this case the vehicle is allowed to pass through the end of the lane, the event is recorded, and the vehicle is removed from the simulation. Ramming accidents, the other type, are rectified by using "greater than possible" deceleration. The event is recorded as an accident together with the speed removed in excess of normal capability.

The acceleration and deceleration capabilities of individual vehicles are altered in accordance with the local road grade. Grade also has a slight effect on desired speed, and for commercial vehicles on long, steep downgrades, crawl speeds are desired. Road curvature and associated superelevataion produce locally an upper bound on desired speed and can influence following behavior at lesser speeds. Vehicles attempting to appraise potential traffic delays or to make lane change plans can "see" only to the limits of the local forward and rearward sight distance.

A one-directional road length of up to 131,000 ft (40 km) can be simulated.* The rightmost lane may be intermittent. Where it exists it corresponds to a climbing (or crawling) lane. The number of continuous lanes is not limited by the fundamental logic; however, traffic generation priming and output routines have been written for two continuous lanes and an intermittent climbing lane. There is no provision for on- or off-ramps.

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* The maximum length, 131,000 ft, is set by the bits allowed for vehicle position in packed data. Some part of this length is required for entrance and exit buffer zones. Other constraints arise from the total number of vehicles which can be in the simulation simultaneously and practical computer running times.

Grade is defined at every point along the road. It can vary linearly with position within user-defined lengths of road.* (Grade variation corresponds to vertical curvature.) The local grade affects acceleration capabilities.

Sight distances to the front and rear are also defined (independently) at all locations with linear dependence on position within user-defined lengths of road.

The effect of curvature and superelevation is defined only where a significant effect exists. The effect carried within the simulation is an upper bound on desired speed which is applied locally. The upper bound on desired speed is constant over the affected roadway length. (Vehicles respond to this bound, if necessary, when approaching the curve.)

The effect of a long, steep downgrade is carried within the simulation as a local average crawl speed for commercial vehicles. The average crawl speed is defined only where applicable and may vary linearly with position over user-defined lengths of road.

As part of the input data the user specifies the locations of check stations. Point measurements of the simulated traffic are made at check stations and spatial or average values are obtained for the segments of road between check stations. Consequently, the check stations will usually be located in concert with geometrical features so as to provide segments of roadway in which traffic is undergoing a transition or in which traffic characteristics should be essentially uniform. It is mandatory to have a check station where a right lane is added or dropped.

The individual simulation vehicles are assigned (under input control) characteristics which in large part determine their behavior. These characteristics include:

Driver type - Determines the vehicles' responses (within performance capability) to leader's proximity and speed; also determines magnitudes of acceptable following distances and lane changing requirements.

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* A <u>linear variation of grade</u> produces a <u>parabolic vertical curve</u> which is consistent with current design practice.

Vehicle type - Identifies length, type (commercial or passenger), and, in conjuction with local grade and current speed, defines acceleration capability.

Desired speed - Each vehicle is assigned a desired speed which subsequently will be affected by local grade and/or be overriden by curve- or crawl-associated values. The explicit assignment of desired speeds is a user option.

Cooperator - Determines if the vehicle will oblige would-be lane changers by trying to provide a usable gap in front of the cooperator.

When the model is run, a variety of events is detected and recorded on magnetic tapes or their equivalent. This initial output is raw data. Another computer program, developed under this contract, reads the raw data and processes them to provide statistical and summary values.

The raw data fall into the following categories:

1. The state of all simulated vehicles, including driver and vehicle types, speed, location, and current activities, output at regular intervals of simulation time.

2. The state of all simulated vehicles, output when one or more ramming accidents occur.

3. Lane changing and vehicle stopping activities, output completely.

4. Recording of all crossings of all check stations by all vehicles.

The data processing program provides outputs for assessment of service level and for validation. Some of the outputs are provided for individual segments of road (between user-specified check stations) as well as for the entire road.

A complete description of the simulation model may be found in the final report of the previous project.* In particular, Volume II contains descriptive material useful to the highway engineer and Volume IV covers computer program details. The interested reader will wish to refer to these volumes when studying the remainder of this section

* "Traffic Simulation for the Design of Uniform Service Roads in Mountainous Terrain," Contract No. DPR-11-5093 (1970).

B. Modifications and Additions to the Model During the Current Project

Some changes were made in the simulation program to improve program efficiency, rearrange output, and so forth which did not alter the simulation model results. Other changes affected simulation model logic either deliberately, in order to improve agreement between simulation results and observations of traffic, or incidentally, in the process of extending the capability of the program or correcting program errors. The former class of changes will be discussed first, independently of the chronological order in which they were made. The latter class of changes will be discussed in the sequence in which they were made so that effects of these changes can be correlated with simulation results. In all cases where parameters or logic changes were made, the new trial values were based on knowledge of the purpose for the model element involved.

1. Changes not affecting simulation model runs: The output programs were modified to delete a great deal of unneeded output (zeros). For example, lists of risks involved in lane changes made to avoid the end of a climbing lane were deleted when there was no climbing lane, empty classes of frequency distributions were deleted, and certain other lines containing only zeros were deleted.

References to an output file which was to have contained perception output were removed to reduce computer memory requirements.

Binary files were blocked to increase input/output efficiency.

The local grade for each vehicle at the beginning of the review period was stored in the packed table.

Two new types of summaries are now printed out. One of these tabulates acceleration noise; the other tabulates summations of acceleration times time and acceleration squared times time. Both tabulations are broken down by road section and by commercial or passenger vehicle types.

The routine which tabulated acceleration frequency distributions was modified to use unequal class intervals, so that greater precision could be obtained in the denser range and empty classes could be minimized. In the middle range, from -2 to +2 ft/sec^2, accelerations are in classes of width 0.5 ft/sec^2 while the more extreme accelerations are classified in wider intervals.

A correction was made in the portions of the program used to determine effective desired speed for vehicles on horizontal curves. Since none of the simulation runs have made use of curved road sections, this change has no effect on results to date.

Finally, a correction was made to handle the situation where a vehicle has stopped near the end of the climbing lane. A division by zero occurred the first time this happened and caused the run to terminate. Changes in subrountines AVATP, STDREV and TSM were made to eliminate this problem. No simulation results are affected by this change.

2. Model logic changes: Program changes, either to extend capabilities or to correct previously undetected bugs, are mentioned below in chronological order, and are keyed to the first simulation run affected for reference. The basic reasons and results of the changes are given here; further details are in Appendix A.

Run V38: Priming logic was slightly altered so that the appearance of relatively rare vehicle types could be forced, rather than strictly relying on probability. Commercial vehicles were given a greater incentive to make lane changes to "move right". Also, changes were made to deter commercial vehicles from making lane change plans requiring a substantial (unrealistic) speed reduction, especially on grades.

Run V45: Close following, for extended periods and accepting some risk, was allowed in platoons. A user-selected percentage of vehicles was allowed to use shorter-than-normal headways if they were in the third to last position in a platoon. Also, logic was implemented to enable vehicles to enter this mode smoothly, and to leave this mode when certain conditions (primarily relative speeds) dictate. This change was made to increase the frequency of fractional second headways and bring headway distributions into agreement with data on urban freeways.

Run V51: The possibility of close following described above was extended to include the second vehicle in a platoon. A small correction was made concerning anticipated acceleration capabilities of commercial vehicles by accounting for the projected speed increase during the next second. (Acceleration capability is speed-dependent.) Changes in the priming logic, affecting initial conditions, were also made. The first corrected an error, which had not yet influenced any runs, involving notation of commercial vehicle types. Previously, it would have been possible to incorrectly distribute commercial vehicles among types (performance capabilities). The second change caused a small correction in the initial distribution to lane and the percentage of commercials.

Run V52: An error was corrected which, under low flow rate conditions, could have deterred some lane changes to improve progress. Previously, if a vehicle was contemplating a lane change, but the lead vehicle in the adjacent lane was too far away, an erroneous conclusion was reached. If the lead vehicle was beyond the range of human capability to detect relative velocity, the potential lane changer would be wary of the lane. The change allowed him to assume the lead vehicle had zero relative velocity and act accordingly. The change, initially, affected all vehicles within sight distance (2,000 ft or 610 m), whether or not their relative velocity could be perceived. This oversight, which had little effect on results, was corrected prior to run V54.

Run V67: Lane changing to avoid a type of potential delay not included in the simulation was observed during data collection activities in California. It was noticed that, nearing the end of a climbing lane, many vehicles moved from the middle to the median lane in anticipation of vehicle merges from the climbing lane. These lane changes did not arise from existing impedances. The lane change planning in the simulation was modified to allow this behavior.

Run V70: Another small problem came to light concerning lane changing under extremely low flow conditions. If there were no simulated vehicles within sight (2,000 ft or 610 m) in a lane, other vehicles would not use the lane to improve progress because model logic did not permit an assessment of potential delays in the locally vacant lane. This was corrected. Also, a logic change was made to cut down on the amount of "weaving" associated with alternately moving left to improve progress and moving right to satisfy the tendency to move right.*

Run V72: A bug in subroutine PACK was discovered that tended to occasionally cause some erroneous lane changing "to move right". Again, under low flow conditions, too much lane changing was observed. This bug, which was traced to a machine or operating system characteristic not present for the initial computer runs, would falsely overmotivate drivers to move right if large gaps existed.

Run V73: A minor change was made to prevent lane changes "to move right" if a delay would occur within 30 sec. Existing logic usually would prevent this, implicitly; the change made it explicit.

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* Some states have laws requiring drivers to "keep right except when passing." If people really did persist in keeping to the right, further model changes would be required to simulate the resultant flow.

Following run 73, a sequence of runs and adjustments were made to obtain improved agreement between the simulation results and field data for flows in both level terrain and on grades. The emphasis was placed on improved distribution of flow to lanes and lane changing frequencies. The sequence of adjustments is recorded in the following paragraphs and tables.

A sequence of moderate adjustments was made to the simulation during the runs 74 through 99. Immediately prior to run 100, significant adjustments were made including a few modifications of logic. Final small changes in parameters and logic were made just prior to run 124. Table XV displays the parameters which have been changed. The paragraphs which follow describe the roles of the parameters and the modifications to logic.

BIAS(2) forms part of a sum which is used by trucks to test motivation for changing lanes to the right in accordance with the tendency to move right. The changes, -30 to -20 to -10, increase the probability of motivation to move right.

ACCMR(2) is used by trucks for a test in the motivation to change lanes in accord with the tendency to move right. Trucks which currently have an acceleration capability less than ACCMR(2) acquire an increased tendency to move right.

AMRLL(1) and AMRLL(2) are part of the sums which are used by cars and trucks, respectively, to test motivation for changing lanes to the right in accord with the tendency to move right. The values are added algebraically to the sum when there is a lane on the left of the one currently occupied. The change of AMRLL(1) from -15 to -18 to -20 decreases the tendency for passenger cars to move right. The change of AMRLL(2) from -5 to -2 increases the tendency of trucks to move right. These parameters have an effect only when there are three (or more) unidirectional lanes available.

TOTC is a factor in the sum which is used to test motivation for changing lanes in accord with the tendency to move right. The sum contains the product (TOTC) $\cdot$ (Projected time (sec) until appraising vehicle would overtake the next vehicle ahead in the lane on the right of the current lane.) An increase in TOTC increases the relative importance of the time-until-delay and increases the tendency to move right.

TABLE XV

PARAMETER ADJUSTMENTS TO SIMULATION STARTING WITH RUN 74

(values are entered in the table only where a change was made)

Program Symbol	Original Value	Values Beginning in Run: 74	87	88	89	90	100a/	101	108	109	124a/
BIAS(2)	-30	-20	-10								
ACCMR(2)	0	0.25									
AMRLL(1)	-15								-18	-20	
AMRLL(2)	-5							-2			
TOTC	0.5	0.8	0.5	0.65		0.57					
PTOTMX	100		120								
ACLD	1.0	1.5									
SPGAIN(3)	0.8		0.75				0.70				
NUM-COMPAR	6.0		9	7							8
DELVCF(4)	0.1125						0.0281				
(5)	0.00833						0.00208				
(6)	0.00139						0.00035				
(7)	0.1125						0.0281				
(8)	0.00833						0.00208				
(9)	0.00139						0.00035				
FTGAIN(1)	0.25						0.7				
(2)	0.25						0.7				
(3)	0.5						1.0				
PRCPT1	0.1×10^{-4}										0.08×10^{-4}
PRCPT2	0.08×10^{-4}										0.065×10^{-4}

a/ See logic changes which are described after the description of parameters.

PTOTMX is used in the logic for motivation to change lanes to the right in accord with the tendency to move right. PTOTMX is the limiting maximum value used for projected time-to-overtake-the-next-vehicle in the lane to the right of the current lane. Increasing PTOTMX increases the tendency to move right when the lane to the right offers an extensive time until a delaying vehicle would be overtaken.

Each vehicle in the simulation carries a summation which is used to increase the tendency to change lanes to the right. The sum is incremented by ACLD in each review period when the vehicle is impeding its follower while not being similarly delayed by its leader. (The summation is attenuated when the above situation is not found.) An increase in ACLD increases the likelihood that impeding vehicles will move to the right when possible.

SPGAIN is employed in evaluating the motivation for changing lanes to improve progress. The speed in a considered lane is reduced so that the move is less attractive. Specifically, SPGAIN(3) is used in evaluating moves into the right-most lane. Reductions in SPGAIN(3) reduce the number of changes into the right-most lane for the purpose of improving progress.

NUM-COMPAR is a constant in the numerator of an algebraic statement in subroutine COMPAR. The value is part of the discounting logic applied to speeds in alternate lanes. An increased value causes more drastic discounting of perceived speeds and reduces lane changes for the purpose of improving progress.

DELVCF(4) through DELVCF(9) are used to limit the character of multisecond lane changing maneuvers which are made to improve progress or in accord with the tendency to move right. The DELVCF are used to calculate the limiting fraction of current speed which is permissible to lose during the lane change. The revision in coefficients curtailed acceptable speed losses to one-fourth the previous values.

FTGAIN(1) through (3) are part of the logic to discount the projected time-until-delay in an alternate lane. The changes increased the discounting and made the alternate lane appear less attractive.

PRCPT1 and PRCPT2 are used to calculate the smallest perceptible speed differences at a distance when the perceived vehicle is a truck (PRCPT1) or a car (PRCPT2). The reduction in values permits simulation drivers to detect smaller speed differences at a distance. This information is used in appraising the desirability and permissibility of changing lanes.

Two program changes were made just prior to simulation run 100. They both dealt with constraints on the characteristics of lane changing maneuvers which were made to improve progress or move to the right. Prior to run 100, voluntary speed losses up to 5 ft/sec (1.5 m/sec) could be made during the maneuvers. The allowable voluntary loss was changed to 3 ft/sec (0.9 m/sec). (A performance-limited vehicle might suffer an additional, involuntary loss on an increasing grade.)

The second program change altered the most severe decelerations which could be used during lane change maneuvers to improve progress or to move to the right. The character of the changes is shown with Tables XVI and XVII.

In Table XVI the first expression is interpreted as the algebraic minimum of XDDPER plus 0.5 times RL, or RL, where XDDPER is the performance limited acceleration capability of the lane changing vehicle and RL is the limiting (most severe) risk level for the lane change maneuver. Values of RL are given in Table XVII.

Prior to simulation run 124, parameters were modified as shown in Table XV and another change was made in the program logic. The change permitted drivers to detect all speed differences, irrespective of magnitude, with all vehicles within 500 ft (152 m). Beyond 500 ft, speed differences are detected only when they exceed thresholds which increase with the square of distance.

The adjustments described above did bring the lane changing frequencies and distribution to lane into improved correspondence with field data. However, subsequent tests showed that the adjustments produced insignificant changes in operating speeds and passenger car speeds. These findings are presented in another section of this report.

TABLE XVI

MINIMUM ACCELERATION DURING
LANE CHANGE MANEUVERS

Lane Change Reason	Expression for Minimum Acceleration	
	Before Run 100	Run 100 and Afterward
1-Avoid Accident	AMIN1 (XDDPER+0.5* RL, RL)	Unchanged
2-Avoid End-of-Lane	AMIN1 (XDDPER+0.5* RL, RL)	Unchanged
3-Improve Progress	AMIN1 (XDDPER+0.5* RL, RL)	AMIN1 (XDDPER+0.2* RL, 0.2* RL)
4-Move Right Tendency	AMIN1 (XDDPER+0.5* RL, RL)	AMIN1 (XDDPER+0.2* RL, 0.2* RL)

TABLE XVII

RISK LEVELS FOR LANE CHANGE MANEUVERS

Lane Change Reason	Limit Risk Levels (RL)	
	Initial	Ultimate
1 - Avoid Accident	-14	-20
2 - Avoid End-of-Lane	-8	-18
3 - Improve Progress	-8	-15
4 - Move Right Tendency	-5	-10

IV. VALIDATION OF THE MODEL

Comparisons were made between simulation output and data collected on the California highways and available in the literature. The flow characteristics included were the relationship between speed and flow volume, traffic distribution to lane, passenger car average speeds and lane change frequencies. Subjective comparisons are made where data from the literature are not sufficiently detailed to use statistical tests. Statistical tests are made with some of the data collected in this project.

A. Relationship Between Operating Speed and Flow Rate

The relationship between operating speed* and flow rate predicted by the simulation model is shown in Figure 30 for two lane, one-way, undisturbed flow on level terrain. The dashed lines are simulation results and the solid lines are typical real traffic curves reproduced from the Highway Capacity Manual.**

The full dashed line in Figure 30 is based on results from simulation runs in which a "conservative" driver population was employed. The general character of this curve agrees very well with the real traffic curves. It is important to emphasize that the speed-flow relationship is a result of the simulation logic and was not obtained by manipulation of input parameters. A series of runs at varied flow rates, with all other parameters fixed, will produce such a relationship as a result of the numerous interactions in the simulation logic designed to duplicate driver behavior under varied circumstances. It appears that the conservative driver characteristics employed depict a 65 mph design speed freeway. The curvature at the low-flow rate end is consistent with the distribution of desired or free speeds which is based on a 60 mph speed limit. It should be noted that the very highest flow rates indicated will be seen infrequently because they are vulnerable to a transition to congestion.

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* HRB Special Report 87 defines operating speed as the highest overall speed at which a driver can travel on a given highway under favorable weather conditions and under prevailing traffic conditions without at any time exceeding the safe speed as determined by the design speed on a section-by-section basis. In the simulation model operating speed is obtained as the average speed of those passenger cars which attempt to travel at the design speed.

** HRB Special Report 87 (1965).

The second (partial) curve in Figure 30 is based on results from simulation runs which employed an "unconservative" driver population. In the "unconservative" driver population, 60% of the drivers will follow closely when they are platooned in more or less steady following situations. This produces the number of fractional second headways which are reported for freeway flows. Also, the maximum flow per lane is equal to the highest values reported for short time periods on freeways.

The unconservative driver population characteristics provide a 70 mph (113 km/h) design speed when employed with a 60 or 70 mph (97 or 113 km/h) speed limit.

A large number of simulation runs have been made with the conservative driver population (65 mph or 105 km/h design speed). Using the flow similarities and some 70 mph (113 km/h) design speed results it has been possible to construct design guides for both the 65 mph (105 km/h) and 70 mph (113 km/h) design speeds.

Simulation runs have also been made with a 75 mph (121 km/h) design speed and corresponding design guides have been prepared. The necessity for the higher design speed can be seen in Figure 30 where speed data from the field sites is displayed. The speeds measured <u>on</u> the 6% grade are higher than the 0% grade speeds for a 65 mph (105 km/h) design speed. Likewise, the speeds measured <u>on</u> the 2.4% grade are higher than 0% grade speeds for a 70 mph (113 km/h) design speed. The field data were collected on two interstate highways near the San Francisco Bay area. The capability to duplicate the field data was necessary for validation and to provide design information for high-speed urban facilities.

Initial attempts to duplicate the high speeds on grade employed a third type of driver population which was more agressive. However, it was found that the speeds observed in the field could be obtained in simulation by using the initial (unconservative) driver population together with preferred speeds consistent with a 75-mph (121 km/h) design speed.*

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* The "desired" speeds for the 75-mph (121 km/h) design were based on an extrapolation of zero traffic speeds in the Highway Capacity Manual. The mean desired speed for passenger cars is 100.12 ft/sec or 68.26 mph (109.86 km/h); standard deviation of desired speeds for passenger cars is 10 ft/sec or 6.82 mph (10.97 km/h).

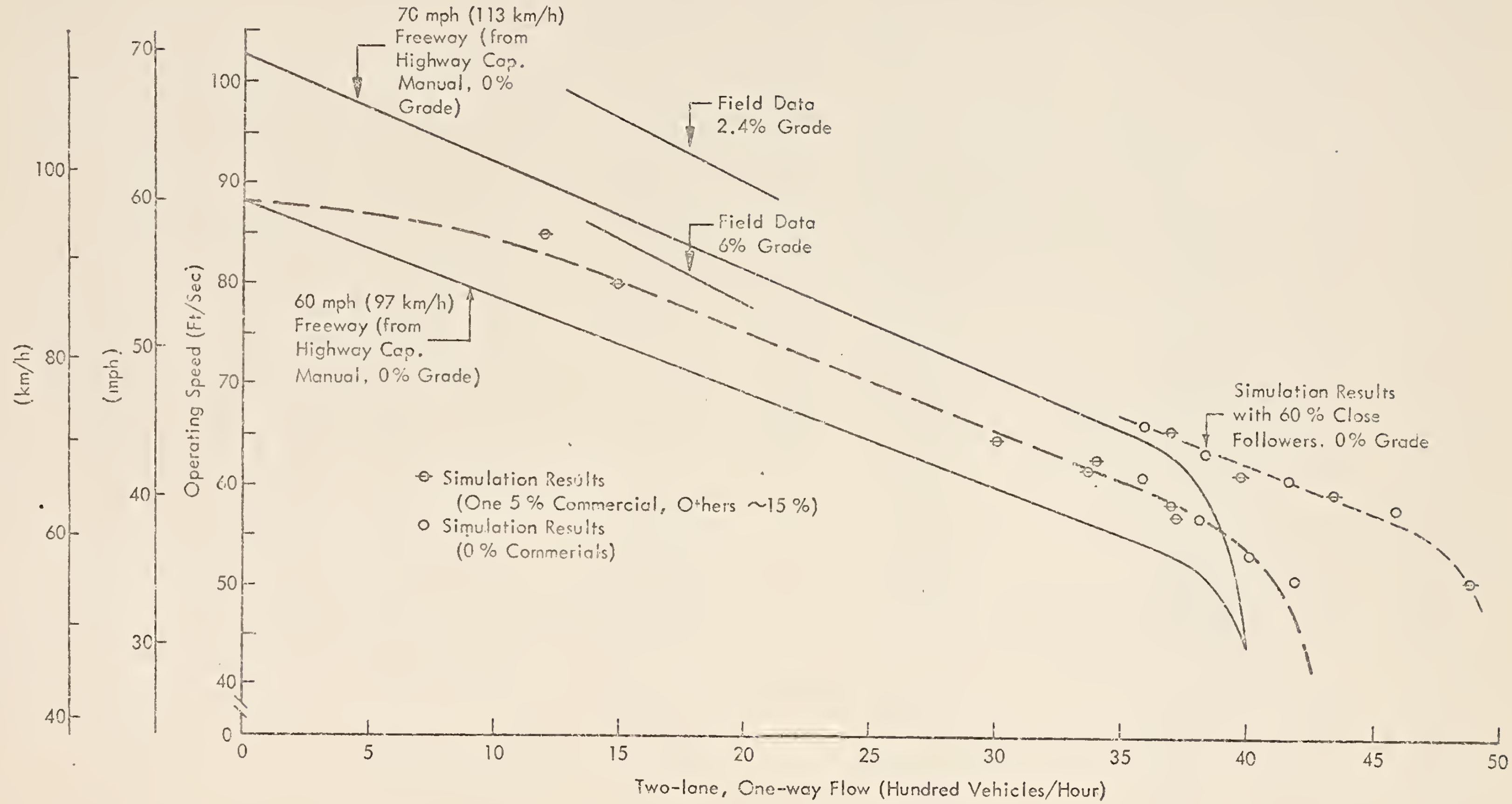

Figure 30 - Operating Speed as a Function of Total Flow for Conservative and Unconservative Driver Populations

The operating speed relation for these conditions is shown in Figure 31 for all passenger vehicles in level terrain. A large number of simulation runs have been made with mixed flows on grades employing the 75-mph (121 km/h) design speed and the unconservative driver population.

The relations between operating speeds and flow rates in Figures 30 and 31 show that the simulation produces the types of relationships observed in the real world. Also, through the choice of driver types and desired speeds, a range of highway design speeds are duplicated. It should also be noted that, in the flows on grades to be presented, pockets of congestion occur in the simulated flows, and the flow characteristics in congestion are correctly duplicated.

B. Traffic Distribution to Lane

Figure 32 shows the good agreement in distribution to lane on two unidirectional lanes in level terrain and at the foot of grades. The results from several early, error-free simulation runs (low S numbers) are also shown.

Figure 33 shows the good agreement in distribution to lane on three unidirectional lanes in gently rolling terrain.

Figure 34 shows the distribution to lane from the simulation compared with regression results from the field data collected on a 2.4% grade. The distribution is a function of both total flow and truck flow. The simulations shown were run with truck flows which were observed on the grade.

Formal statistical tests were also made comparing the simulation and the regression results (field data) in Figure 34. The parameter used for these tests was the difference between the fraction of simulated traffic in the right lane and the fraction of real traffic in the right lane. The test results did indicate a statistically significant difference between the simulation and regression results; in other words, the difference between the simulation and regression results was found to have some value other than zero. This finding is due to the anomalous behavior of run S131, during which the average simulated result was greater than the regression mean. This was not true of any other run. It is likely that this variation is due to lack of fit of the regression equation rather than due to the simulation In each of the other five runs analyzed, the difference between the simulation and regression traffic in the right lane was less than 4% of the total nontruck flow. From an engineering standpoint, these differences do not affect the validity of the model.

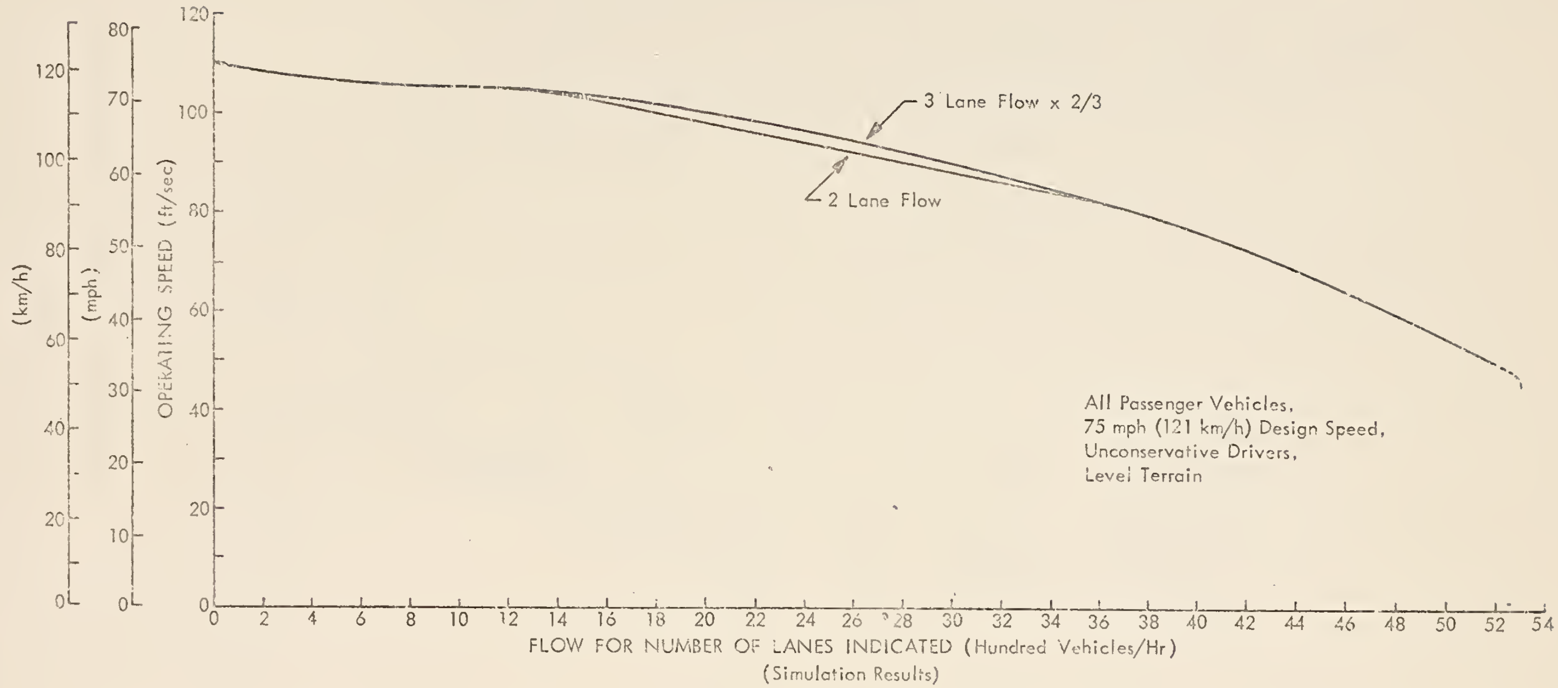

Figure 31 - Operating Speed as a Function of Flow for Two- and Three-Lane, One-Way Roads

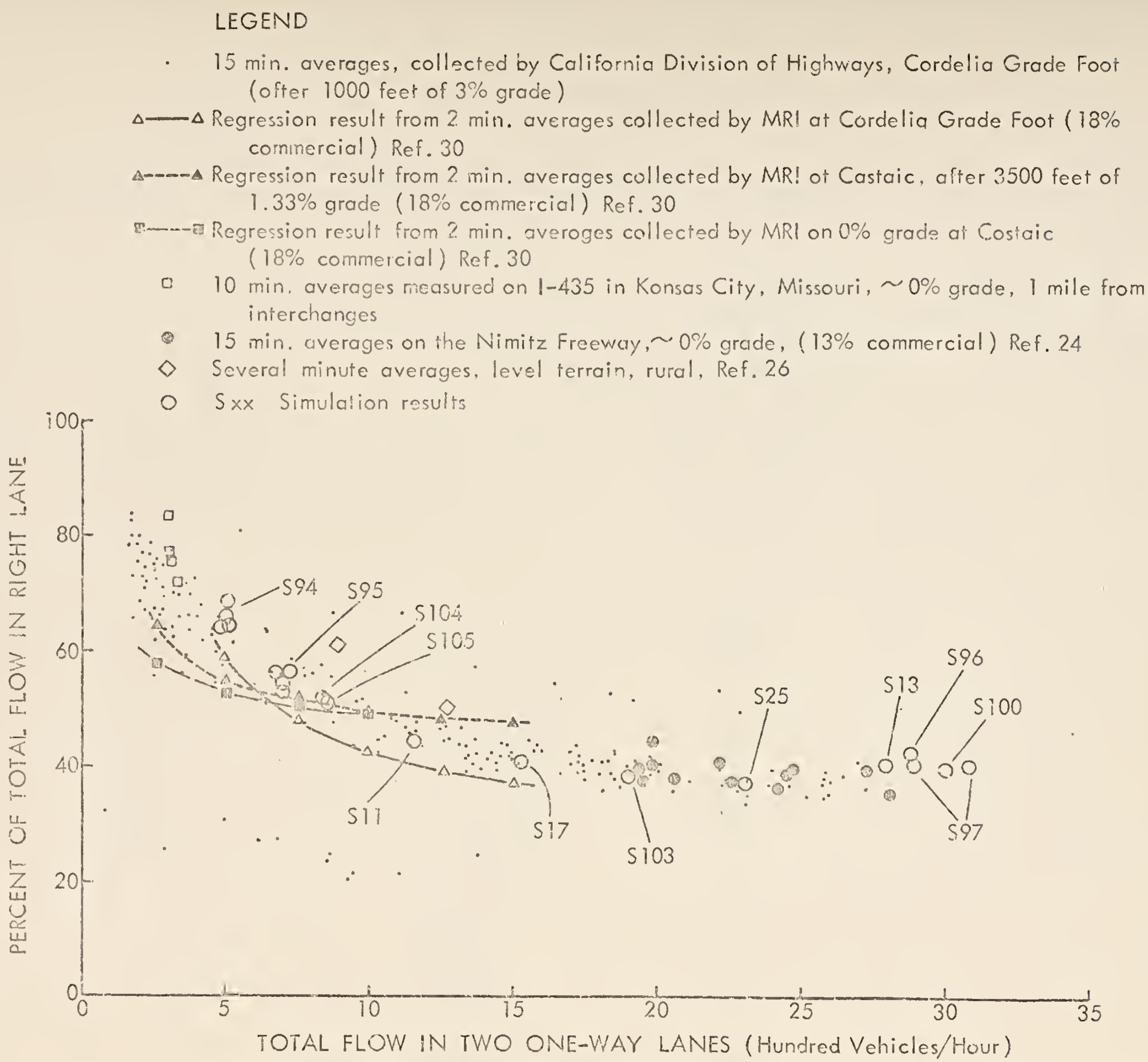

Figure 32 - Flow in Right Lane of Two One-Way Lanes, Level Terrain and Grade Foot

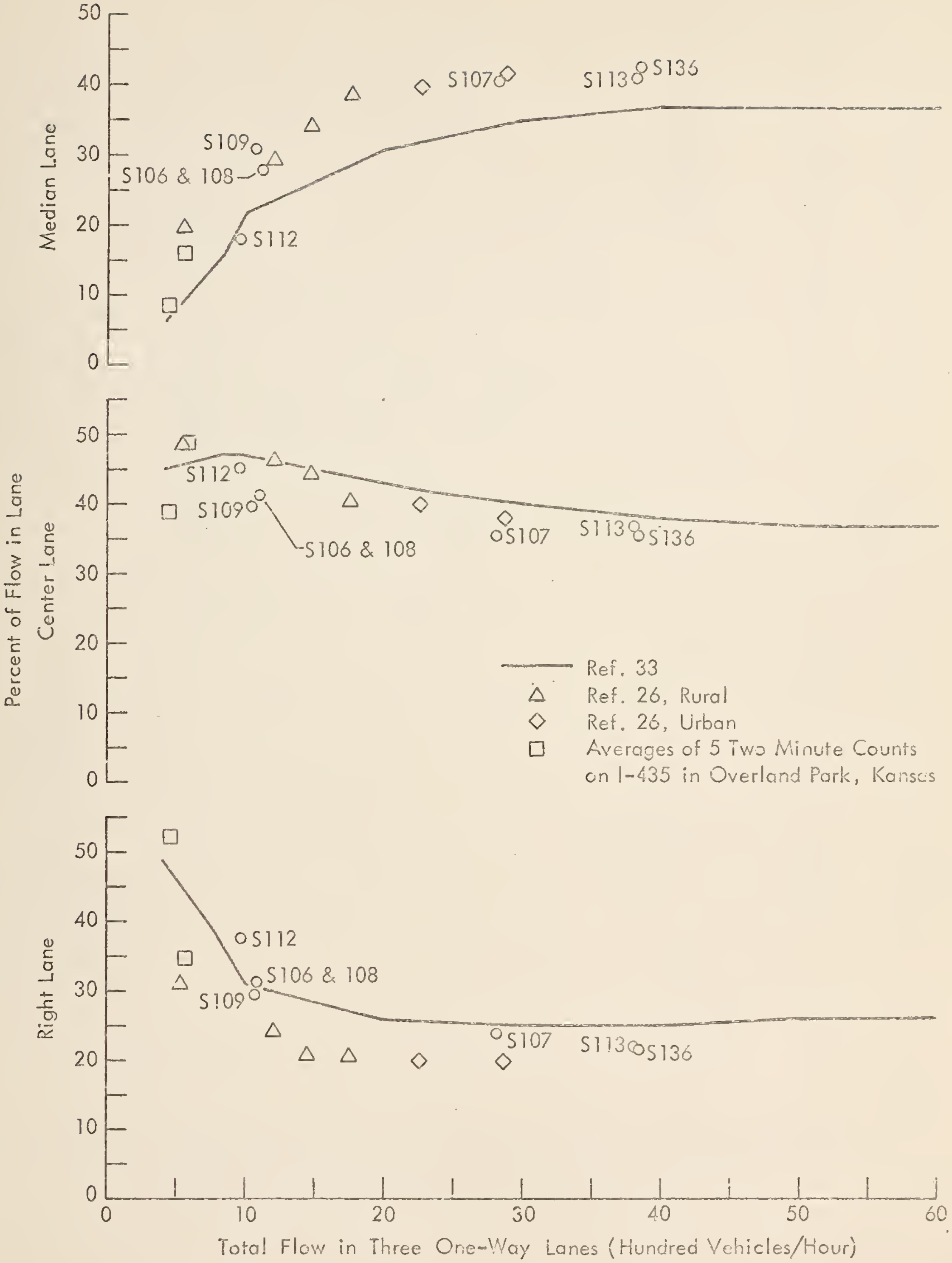

Figure 33 - Distribution of Flow in Three One-Way Lanes, Level or Rolling Terrain

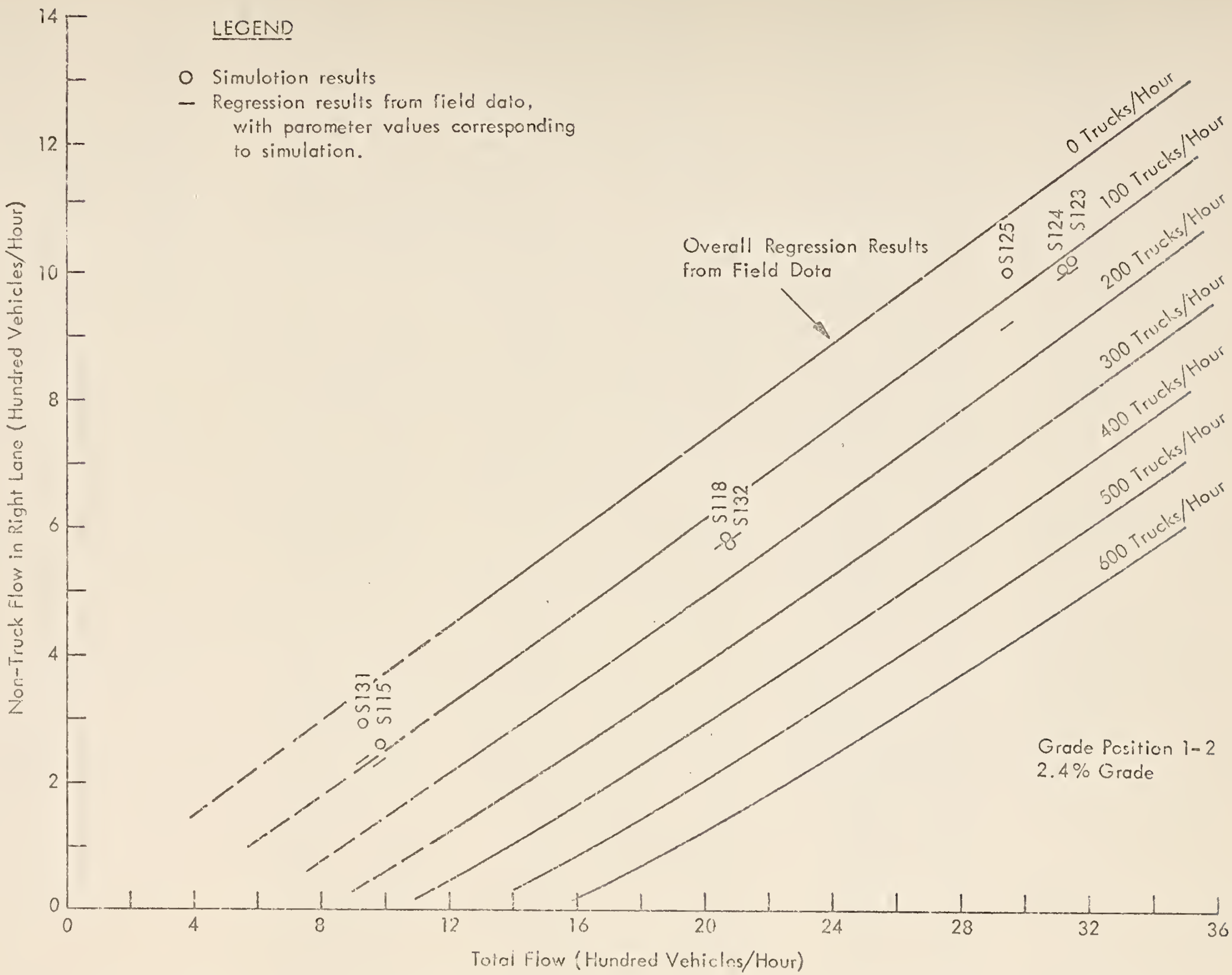

Figure 34 - Nontruck Flow in the Right Lane of Two One-Way Lanes, 2.4% Grade

Figure 35 shows the distribution to lane from the simulation compared with regression results from field data collected on a 6% grade. Again, the distribution depends on both total flow and truck flow rate. It should be noted that this distribution (and vehicle speed) is sensitive to the character of the truck population. Simulation S128 had none of the very lowest performance trucks observed on the grade. Simulation S129 had a greater than average fraction of lowest performance trucks. The result in S129 is the expected one; more nontruck vehicle vacated the right lane.

The results from simulations S126, S127, and S128 were compared with the regression results. The tests indicated a statistical difference between the simulation and field data. Again, this difference does not have engineering significance. The mean differences between simulation and regressions traffic in the right lane are 4.5%, 0.9%, and 2.1% of the total nontruck flow for runs S126, S127, and S128, respectively.

Figure 36 shows the good agreement in distribution to lane between simulation and regression results (field data) for three unidirectional lanes. The third lane is a truck climbing lane added on the right for a 5% grade. The field data were collected on I-80 (grade position 4-2) about 2 miles from the grade foot. The simulation runs used a truck population chosen to match, as closely as possible, the trucks observed on the grade. Also, passenger car performances were reduced to reflect the effects of elevation. Notice that the regression results, which are obtained separately for each lane, do not sum to exactly the total flow with no truck flow.

Statistical tests were made for the comparisons in Figure 36. Runs S73 and S114 were used in this analysis. Significant differences were found in the fraction of traffic present in all three lanes. However, only run S114 is truly representative of the final adjustment of the simulation, and for this run the agreement between simulation and regression results is good.

C. Lane Changing Rates

Figure 37 shows generally good agreement between simulated and observed lane changing rates for two unidirectional lanes in level and rolling terrain. Only those results of early simulation runs (low S numbers) with low and medium flows were used because the subsequent adjustments were found to influence high flows markedly. The field data reported in the literature were not adequate to enable formal statistical comparisons to be made.

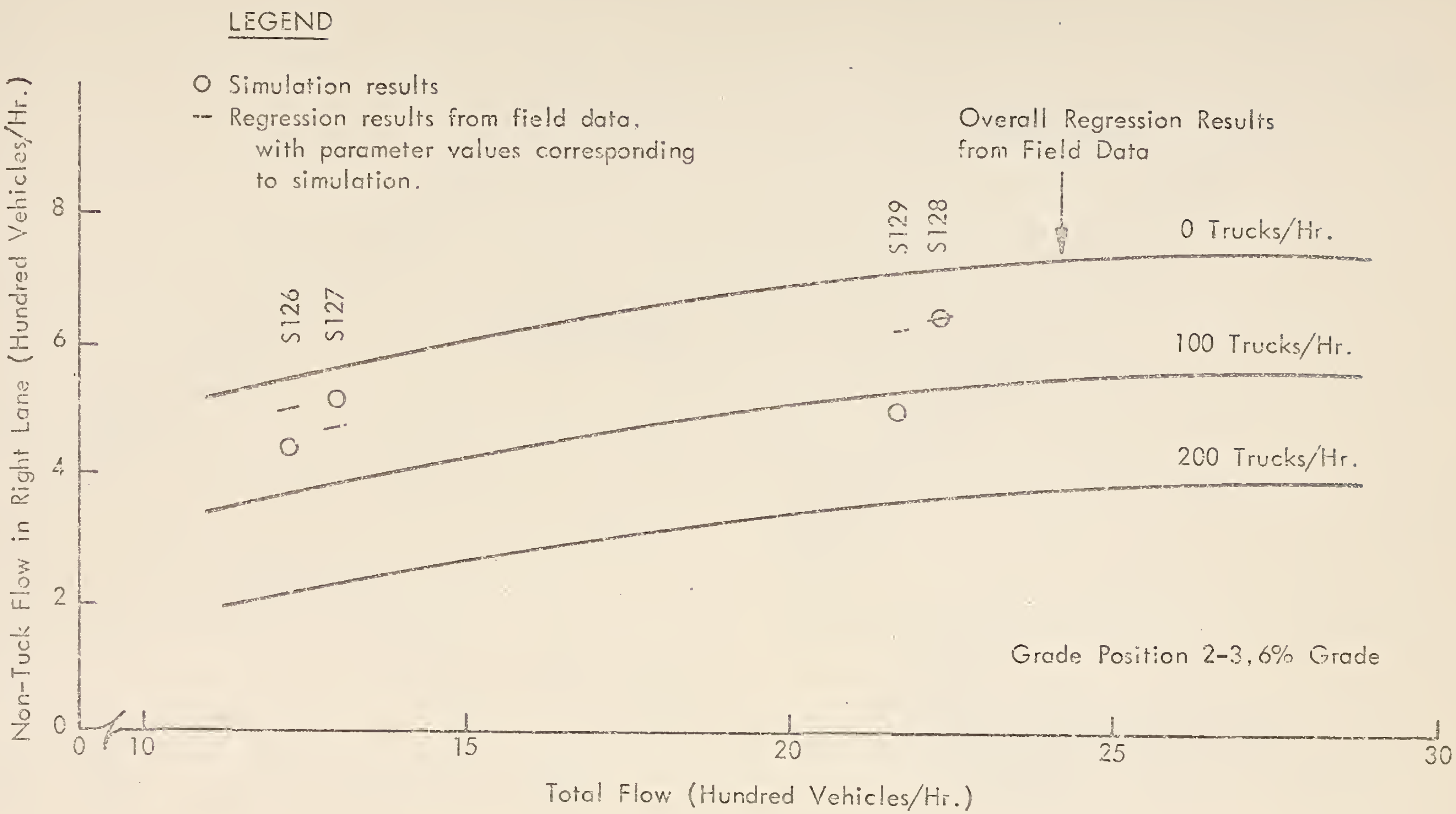

Figure 35 - Non-Trucks in Right Lanes on 6% Grade, Two Unidirectional Lanes

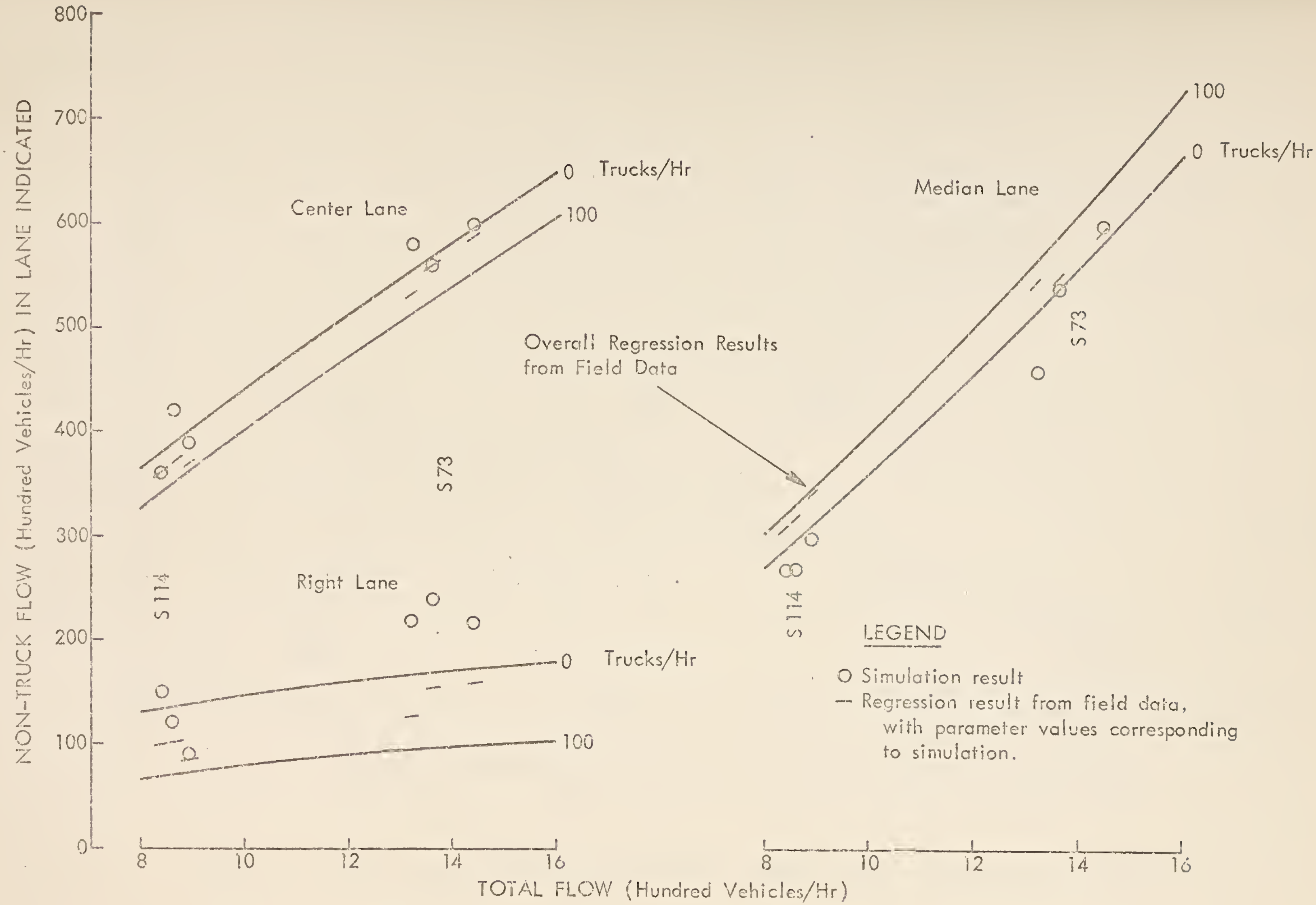

Figure 36 - Distribution to Lane of Non-Truck Traffic for Three-Lane, One-Way Flow on an Extended 5% Grade

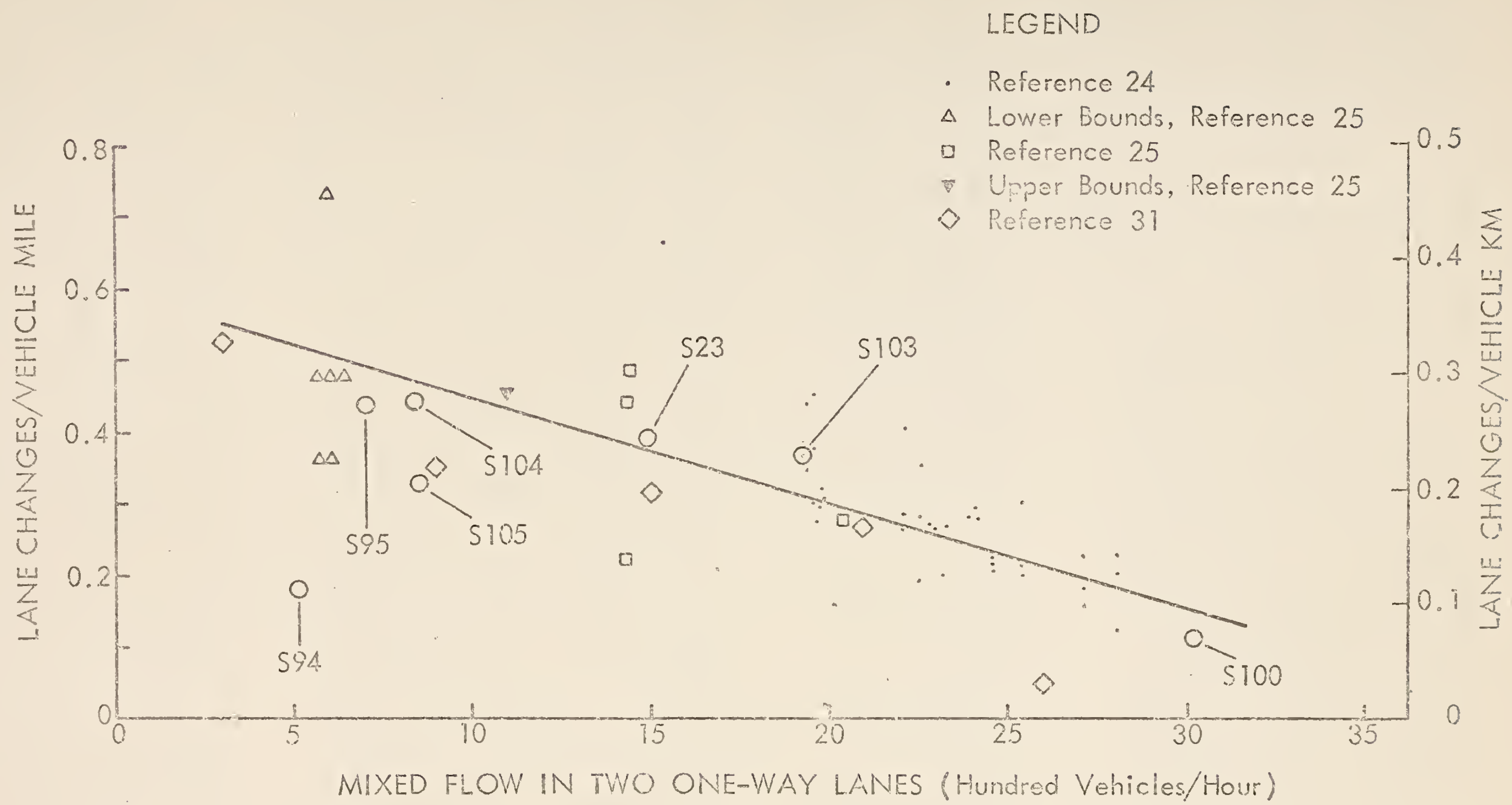

Figure 37 - Lane Change Rates, Two One-Way Lanes, Level and Rolling Terrain

Figure 38 shows adequate to good agreement for lane changing rates for three one-way lanes in level terrain. The lane changing frequencies for intermediate to high flow rates are still high, but were much improved by the adjustments. The source of these high frequencies was identified by examining the details of the simulation runs. In moderate to high density flows, individual lanes experience moderate acceleration and deceleration waves. These waves trigger a few lane changes in the simulation which would not occur in the real world, where drivers can examine conditions over a reasonable time interval to assess motivation for lane changes. This problem is shown later to have a negligible effect on speeds and, thus, on level of service. The field data from the literature were not adequate to conduct formal statistical tests.

Statistical tests were employed to compare simulation results and field data for lane changing rates on the 2.3% grade (grade-position 1-2), on the 6% grade (grade-position 2-3), on the 5.4% grade, (grade-position 3-3), and on the 5.0% grade (grade-position 4-2). The regression results from analysis of field data were employed. From the simulation runs lane changing samples consisted of 1 min values over 1,000 ft lengths. This sample corresponds to the measurements made in the field.

The statistic employed in tests was the difference between a simulation sample and the rate indicated by the regression equation. A two-way analysis of variance was performed first for each grade position. The treatments were time (the simulation minute) and simulation run. In each case it was possible to accept three hypotheses: (1) that there was no significant time effect; (2) that there was no significant simulation run effect; and (3) that there was no significant interaction effect. A 0.05 level of significance was used. These results indicated that it was fair to treat all simulation results for a specific grade simultaneously. The 95% confidence interval for the differences (simulation results--regression value) was then formed. When this interval included zero it was not possible to reject the hypothesis that the difference between simulation and regression could be zero. The results for the individual grades are now presented.

Figure 39 compares the simulation and field lane change rates on the 2.4% grade. Real world mean values for level and rolling terrain are also shown. The simulation results are high. However, the final adjustment (which was made between S123 and S124) effected a decided improvement without disturbing other measurable values already in agreement. The higher-than-average rate in S125 is due to the presence of the lowest performance trucks, a component of the vehicle population which did appear on the grade but only at low frequency. (It is also true in real world observations and

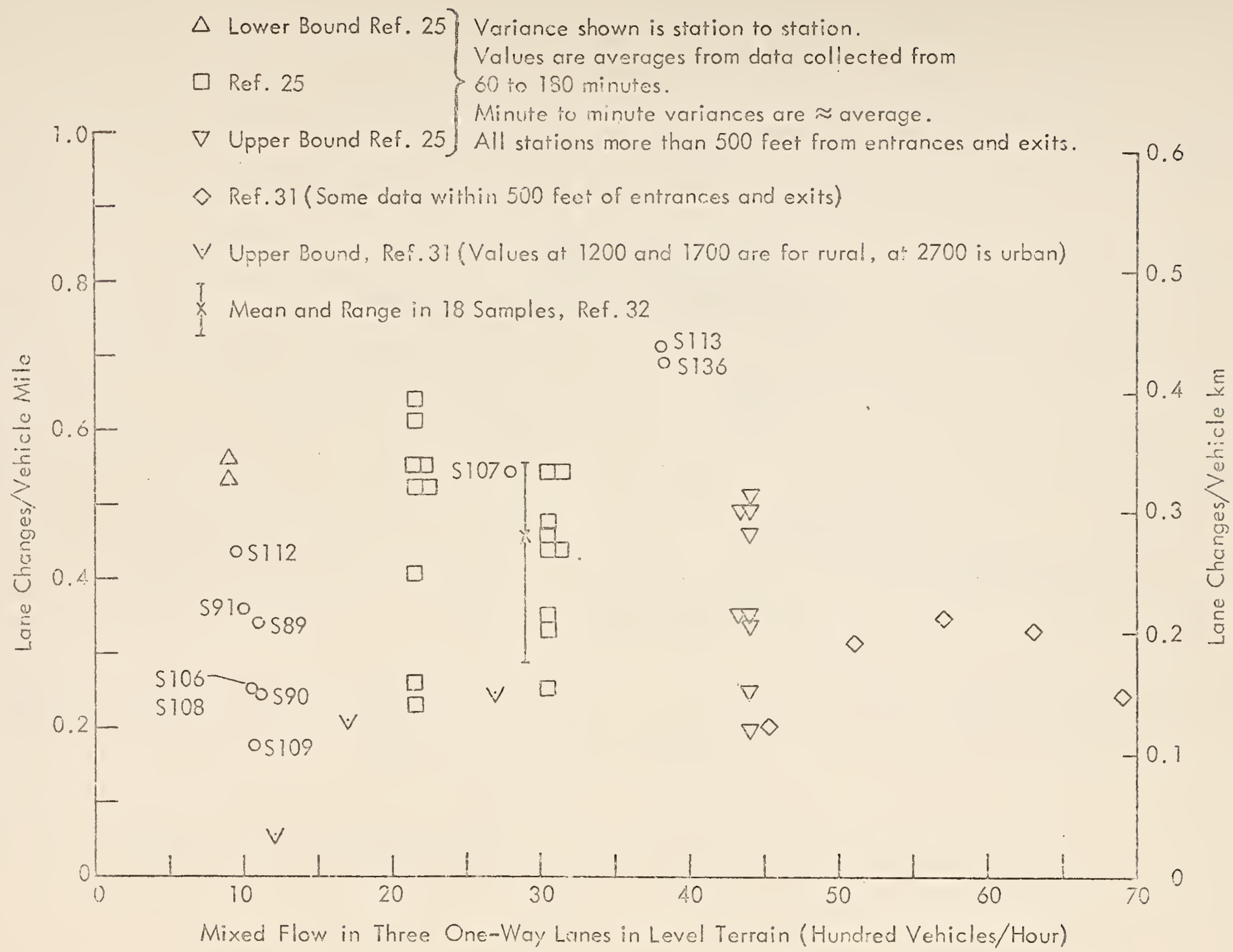

Figure 38 - Lane Changing Rates in Level or Rolling Terrain, Three One-Way Lanes

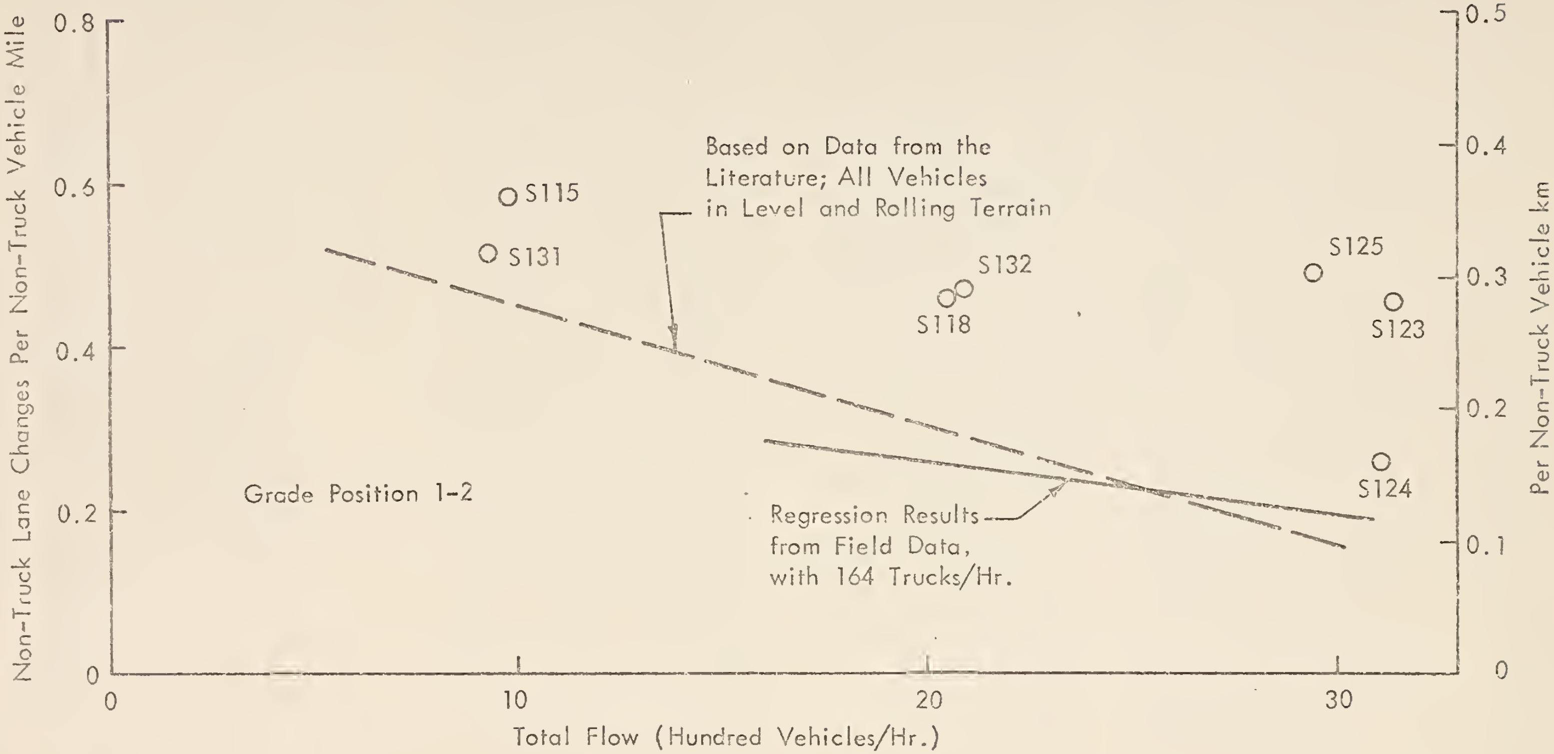

Figure 39 - Lane Change Rates on a 2.4% Grade, Two One-Way Lanes

in the simulation that a sizable number of very low performance trucks will cause all passenger cars to vacate the right lane on a long upgrade. The ensuing lane change rate on the grade is very low.)

Formal statistical tests were conducted using data from Figure 39. The parameter used was the difference between the simulation and regression lane change rates per vehicle-mile. The statistical tests indicated that simulation lane changing was between 21% and 27% higher than observed lane changing. However, the greatest differences occur in runs S123 and S125. As noted above, S123 preceded the final adjustment and S125 contained the lowest performance trucks. Thus, the tests merely reconfirm the discrepancies noted subjectively in Figure 39.

The simulation lane change rate on the 6% grade is in satisfactory agreement as shown in Figure 40. Again, the influence of very low performance trucks is seen in S129 as a case where very low performance trucks are present in greater numbers than in the observed flow, but not in sufficient number to drive all passenger vehicles from the right lane. Formal statistical tests indicate that there is no difference in lane changing rate between the simulation and regression (field) results.

Figure 41 shows comparison of the simulation lane change rates on three one-way lanes, 5% grade, with regression results from field data. The truck population in the simulation was selected to correspond with the population observed in the field. The three-minute simulation samples from separate 1,000 ft (305 m) sections illustrate the variance in time samples of this kind of data. Formal statistical tests found no difference between simulation results from runs V73 and V114 and regression results from grade position 4-2; however, unexplained differences were found when the regression results from grade position 3-3 were used.

D. Passenger Car Average Speeds

Passenger car speeds on the 2.4% grade are shown in Figure 42. Attempts to obtain an accurate representation of the truck population are partly thwarted by the stochastic processes in vehicle generation. Simulations S123 and S124 contain none of the lowest performance trucks. Simulation S125 contains more than the average amount of lowest performance trucks. The simulations exhibit the correct speeds, the correct change with flow and the correct speed differences between lanes.

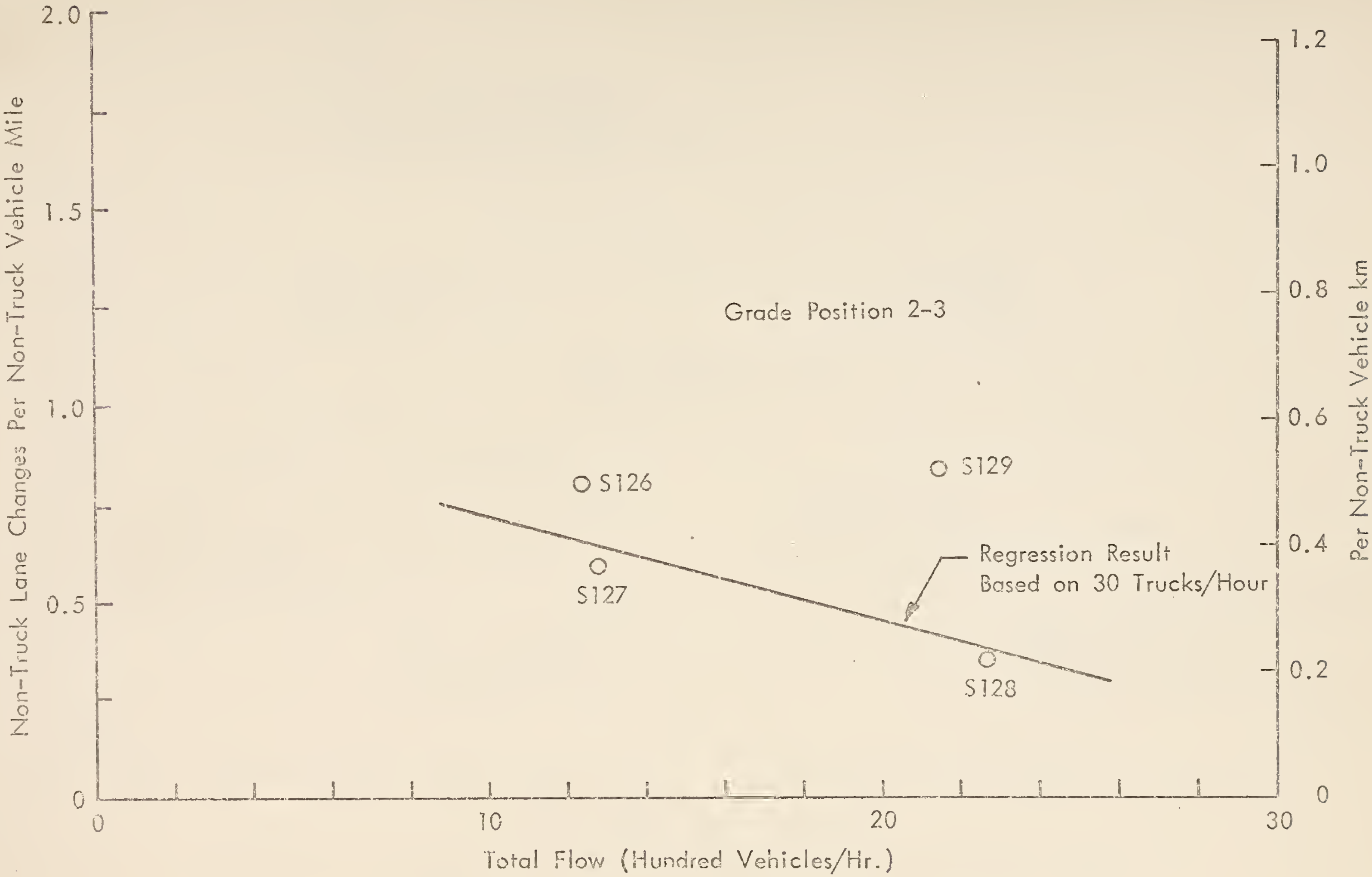

Figure 40 - Lane Change Rates on 6% Grade, Two One-Way Lanes

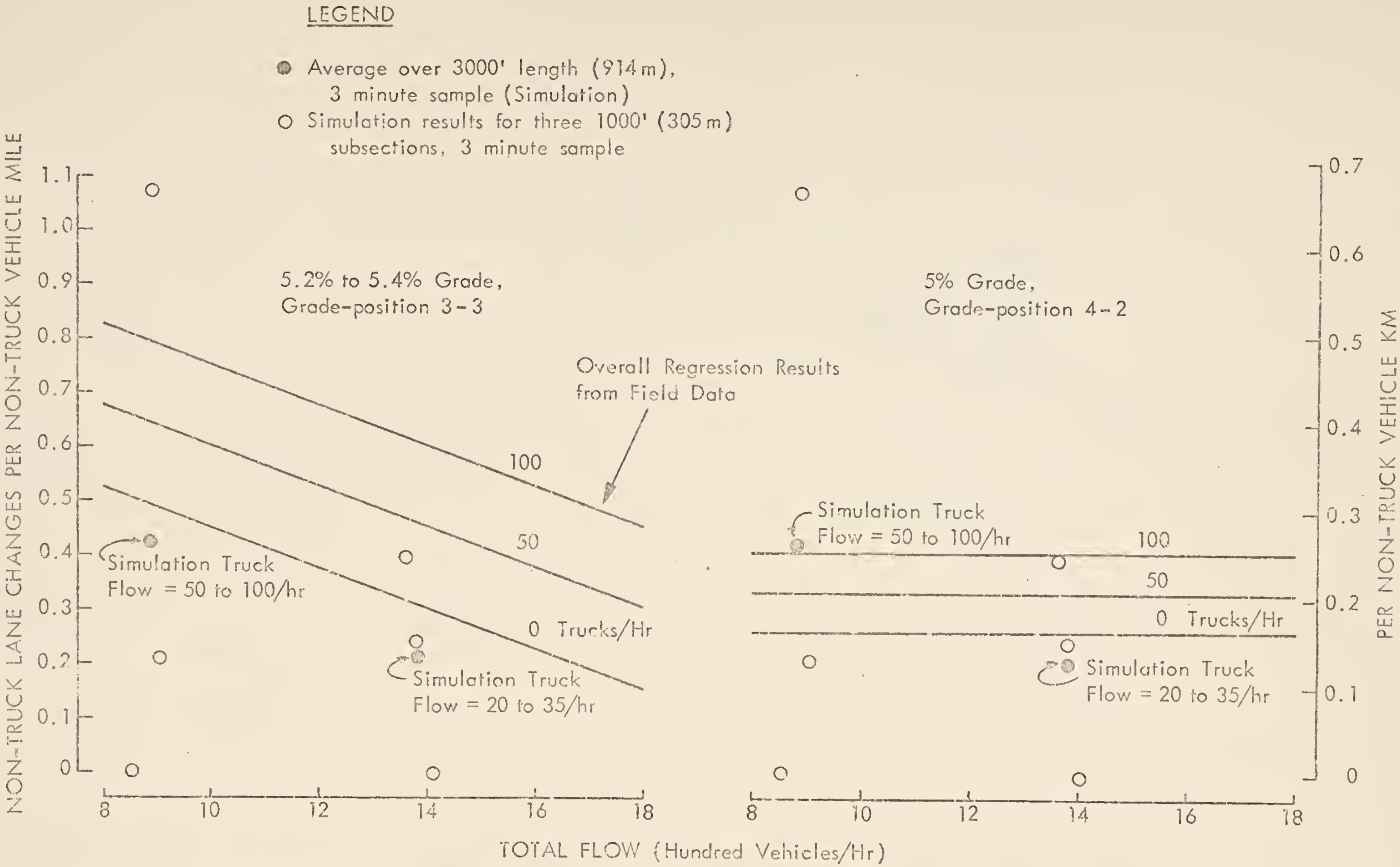

Figure 41 - Lane Change Rates on 5% Grade with Three, One-Way Lanes
Comparison of Simulation with Field Data

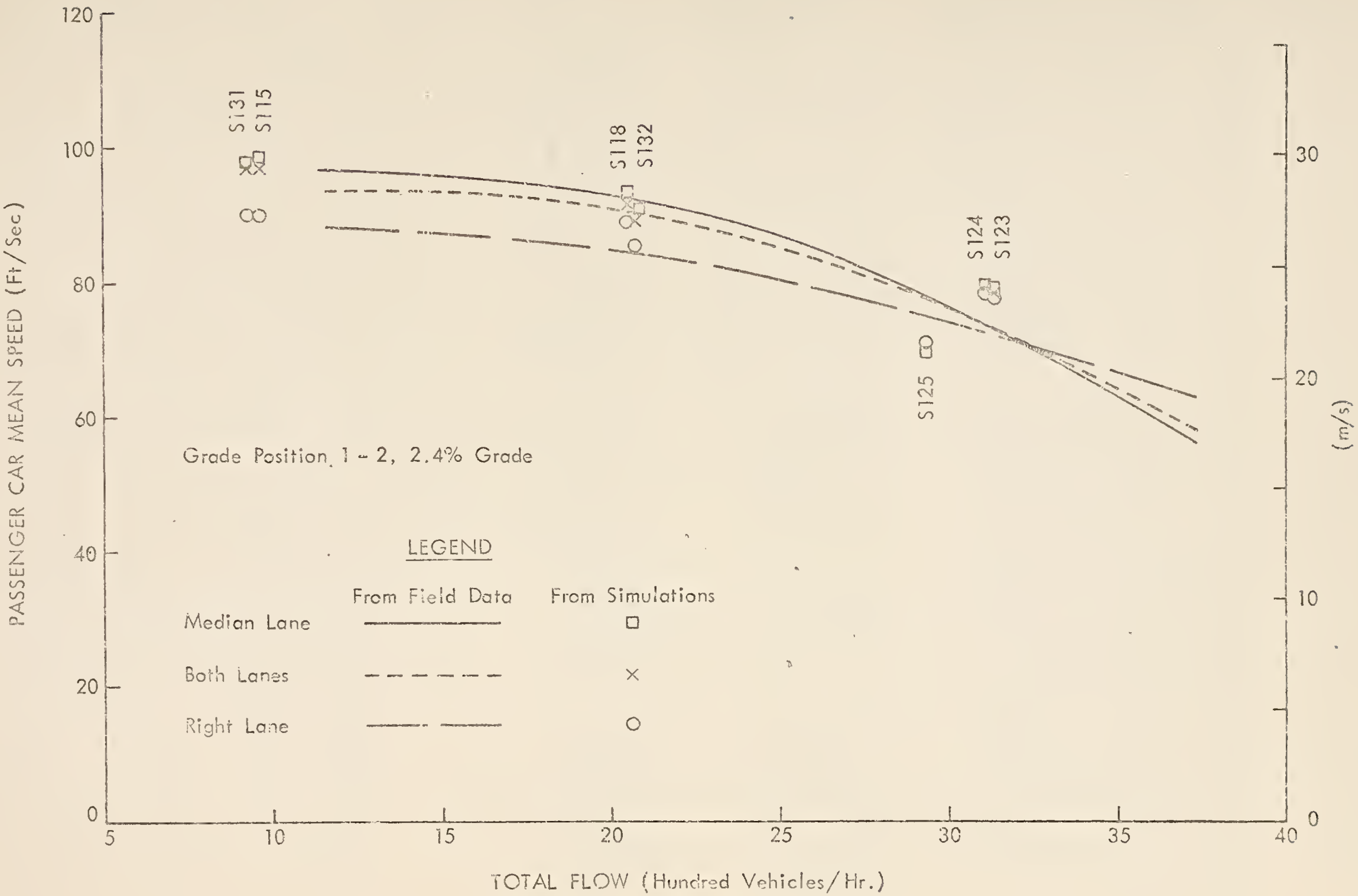

Figure 42 - Passenger Car Speeds on 2.4% Grade, Two One-Way Lanes

The simulations employed for Figure 42 used the unconservative driver population and a 75-mph highway design speed. The field data were collected on I-580 near the San Francisco Bay Area in the afternoon, and include some rush hour traffic.

Passenger car mean speeds on the 6% grade are shown in Figure 43. Again, comparisons are made difficult by the sensitivity to the truck flow and truck population. Simulation S128 has none of the lowest performance trucks while S129 has a slightly higher truck flow and lowest performance trucks appear at greater than the average frequency. When the truck flow rates and populations are considered, the simulation speed values appear satisfactory. The change with flow rate and the speed difference between lanes is in good agreement. The field data for Figure 43 were collected on I-680 near the San Francisco Bay Area on a Sunday afternoon.

Figure 44 compares simulation results with field data (regression) on a 5.0 to 5.4% grade with three lanes. Each of the simulation results are for 3 min of time with measurements over the sections which are each 1,000 ft long. The overall mean speeds are in excellent agreement. The speed by lanes exhibits differences which are expected considering the simulation sample size.

The simulation runs used in Figure 44 employed the unconservative drivers but with desired speeds assocated with a 60-mph speed limit. (This provides characteristics associated with a 70-mph design speed and suppressed speed limit.) The field data were collected on I-80 in a remote rural area near Donner Pass.

E. Effect of Truck Flow Rates on Passenger Car Speeds

In the analyses of field data the influence of truck flow rate on car speeds could be detected at only one site, the 6% grade with two one-way lanes (grade position 2-3). There the grade was steep enough and the truck flow varied over a sufficient range for the correlation to be detected. However, the speed on this grade was sensitive not only to the truck flow but also to the truck population. Thus, it was not possible to run specific simulations with stochastic truck arrivals (although it was attempted) which could be used in a direct comparison with the field data regressions. Instead, it was necessary to employ the design guides developed from the results of a large number of simulation runs. A fair comparison with the field data also requires that weight factors be used to bring the analytical truck population into correspondence with the field

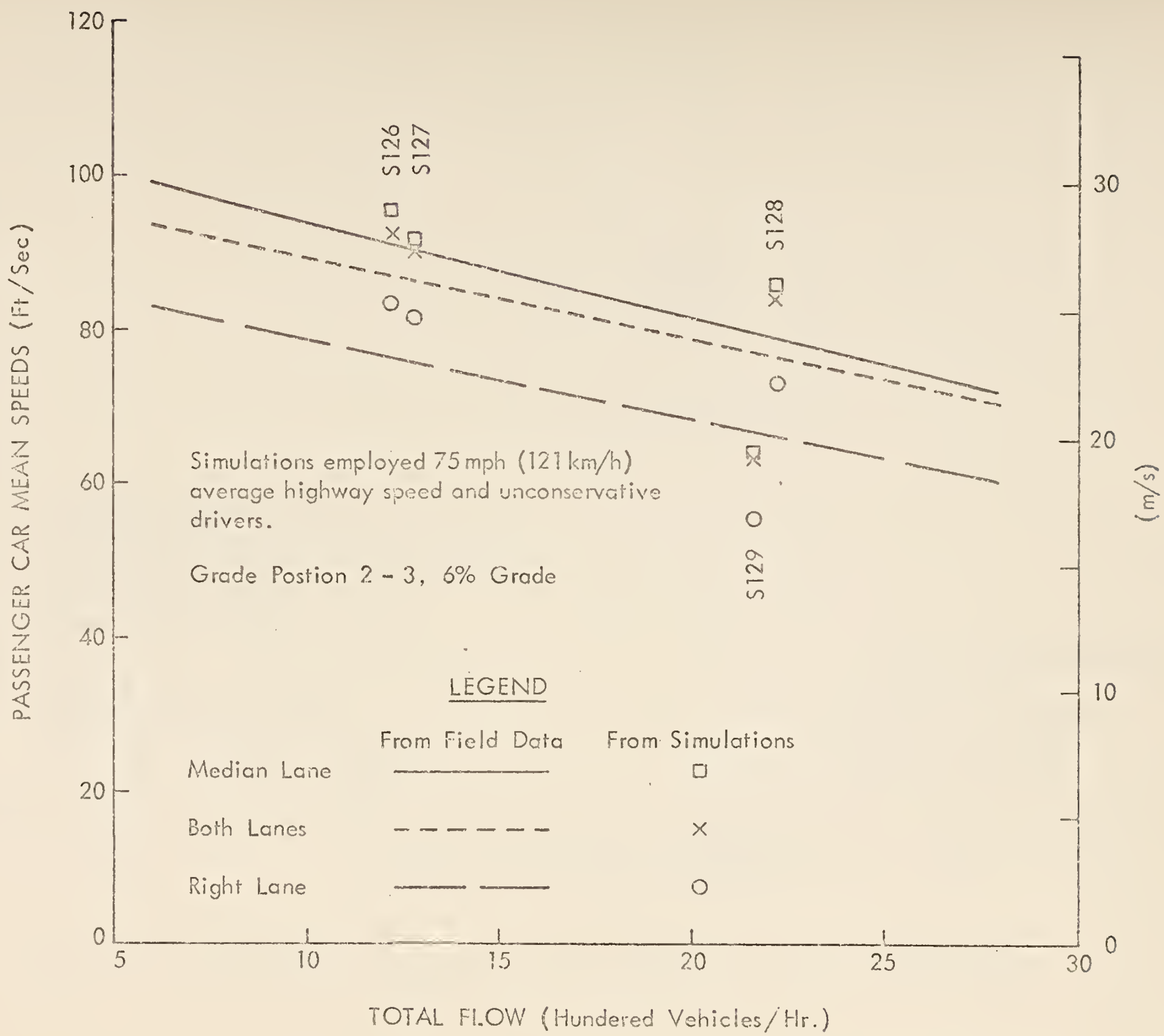

Figure 43 - Passenger Car Speeds on 6% Grade, Two One-Way Lanes

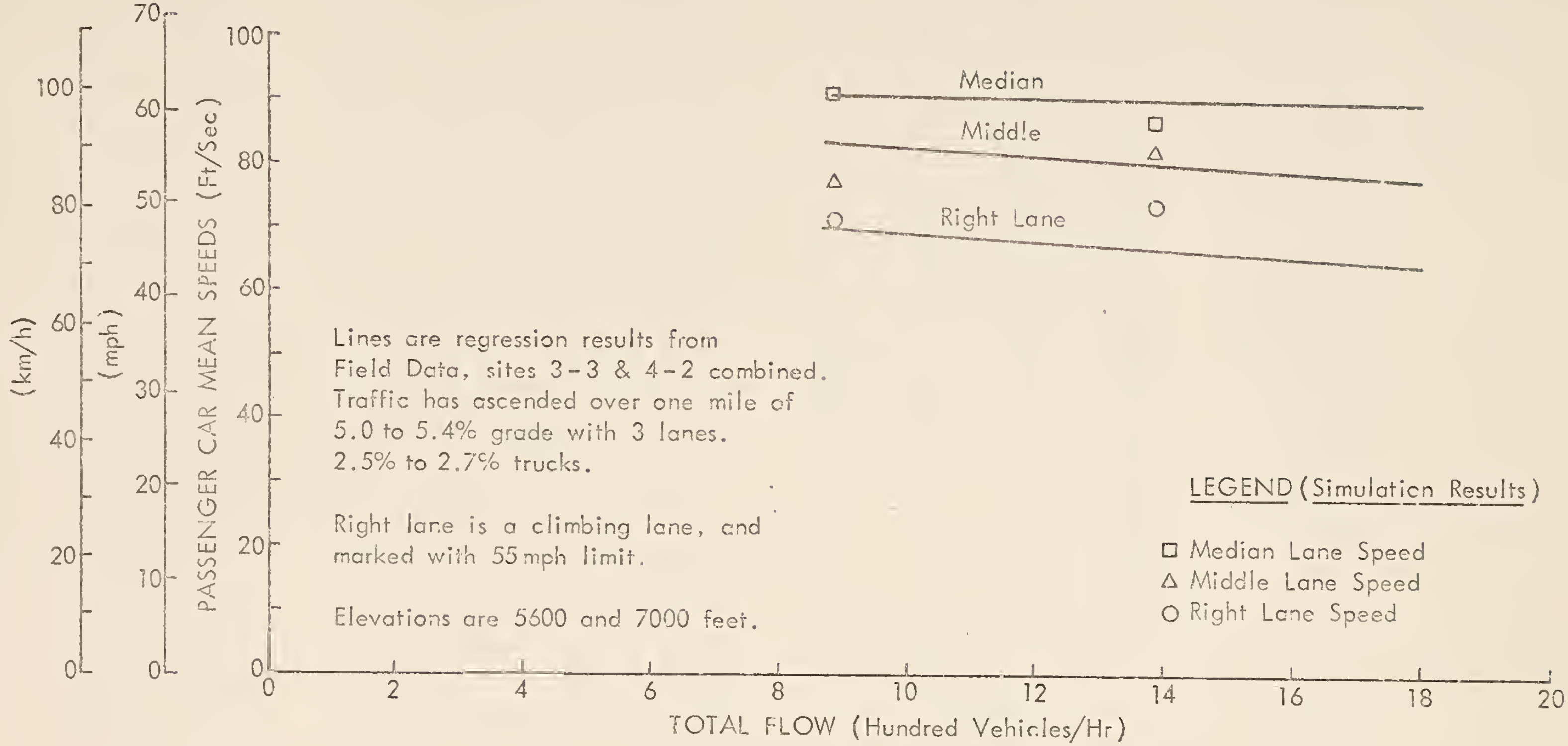

Figure 44 - Passenger Car Speeds on a 5.0 to 5.4% Grade, Three Lanes

population. Lastly, it is necessary to recognize that every truck type observed in the field did not travel through the speed trap in each (short) measurement period. Consequently, the analytical representations must employ several samples of trucks drawn from the population observed in the field.

In conclusion, the requirements enumerated above for a fair comparison must employ the concepts of the design guides and weight factors. The comparison is made later in this report after the necessary concepts have been introduced.

F. Comparison with Data from Newman and Moskowitz

In Reference 6 Newman and Moskowitz present distributions of overall speeds measured over a 5,000-ft course on a grade. The varying grade profile has been duplicated in simulations and overall speeds obtained for the same 5,000 ft (1,524 m). Figure 45 shows a comparison of results from a simulation run and from the reference. The passenger car speed distribution from the simulation is very similar to the one from the field data. Closer correspondence might be obtained by a small reduction in the simulation flows, especially the truck flow.

It was desired to make another comparison at different flow conditions. The additional data in Reference 6 at markedly different flows consist of two small samples which were apparently chosen by the authors to illustrate the extremely different results which can arise from two nominally similar flows. The results from Reference 6 are presented in Figure 46. The flows in the two samples are very similar. However, as the authors point out, the trucks which made passes in one sample (from Figure 12 of Reference 6) apparently did so with small speed reductions while trucks in the other sample (from Figure 13 of Reference 6) either had less performance capabilities or were forced to await openings in the median lane traffic. The simulation results are more nominal and provide a passenger car speed distribution between the reference values.

It should be noted that extremes such as those discussed above have been obtained in simulation runs and are part of the reason that design guides are constructed from codified results. In a similar vein the practical application of design guides should ideally include an account of both the traffic flow variance over short times and the variance of traffic conditions at nominally similar flows.

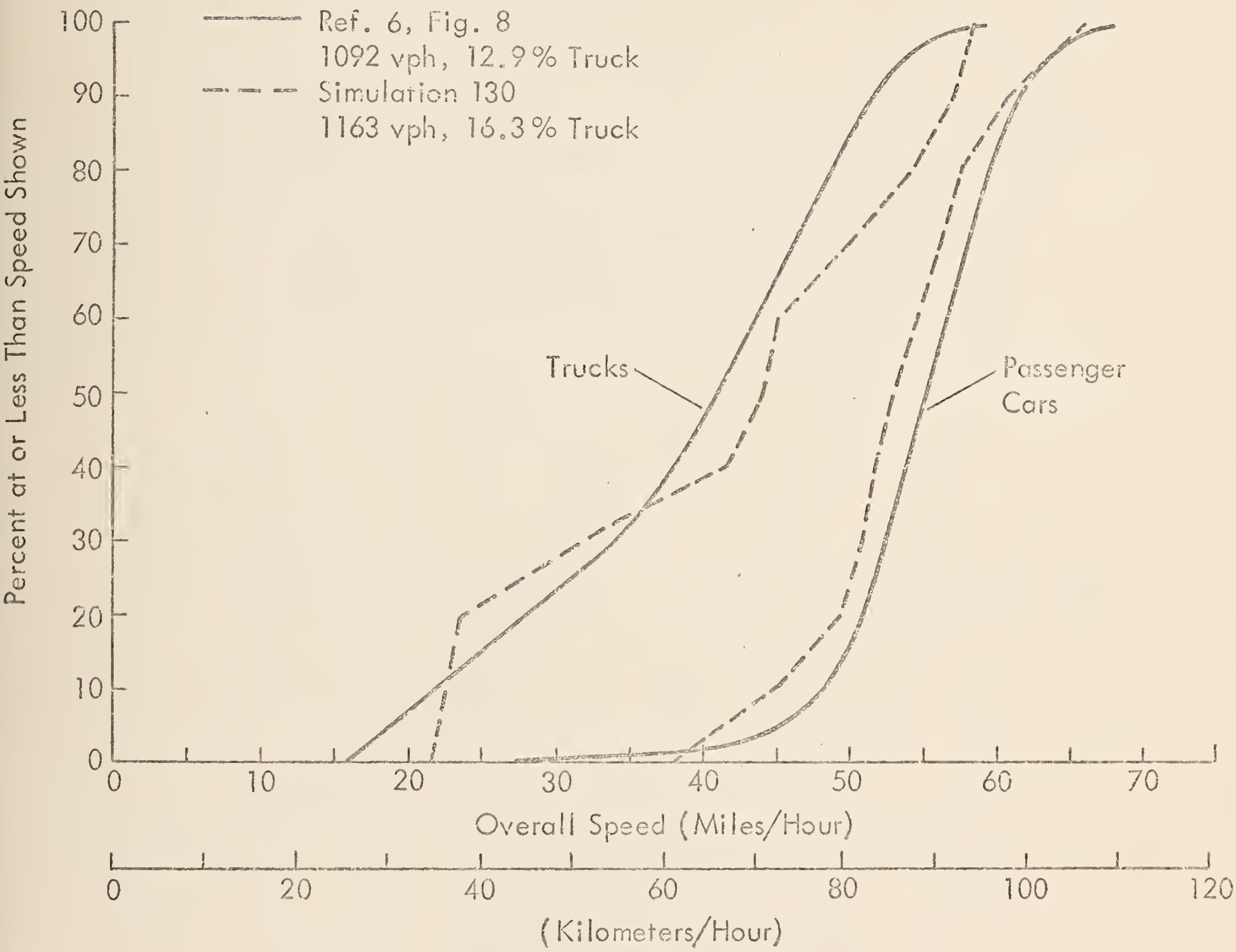

Figure 45 - Distributions of Overall Speeds for Trucks and Cars on 5,000 ft of 3% to 5% Grade

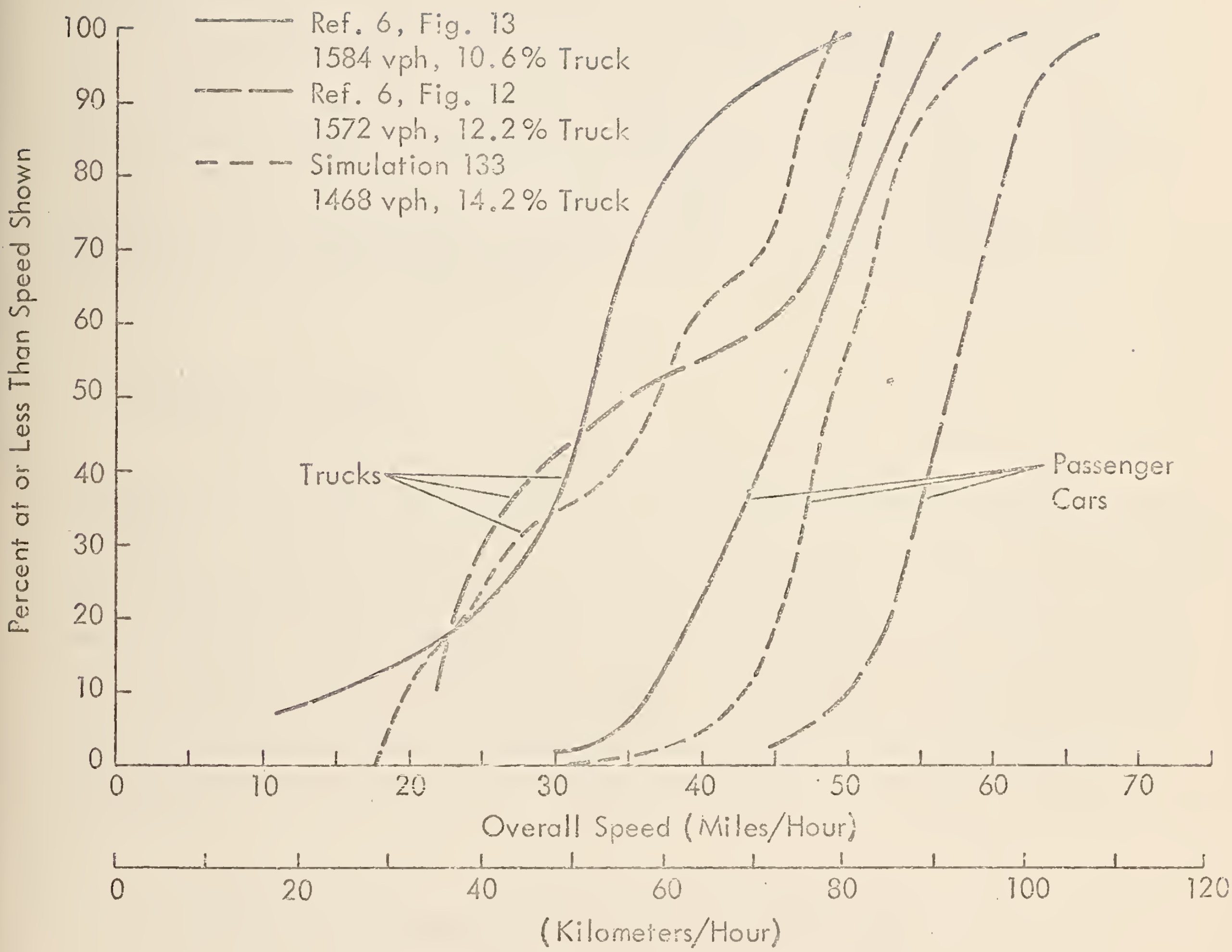

Figure 46 - Distributions of Overall Speeds for Trucks and Cars on 5,000 ft of 3% to 5% Grade

G. Tests for Start-Up Transients

The tests for starting transients employed runs in which 7 min of time are simulated. The results for individual minutes 2 through 7 were summarized separately and compared. Three simulation runs were used in these tests: V127 (6% grade), V130 (4% grade) and V135 (0% grade). Statistical tests were conducted to detect any time dependence of passenger vehicle speeds. Significant test results were examined to see if a starting transient could explain the dependence. Only one run, V130, exhibited a time trend in passenger car speeds. However, during this run, the weighted truck flow rate during minutes 5 through 7 was more than twice that during minutes 2 through 4. This change in flow rate, rather than a start-up transient, explains the observed trend in speeds. Similar tests were conducted on lane changing rates and degree of platooning. No time trends were found. Thus, it is concluded that the ability of the simulation to duplicate real traffic conditions is not affected by start-up transients.

H. Validation Summary

The simulation was validated by comparison of the output with traffic data collected in California and with other data available in the literature. The simulation was found to duplicate the main characteristics of traffic flows both in level terrain and on grades. There is good agreement between the output and the typical relationship of operating speed and flow rate. The distribution to lane is excellent and the lane changing frequencies are satisfactory to good. Tests have shown the influence of start-up transients to be negligible. Finally, the simulation meets the original goal since it produces these results under a variety of conditions with internal logic rather than through external adjustment of parameters.

I. Comparisons With Results From Early Simulation Runs

Two flaws were discovered in the program used for early simulation runs. It was found that the logic used for lane changing motivation produced higher lane changing frequencies than expected, so a compensating adjustment was made. In addition, a programming error was discovered in a subroutine. Thus, during the refinement of the simulation over the period of the project, runs were made under three main conditions.

1. Initial adjustment of lane changing logic with subroutine error.
2. Initial adjustment with subroutine error eliminated.
3. Final adjustment with subroutine error eliminated.

These flaws raised questions as to whether the results of early runs should be used in the development of design guides. To resolve these questions, comparisons were made to determine if the errors caused significant changes in operating speeds and consequently, in levels of service.

Condition 1 is clearly the worst case because both errors are present. Therefore, the comparison was made between runs under Conditions 1 and 3. Five runs which had been made under Condition 1 were repeated under Condition 3. All possible sources of variation except for the two errors were eliminated. Identical inputs were used, including the same random number seed. The operating speeds and passenger car overall average speeds for each corresponding pair of runs were compared statistically. All speed differences were found to be negligible. Therefore, it was concluded that the results of the original runs could be used in the development of design guides, because the speeds and levels of service obtained from the original and adjusted simulations were statistically equal.

V. SIMULATION RESULTS

A. General Results

The simulation model has been employed to obtain traffic flow data on level roads, on 2%, 4%, 6% and -6% grades,* on the foot and crest vertical curves, and on 4% and 6% grades with climbing lanes. This section presents some general observations about the characteristics of the flows, particularly those characteristics which permit generalization to design guides. The characteristics have been observed in the field and also in the simulation results.

Trucks which are performance-limited on an upgrade begin to lose speed somewhere on the vertical curve at the grade foot. Lane changing increases and traffic gradually redistributes itself in two available lanes with a majority of passenger vehicles in the median lane. These transition conditions associated with the grade foot persist for approximately 4,000 ft on 2% grades and for 3,000 ft on 4% and 6% grades.

As traffic proceeds up the grade beyond the foot transition, the flow achieves the characteristics which do not change with increased distance on the grade. This "on-grade" flow is <u>not</u> "steady" in the sense that its local properties remain relatively unchanged with time. However, over reasonably short times (3 min) and distances (1,000 or 2,000 ft), the average flow characteristics are unchanging. More importantly, these average flow characteristics appear useful as measures of level of service.

At the grade crest another transition occurs as the performance-limited commercial vehicles accelerate and traffic redistributes itself to lanes. The crest transition begins with the vertical curve which reduces grade and, according to simulation results, extends for approximately 2,000 ft for 4% and 6% grades.**

Generally, similar flow characteristics occur when a climbing lane is present. In this case the foot transition region contains the lane addition and the crest transition region contains the lane drop.

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* Upgrades positive.

** It requires more than 4,000 ft for low-performance trucks to regain their zero grade speeds. However, the major disruption associated with the grade is relieved in about 2,000 ft.

The simulation results were studied for characteristics that would permit the results from several runs to be codified. It was found that on a sustained grade the relationship between operating speed and flow rate has the same characteristic shape obtained in zero-grade flows. However, for the sustained grade flow the capacity diminishes with increasing grade and truck flow rate. (This finding is consistent with the concept of equivalence.) In brief, the relation between operating speed and percent of capacity is consistent over a range of grades and mixed flows. This consistency has been used to codify simulation results and to derive design guides.

B. Construction of Design Charts

It was shown in Section IV-A that the simulation produces the operating speed vs. percent capacity relationships that are observed in real traffic. A similar relationship was found (by simulation) to exist in the flows of mixed traffic on extended grades. It is emphasized, however, that in the on-grade flows the speeds (even operating speeds) are averages over a wide range, frequently with localized regions of free flowing and highly impeded flows. In addition, the effective capacity on the extended grade is reduced by commercial vehicles.

The design charts are constructed by combining and interpreting the results from numerous simulation runs. The combination is effected by using the operating speed vs. percent capacity relations to obtain an "implied capacity"* for each simulation datum. The combination of implied capacities is used to define implied capacity as a function of grade and percent commercials. An example is now presented.

Figure 47 shows the operating speeds vs. percent capacity for two lanes one-way on any grade with a 75 mph (121 kmph) design speed. This figure is simply the nondimensional version of the operating speed versus flow curve presented in Figure 31. Figure 48 was then generated by using Figure 47 together with simulation results. The operating speed from a simulation was used in Figure 47 to read percent capacity. Then the implied capacity was calculated from

$$\text{Implied capacity} = \frac{\text{Simulation flow rate}}{(\text{percent capacity}/100)}$$

* The phrase "implied capacity" is used because an actual test to obtain the capacities has not been made at <u>each</u> condition.

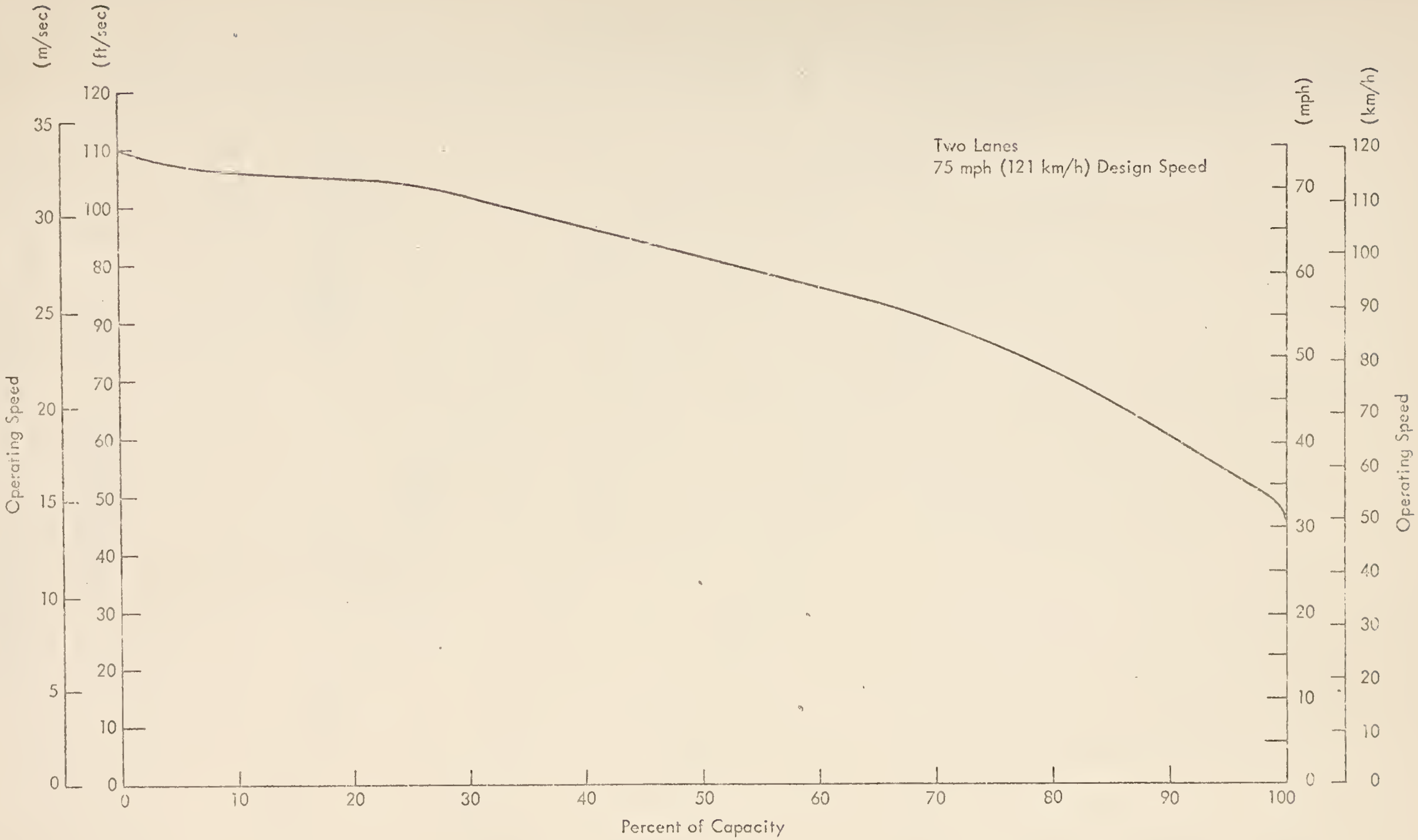

Figure 47 - Operating Speed Versus Percent of Capacity, 75 mph (121 km/h) Design Speed

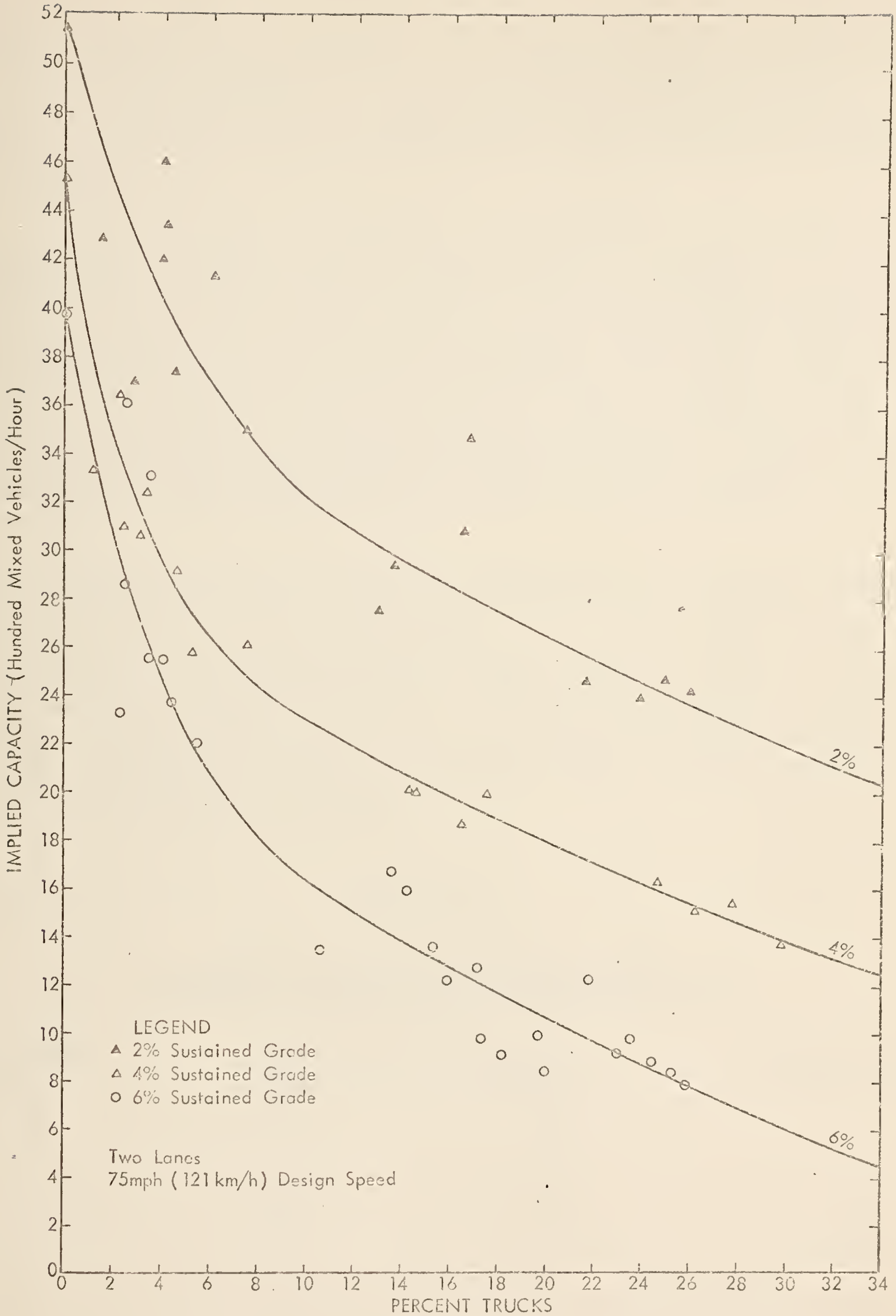

Figure 48 - Implied Capacities on Two Upgrade Lanes, 75 mph (121 km/h) Design Speed

The result was plotted in Figure 48 at the values for percent commercial and grade employed in the simulation. The lines in Figure 48 were drawn to be slightly conservative. That is, the lines were drawn slightly below the apparent mean of the points. (For interpretative application this means that capacities will be underestimated by the lines more frequently than overestimated.)

An observation is made about the intercepts in Figure 48 before continuing with the construction of design charts. The values of implied capacity at zero percent commercials are based on an approach to the limit zero in the vicinity of a single isolated, heavy truck. The lines were drawn using the limit values since they appeared to provide a conservative fit to all available data points in this and similar figures. In reality when the percent commercials falls below 1 or 1-1/2%, the commercials are essentially isolated so that operating speeds and capacities for passenger vehicles may approach zero-grade values during the long absences of commercial vehicles.

Figures 47 and 48 provide the information of interest. However, their main purposes are, first, to codify results from numerous simulation runs and, second, to prepare design guides. The design guides are based on operating speeds and percent capacity. Used together, Figures 47 and 48 provide the combinations of flow rate, traffic composition, and percent grade for any percent capacity or operating speed. For reference, Tables XVIII and XIX present the definitions from the 1965 capacity manual for boundaries between service levels.

TABLE XVIII

SERVICE LEVEL BOUNDARIES FOR RURAL MULTILANE HIGHWAYS WITH UNINTERRUPTED FLOW

Separating Levels	Minimum Operating Speed mph	Minimum Operating Speed ft/sec	Maximum Percent of Capacity
A & B	60.0	88.0	30
B & C	55.0	80.7	50
C & D	45.0	66.0	75
D & E	35.0	51.3	90
Limit E	27.5	40.3	100

TABLE XIX

SERVICE LEVEL BOUNDARIES FOR FREEWAYS AND EXPRESSWAYS WITH UNINTERRUPTED FLOW AND 70 MPH DESIGN SPEED

Separating Levels	Minimum Operating Speed mph	Minimum Operating Speed ft/sec	Maximum Percent of Capacity	Number of Lanes (one-way)
A & B	60.0	88.0	35	2
			40	3
			43	4
B & C	55.0	80.7	50	2
			58	3
			63	4
C & D	50.0	73.3	75 (PHF)[a]	2
			80 (PHF)	3
			83 (PHF)	4
D & E	40.0	58.7	90 (PHF)	≥ 2
Limit E	30.0	44.0	100	≥ 2

a/ PHF is peak hour factor (maximum percent of capacity should be a function of peak hour factor).

Design information includes the following factors: number of lanes, grade, design speed, total flow rate, percentage of trucks, implied capacity, service level and operating speed. All of these factors can be examined through a family of sets of nomographs or design charts.

A design chart set consists of two figures. Figures 49 and 50 are a sample set for the 75-mph (121 kmph) design speed, two-lane one-way case. Figure 49 is a copy of 47 with service level information added. Figure 50 presents the information from 48 in a directly applicable form. The two examples indicated on Figure 50 are described below.

In the first example it is desired to estimate the freeway service level and operating speed on a 2% sustained grade with 10% trucks in a mixed flow of 1,800 vph. An initial point is located on Figure 50 at the intersection of the 2% grade line and the 10% trucks line. From the initial point the horizontal line (1-1) is followed to the intersection with 1,800 vph. From the intersection the fan of constant percent truck lines is followed (along 1-2) to the scale for percent of implied capacity. Percent of implied capacity is read as 56. And the answer is read on Figure 49 at 56% of implied capacity service where level is C' and operating speed is 60 mph (97 kmph).

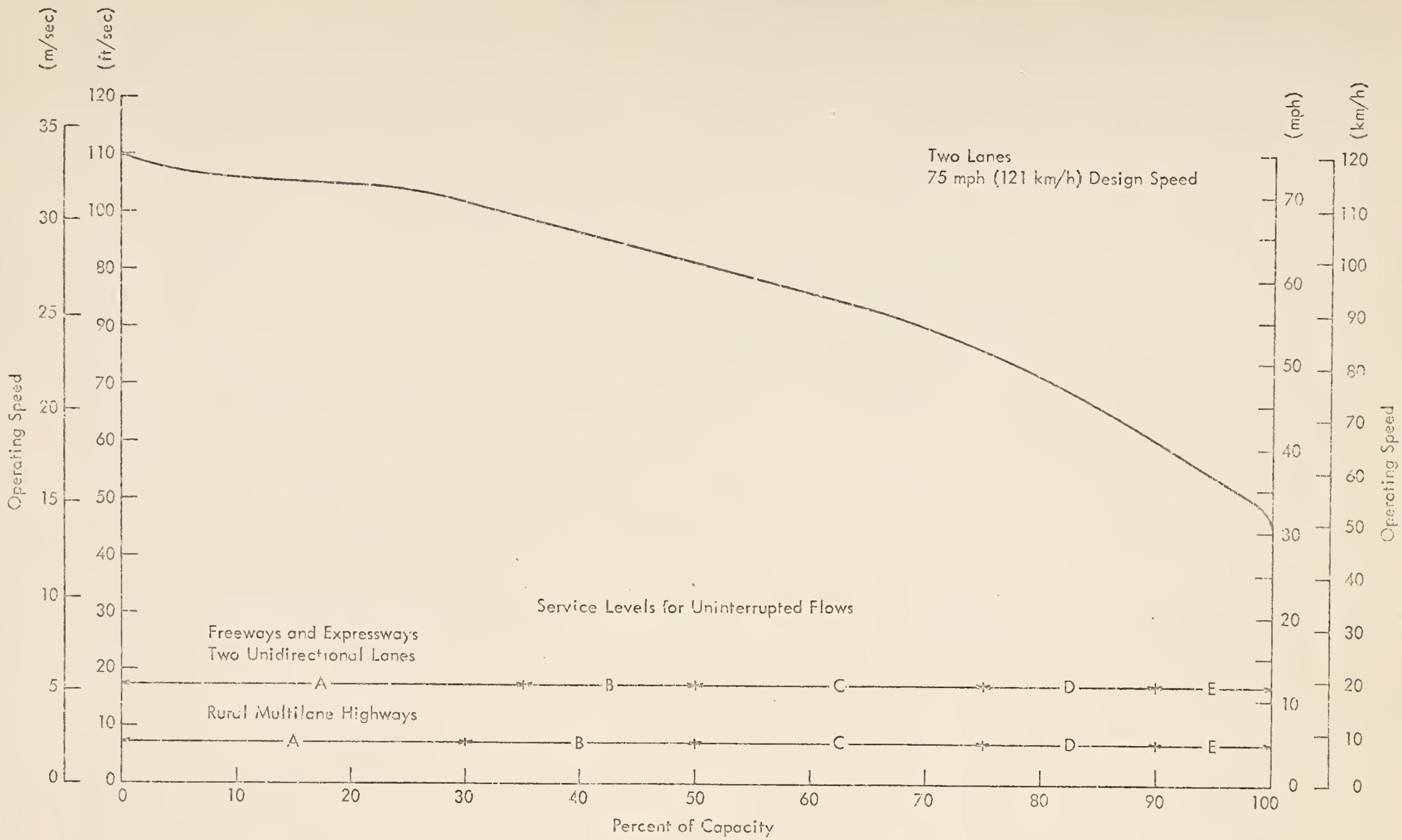

Figure 49 - Operating Speed Versus Percent of Capacity, 75 mph (121 km/h) Design Speed

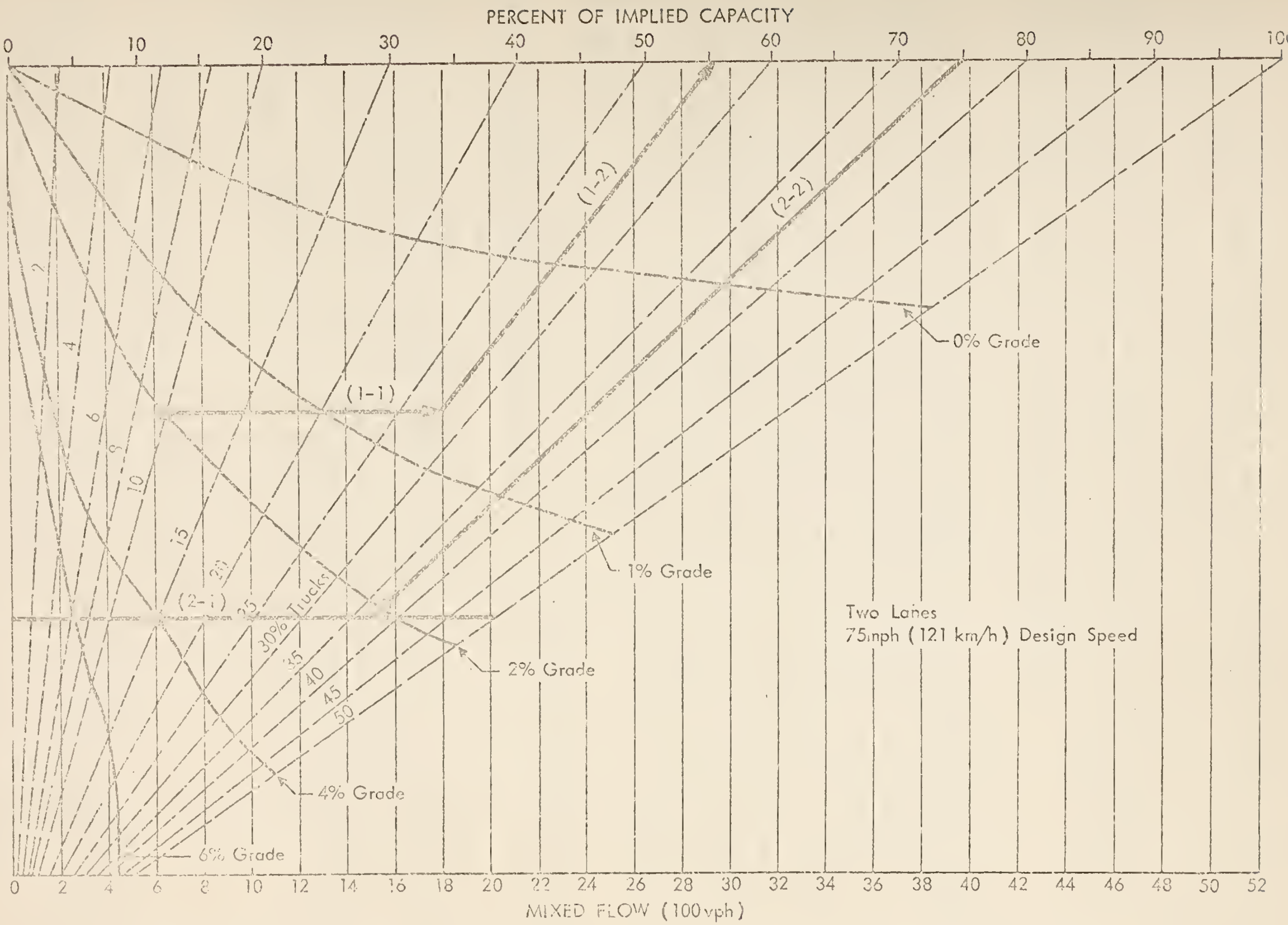

Figure 50 - Implied Capacities Versus Percent Trucks and Sustained Grade, Two Lanes, 75 mph (121 km/h) Design Speed

In the second example the maximum flow for service level C'* on a rural multilane highway is sought for a 4% sustained grade on which the flow will contain 15% trucks. The intersection of the 4% grade line and the 15% trucks line is located on Figure 50 and a horizontal line is passed through that point (line 2-1). From Figure 49 the upper limit of implied capacity for level C' is 75%. Figure 50 is entered on the percent of implied capacity scale at the value, 75. The fan of lines is followed (along line 2-2) to the intersection with line (2-1). At that intersection the answer is read as 1,520 vph (mixed vehicles).

Figure 50 and others like it are based on a simple concept which involves the horizontal line passing through the intersection of a percent grade and a percent truck curve. All service levels, A' (if possible) through E', are represented along the horizontal line. At the left-hand end the percent of capacity is zero and flow is zero. This is the highest possible service level. At the right end of the line, where it intersects the last of the fan of lines, the mixed flow is equal to the estimated capacity. For the second example the estimated capacity is 2,020 vph. The fan of lines actually serves a dual purpose. First, individual lines in the fan identify the intersection of the given percent trucks with a sustained grade line. Second, from any point on a horizontal line the fan can be used as a guide to the scale for percent of implied (or estimated) capacity.

Design chart sets are presented in Appendix B for the sustained grade conditions shown in Table XX.

In the next section the design chart sets are extended for application to grade feet and crests and to rolling terrain. However, it must be recognized that the charts apply to a specific truck population and provide an estimate of the most likely flow conditions during short time periods (2 to 3 min). Also, additional results from the simulation provide measures of comfort and safety. These subjects are discussed in the sections which follow.

C. The Vehicle Population and Weight Factors

The performance characteristics of the vehicles, especially the trucks, influence the service levels and capacities in on-grade flows. The design charts are based on passenger and truck populations with the characteristics presented in Tables XXI and XXII.

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* Service levels are primed to remind the user that level depends on operating speed and percent of capacity. Comfort and safety on grades may not equal that in level terrain.

TABLE XX

SUSTAINED GRADE DESIGN CHART SETS

Design Speed		Speed Limits		No. of	
mph	km/h	mph	km/h	Lanes	Grades (%)
75[a]	121	75[a]	121	2 & 3	0,[b] 1, 2, 4, & 6[c]
70	113	60 & 70	97 & 113	2 & 3	1, 2, 4, & 6[c]
65	105	60 & 65	97 & 105	2 & 3	1, 2, 4, & 6[c]

a/ The 75-mph (121 km/h) design speed and speed limit exceed normal standards and regulations. These characteristics were used to duplicate traffic data recorded on I-580 and I-680 east of the San Francisco Bay area.

b/ On level terrain, trucks have a significant effect on the flows with the 75-mph (121 km/h) design speed and speed limit. At the lower design speeds and speed limits, trucks have insignificant effects on 0% grade in uninterrupted flows. (These observations are based on simulation results.)

c/ The design values supported directly by simulation results are: two-lane with 0, 2, 4 and 6% grades; and three-lane with 0, 4 and 6% grades. The guide values for the other lane-grade combinations are based on similitude and interpolation.

TABLE XXI

CHARACTERISTICS OF PASSENGER VEHICLE POPULATION

Simulation Index No.[a]	% in Passenger Population	Length (ft)	Maximum[b] Acceleration (ft/sec^2)	Maximum Speed[b] ft/sec	Maximum Speed[b] mph
1	49.80	18	14.7	147	100.2
3	45.13	18	11.7	130	88.6
5	5.07	18	8.1	101	68.9

a/ Indices 2 and 4 were not used.

b/ On zero grade at sea level conditions.

TABLE XXII

CHARACTERISTICS OF COMMERCIAL VEHICLE POPULATION

Index No.	Lb/NHP Represented	% in Commercial Population	Length (ft)	Max. Accel.[a] (ft/sec^2)	Performance Limited Steady Speed (ft/sec) on Grade[b] 0%	1%	2%	3%	4%	5%	6%	7%
7	75	13.5	25	13.00	108.5	101.4	94.9	88.9	83.4	78.2	73.4	68.9
8	150	36.5	40	9.25	96.3	83.9	73.6	65.1	57.8	51.6	46.2	41.4
9	250-350	36.5	50	5.66	82.1	65.8	53.8	44.5	37.2	31.2	26.2	22.1
10	> 350	13.5	60	3.80	61.3	41.9	30.5	22.9	17.5	13.5	10.4	7.9

a/ On zero grade at sea level.
b/ Sea level conditions.

Attempts were made to run the simulation with two distinct truck populations, the heavy population in Table XXII, and the national average as defined by the investigation of Wright and Tignor.* The stochastic character of vehicle arrivals resulted in truck samples which varied from both of the populations. However, it was clear that the composition of the truck sample had a marked influence on simulation results. The fraction comprised of lowest performance trucks had the most influence.

Weight factors were derived to adjust all the truck populations which occurred in simulation runs to a common or reference base. The reference population is the one defined in Table XXII.** The weight factors were derived through two cycles of iteration. (That is, a second set of weight factors was derived to improve on the initial set.) In each iteration it was the goal to reduce the scatter of points around curves of the type shown in Figure 48. The results supplied the following relation:

$$\text{Percent reference trucks} = \frac{100}{F} (3.16\ f_{10} + 1.41\ f_9 + 0.14\ f_8 + 0.06\ f_7)$$

where Percent reference trucks = Percent in terms of reference population defined in Table XXII.

F = Total flow rate of mixed vehicles.

f_{10} = Flow rate of Index No. 10 trucks.

f_9 = Flow rate of Index No. 9 trucks, etc.

When these weight factors are applied to the base population, the "percent reference trucks" equals the percent based on direct counts on sustained grades of 2, 4, and 6%. <u>It should be noted that percent trucks as used in the tables and figures of this report means "percent reference trucks" unless otherwise stated.</u>

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* "Relationship Between Gross Weights and Horsepowers of Commercial Vehicles Operating on Public Roads," John M. Wright and Samuel C. Tignor, <u>SAE Transactions</u>, Vol. 73 (1965).

** The truck population in Table XXII contains a larger fraction of low performance types than the population measured by Wright and Tignor.

The weight factors are related to the speeds of trucks on the grades. The derived weight factors can be approximated in terms of the speed differences between the truck types used in the simulation. This is an approximation because the speed differences between types are not exactly the same on 2%, 4% and 6% grades. The weight factors as a function of speed differences are depicted in Figure 51. It should be noted that the slowest truck in a sample (3-min sample) is assigned the weight factor 3.16, or 3.0 in the linearized form.

Figure 51 provides a means for assigning weight factors to trucks without first equating them to a simulation truck type. Also, the strong sensitivity of flow characteristics to the slowest truck in a sample suggests that design guide information can be expressed as a function of the speed of the slowest truck. Figure 52 presents implied capacity vs. the speed of the slowest truck and the percent trucks. (Recall that percent trucks is the percent of reference trucks as obtained by applying the weight factors to a subject truck sample.) Figure 52 can be used to estimate capacity so that percent of capacity can be calculated. Then, estimates for the service level and operating speed can be read from Figure 49.

Figure 52 can be used for capacity estimates on grades which were not explicitly simulated. The 1% grade line in Figure 50 was obtained this way. Also, Figure 52 can be used to estimate flow conditions in the foot and crest transition regions when the speeds of the truck sample are known or estimated. (Figures 51 and 49 are also used.) Estimates of operating speeds have been made and compared with simulation results in the foot and crest transition regions, and found to be useful. The difference between the estimated speeds and the simulation results are presented and discussed later in this report.

Figure 52 and similar figures have been used to extrapolate to very large percentages of trucks. The simulation results extend up to 20% or 30% trucks for the various grade and number of lane combinations.

The flow characteristics in rolling terrain should be equivalent to a sequence of foot and crest transition flows. As an example, consider the influence of a short grade on a facility with two upgrade lanes. The alignment has a sag vertical curve at the foot followed by 400 ft (122 m) of 4% grade. It is estimated that the truck population, which constitutes 17.5% of the peak-hour flow, is slowed to the speeds shown in Table XXIII.

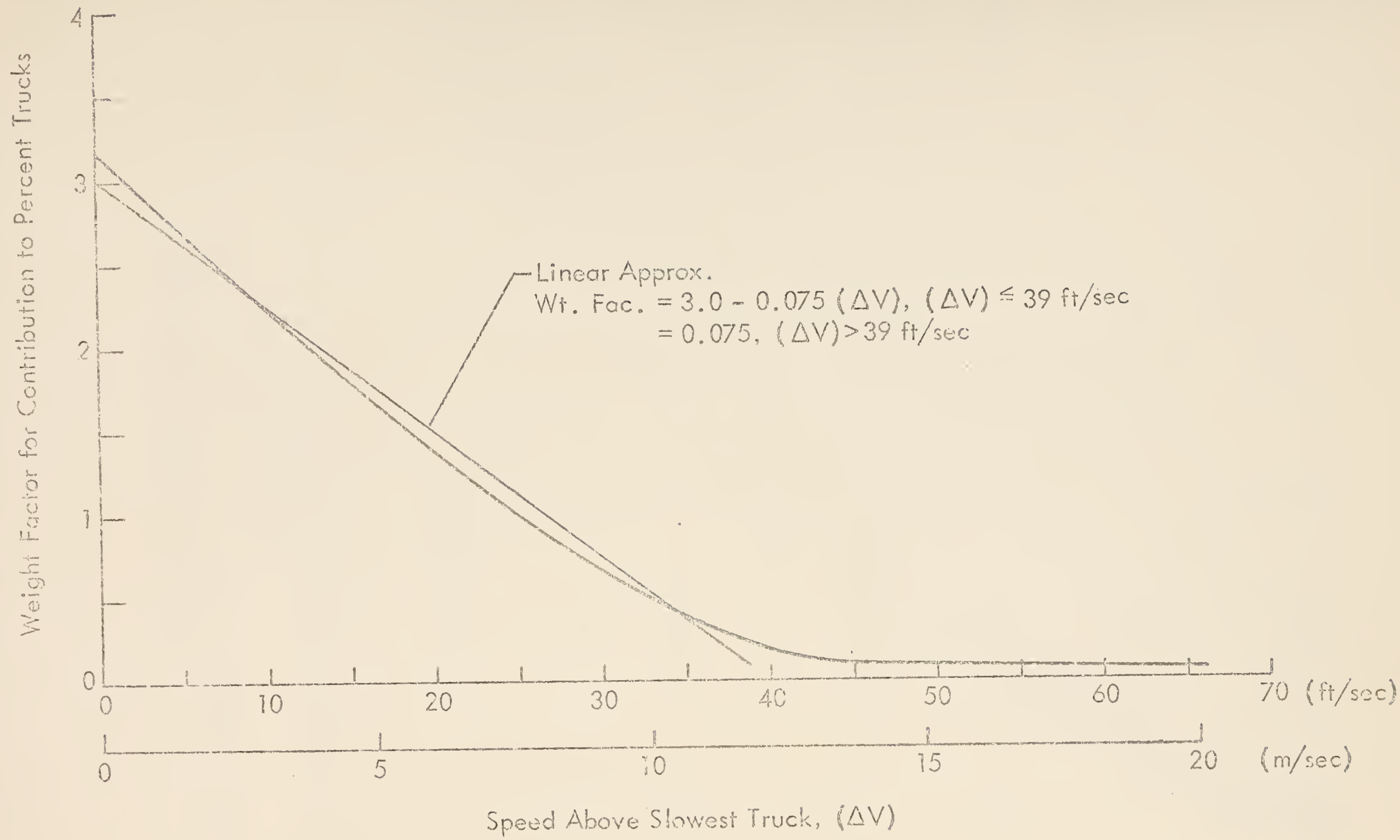

Figure 51 - Weight Factors for Trucks Versus Speed Above Lowest Speed Truck

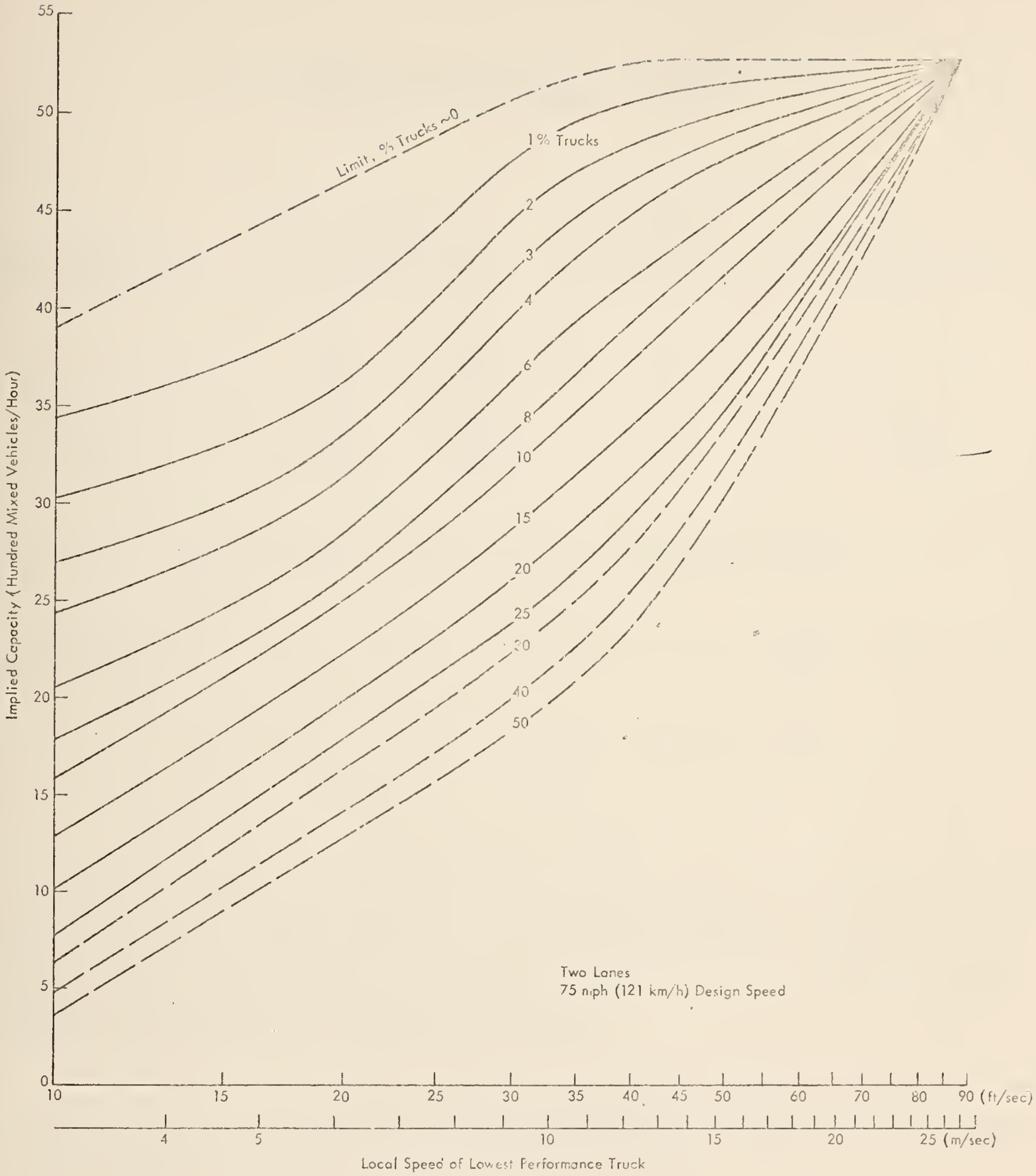

Figure 52 - Implied Capacity Versus Speed of Slowest Truck and Percent Trucks, Two Lanes

TABLE XXIII

MINIMUM SPOT SPEEDS OF TRUCKS ON A SHORT GRADE AND ASSOCIATED WEIGHT FACTORS

Percent of Truck Population	Minimum Speed (ft/sec)	(m/s)	Speed Above Slowest (ft/sec)	Weight Factor (From Figure 51)
5	45	13.7	0	3.16
8	50	15.2	5	2.72
21	62	18.9	17	1.61
33	71	21.6	26	0.92
33	80	24.4	35	0.37

Applying the weight factors, the percent of reference trucks is

$$\text{Percent reference trucks} = 17.5\Big[(0.05)(3.16) + (0.08)(2.72) + (0.21)(1.61) + (0.33)(0.92) + (0.33)(0.37)\Big] = 19.9$$

The estimated capacity is read from Figure 52 at 19.9% trucks and 45 ft/sec (13.7 m/s) for the slowest truck. The estimated capacity is 3,420 mixed vehicles/hour. Figure 49 may be used to estimate service level. Service near the crest of the short grade will fall below level C' if mixed flow exceeds 75% of 3,420 or 2,562 vehicles/hour.

In the above example it must be recognized that the service would be depressed over a very short section of highway. Variations over time and grade length are discussed later in this report.

The appendix with design guide sets (Appendix B) also contains figures similar to Figure 52 for two and three lanes with design speeds equal to 65 mph (105 km/h), 70 mph (113 km/h) and 75 mph (121 km/h).

D. Precautions in the Use of Design Charts

The design charts are based on a truck population with a large percent of low-performance vehicles, and the basic curves were drawn conservatively. However, the charts are based on flows over short time periods. They do not include provision for peaking or variance during a design hour.

The simulation results indicate that the implied capacities are not "practical capacities." Temporary local congestions can occur in the on-grade flows over a wide range of percents of implied capacity. When 90% of implied capacity is approached, temporary local congestions are almost certain to occur. When flow exceeds 90 or 95% of implied capacity, the flow is vulnerable to breakdown. It appears that breakdown on a 2% grade will occur in a fashion similar to flows in level terrain with nearly uniform high densities and low speeds. On the 4% and 6% grades the maximum flows with trucks appear to occur as a sequence of congested and flowing conditions on the grade. Flow breakdown on these steeper grades is probably not a smoothly spreading phenomenon. Instead, if the spots of congestion grow, the storage space on the grade becomes progressively filled with congestion queues.

Some of the poorest service levels simulated occurred in runs on the 4% grades with two lanes upgrade. The service was depressed in local sections on the grade by a flow feature which might be described as persistent congestion. At high flow rates this congestion was triggered by a single event, i.e., a sequence of disruptive events, such as a truck passing a platoon of other trucks In another case a very conservative driver followed the truck performing the pass so that the queue was slow to accelerate when the truck returned to the right lane. In each case a queue 600 to 1,000 ft long built up in the median lane. This local spot of congestion did not dissipate; it followed the slow truck(s) up the grade. A flow of higher speed vehicles went through the congestion but the congested queue remained with a slowly varying length. Runs in which persistent congestion occurred on 4% grades implied lower capacities as a result of the reduced operating speeds which occurred in the flows.

E. Measures of Comfort and Safety on Extended Grades

The design guides illustrated earlier in this report were based on operating speed and percent capacity. Safety, driver comfort and freedom to maneuver are also to be considered in assigning service level. On level terrain the percent capacity is an implicit measure of these added features, with general deterioration of service level as 100% capacity is approached.

In the simulation, several items are obtained as measures of risk and driver work load. The measures selected for presentation are identified in Figure 53. A brief explanation of these measures is given here.

All the measures are quantified to depict the risk exposure and work load experienced by individual passenger vehicle drivers. Lane changes per (passenger) vehicle-mile are measures of driver work load and also risk since the preparation and conduct of the maneuver requires extra tasks which may delay or degrade essential tasks. A direct measure of risk exposure is the time (seconds) per (passenger) vehicle-mile during which risk is greater than some nominal value. The nominal value chosen here is -4 ft/sec^2 (-1.2 m/sec^2). That is, the situation would normally elicit a deceleration more severe than 4 ft/sec^2 (1.2 m/sec^2). A dual interpretation, both work load and risk, is attached to the percent of time which passenger vehicle drivers spend in searching for and conducting lane changes. Last, lane change interactions which involve more than nominal risk are a doubly important measure of risk exposure. The lane-changing driver has extra tasks and must simultaneously (in order to make the lane change) accept and impose risks by his relative position and speed with respect to nearby vehicles. This measure is quantified as the number of more than nominal risk interactions per passenger vehicle-mile. Nominal risk is the same value, -4ft/sec^2 (-1.2 m/sec^2), defined previously.

The measures are plotted against fraction of capacity. This organization of values appears to provide the best overall representation. The number or fraction of trucks does play a complex role.

Figure 53 shows that on extended grades all the measures of work load and risk exposure rise as percent capacity increases. They reach a peak and diminish as a capacity is approached. The 4% and 6% grade values are usually higher (worse) than the values for 0% and 2% grades.

The values in Figure 53 are for the unconservative driver population (with 60% close followers) which is associated with the 75-mph design speed and 75-mph speed limit. Conservative driving associated with the 65-mph design speed and speed limit produces much lower values for more-than nominal risk (seconds/passenger car mile).

Figure 54 shows similar measures for flows with a climibing lane available. The values for three lanes are similar to those for two lanes except that the frequency of lane-changing risks is greater for three lanes than for two lanes.

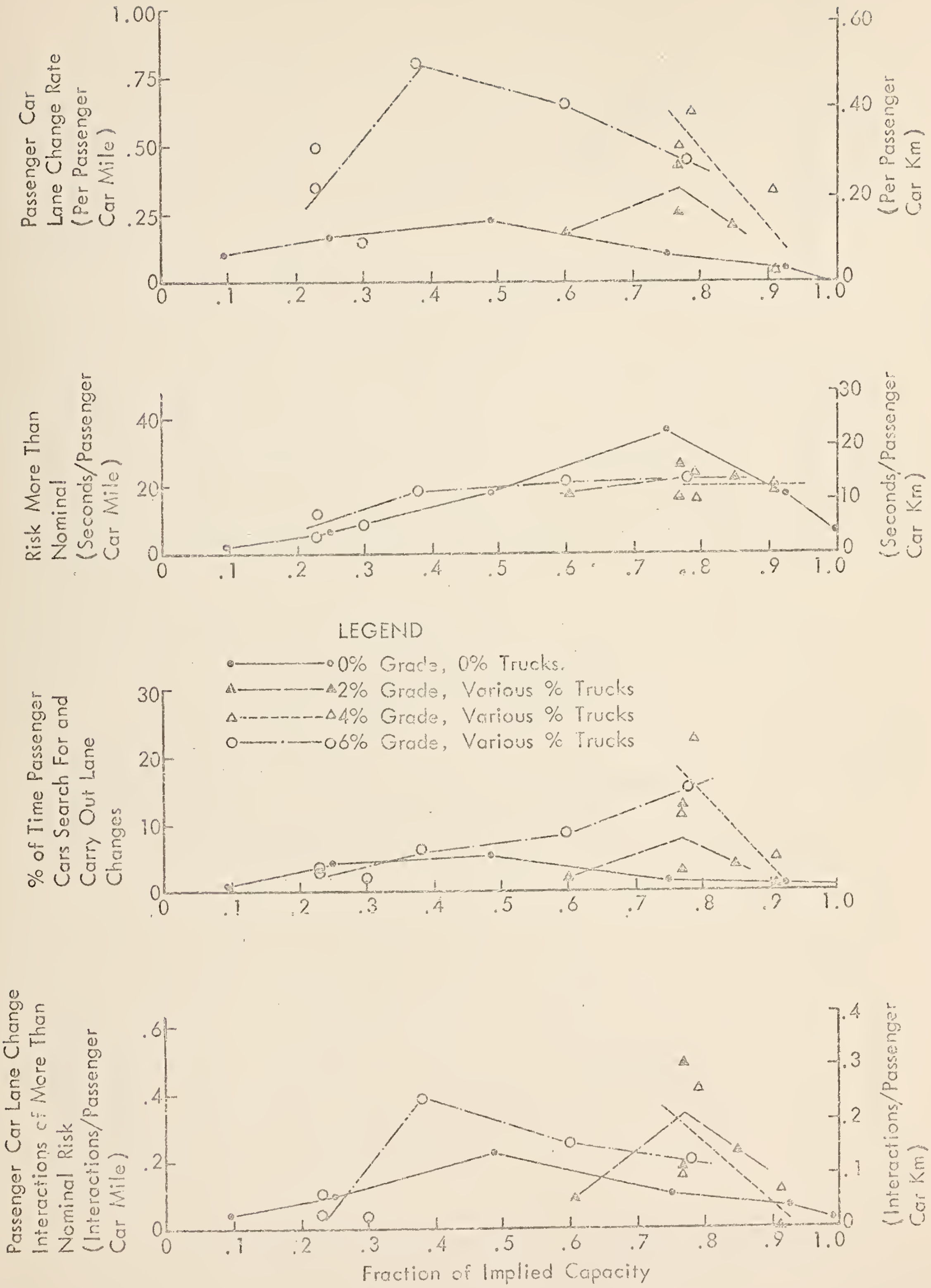

Figure 53 - Measures of Driver Work Load and Risk Exposure for Passenger Cars on Two Lanes Upgrade (Simulation results for 75 mph design speed highway)

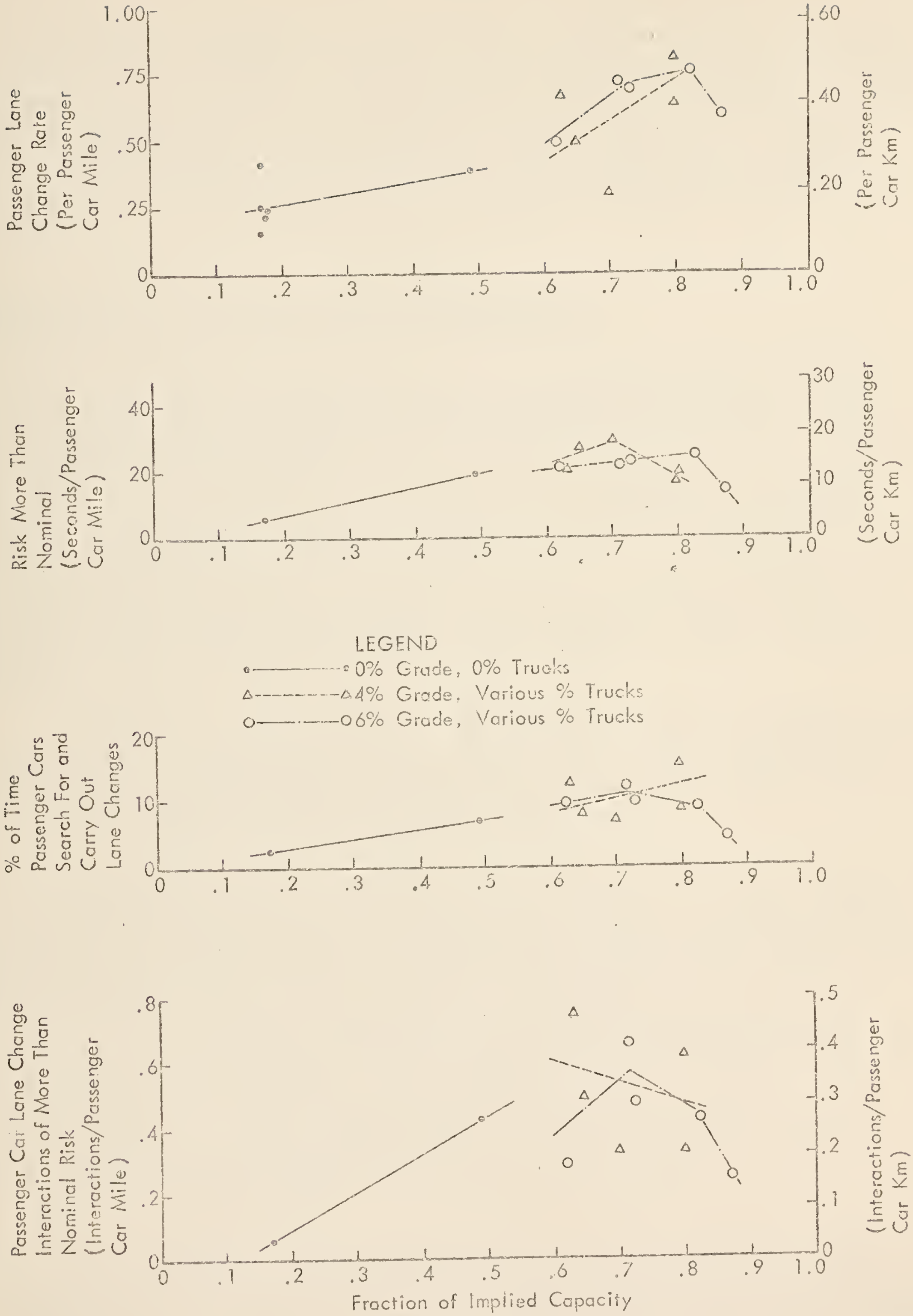

Figure 54 - Measures of Driver Work Load and Risk Exposure for Passenger Cars on Three Lanes Upgrade (Simulation results for 75 mph design speed highway)

At the foot and crests of grades the flow undergoes transition between its level and on-grade characteristics. The work load and risk exposures in the transition flows are similar to the on-grade values.

Very few accidents occurred in the simulation runs. (The simulation logic detects accidents, records them, and rectifies the situation so that the run can proceed.) All accidents occurred in platoons in which the headways were smaller than normal due to the recent entry by a lane changer. One accident was a two-collision chain reaction. No attempt is made to interpret accidents since they must be extremely rare in a realistic flow.

F. Comparisons with Current Recommended Practice

For multilane rural highways in level and rolling country the AASHTO Policy on Geometric Design of Rural Highways recommends a design capacity which provides average running speeds of 45 to 50 mph. In mountainous terrain the design to an average running speed of 40 to 45 mph is recommended. Figures 55 and 56 show the flows indicated by simulation results for an operating speed of 50 mph (80 km/h) and overall average speeds for passenger vehicles of 45 mph (73 km/h). Figure 55 is for the 65 mph (105 km/h) design speed; Figure 56 is for the 70 mph (113 km/h) design speed. Both figures are based on the reference truck population in which 13.5% are in the 350 to 450 lb/NHP range.

It should be noted that the simulation results are based on flows measured over relatively short time periods (3 min). The AASHTO design recommendations deal with actual hourly volumes with the possibility of significant variations in flow rate during the hour.

The AASHTO policy recommends the consideration of a climbing (third) lane upgrade for multilane highways when there is a grade whose length exceeds a critical value and directional-design-hour volume exceeds 1.3 times design capacity and is 1,000 vehicles/hour or more. The minimum flows that warrent consideration of a climbing lane are shown in Figure 57. For comparison, simulation results are shown for flows which should provide average passenger car speeds of 45 mph (73 km/h). The AASHTO recommendations appear to be consistent with a 45-mph (73-km/h) average running speed. The AASHTO values for the 6% grade may underestimate the speed depressions associated with very small and very large fractions of truck flow.

The simulation results in Figure 57 are based on the 65-mph (105 km/h) design speed. The results with the 70-mph (113 km/h) and 75-mph (121 km/h) design speeds indicate larger mixed flows are possible for a passenger car average speed of 45 mph (73 km/h).

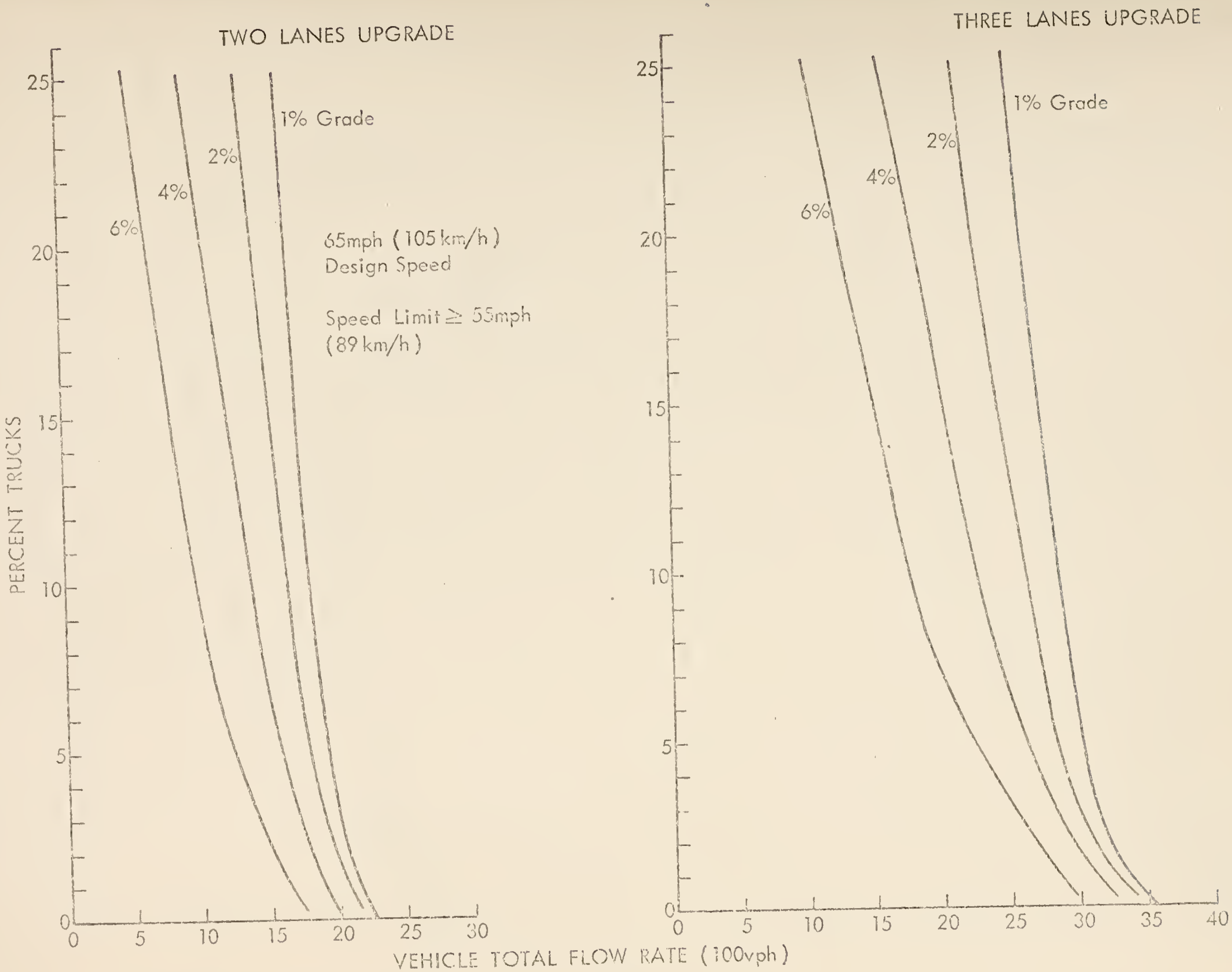

Figure 55 - Maximum Flow Rate for Passenger Car Average Speeds of 45 mph (73 km/h)

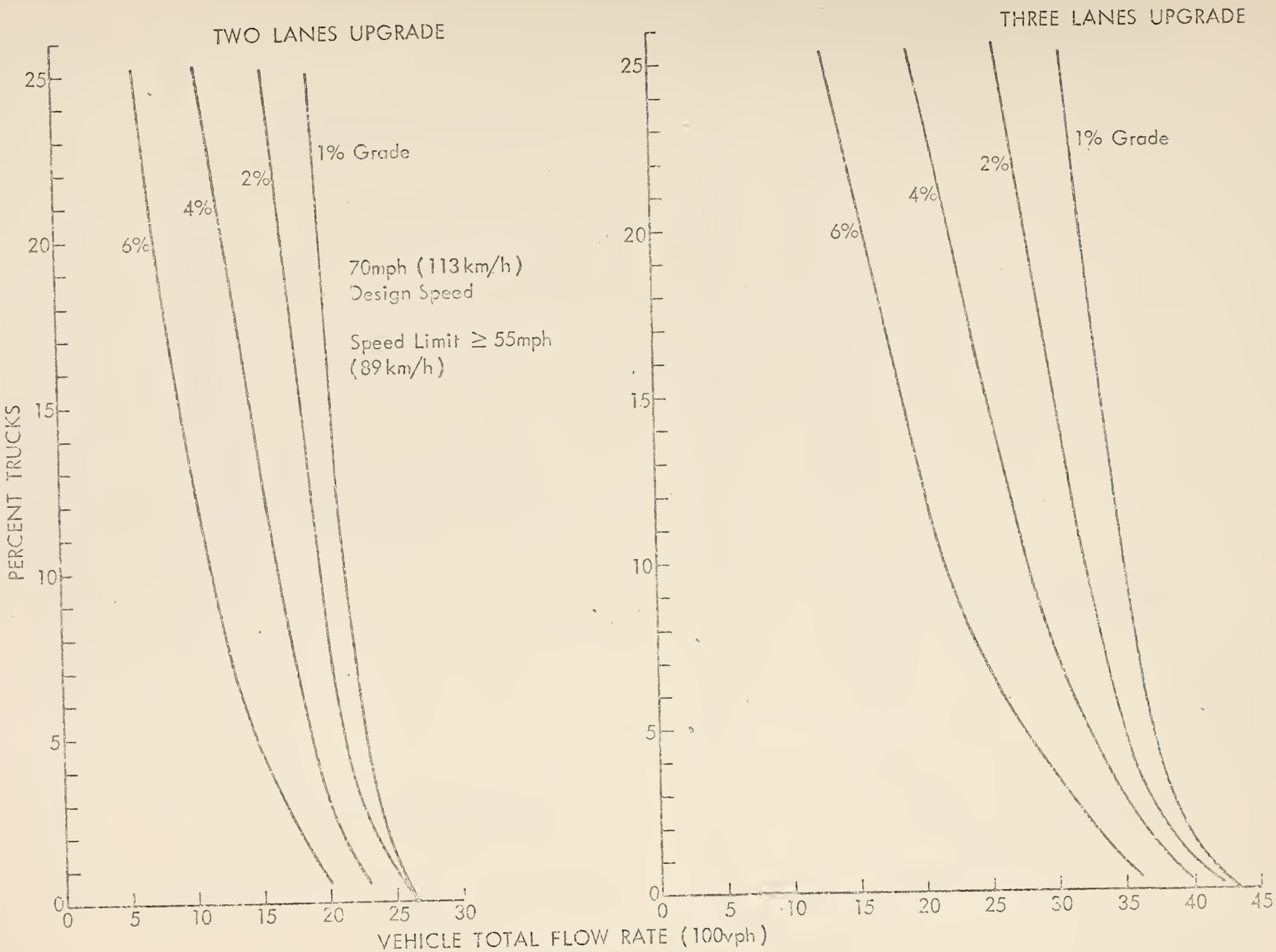

Figure 56 - Maximum Flow Rates for Passenger Car Average Speeds of 45 mph (73 km/h)

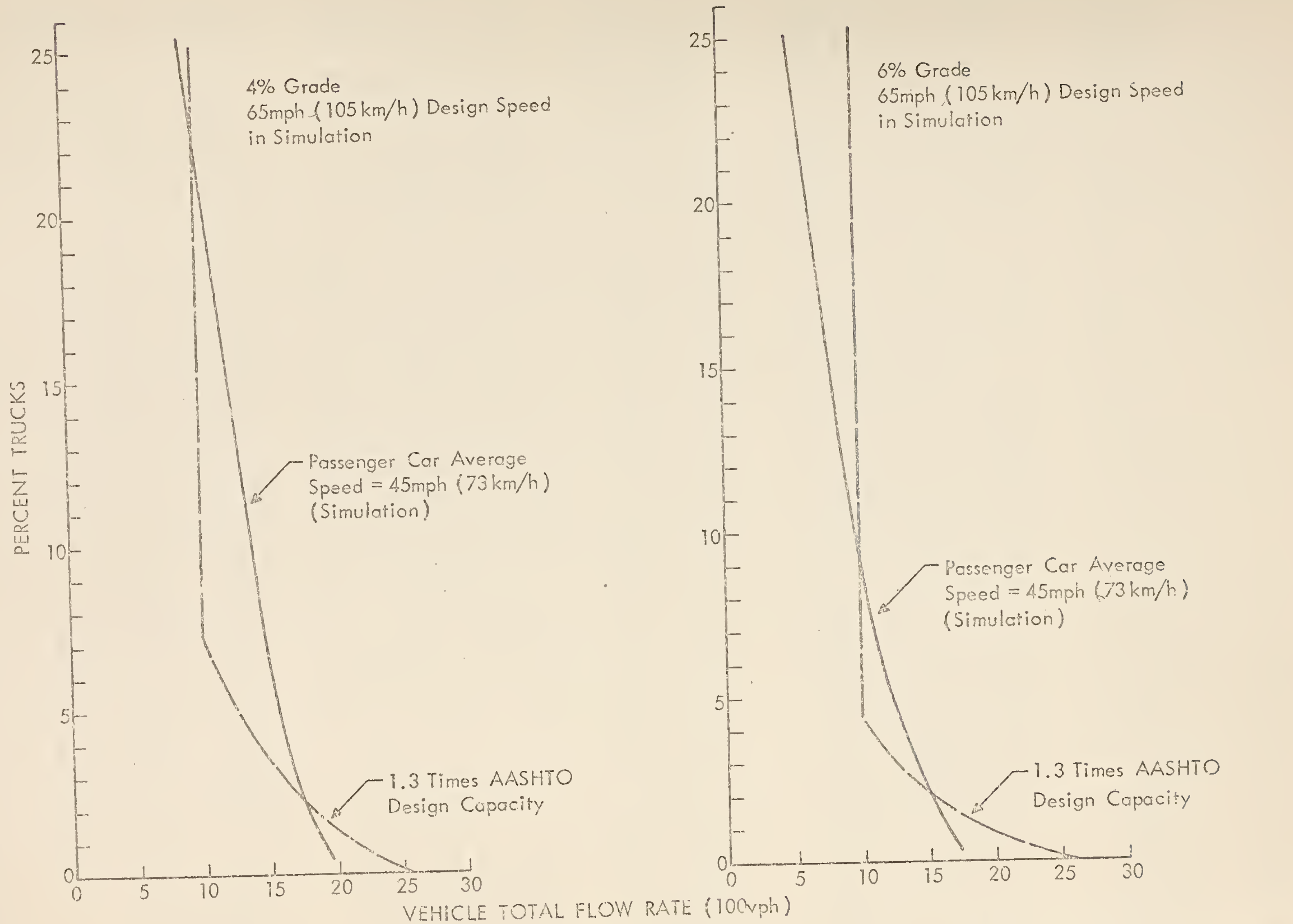

Figure 57 - AASHTO Recommendations for Considering Climbing Lane and Comparable Simulation Results

G. Comparisons with Field Data from the 6% Grade (Grade Position 2-3)

When the simulation results are compared with field data, it is necessary to inquire how a fair comparison must be made. Many of the issues raised in answering this question are also pertinent when simulation results are used to estimate traffic conditions, or when one set of field observations is compared with another.

The field data were collected in 1-min time intervals, and it was found in regression analyses that passenger car speeds were correlated with truck flows during that minute and, to a lesser extent, with truck flows in adjacent minutes. Observations at the field site also suggested that a 2- to 3-min period was most suitable for connecting traffic flow characteristics with volume and the vehicle population. The use of intervals much larger than 3 min will average over flows and compositions having noticeably different consequences to the operating characteristics. Thus, 2 to 3 min is a good compromise.

The field data collection included the measurement of speeds for a randomly selected sample of trucks, campers, and passenger vehicles pulling tracters. The on-grade speed characteristics of these potentially impeding vehicles is adequately defined by these measurements. (Speeds of 52 trucks and 151 campers plus trailer combinations were measured.)

We now consider what the regression results provide. The appropriate regression results are based on 2-min samples of traffic. Passenger car speeds are explicitly related to the total flow rate and to the truck flow rate. However, at any specified combination of total flow and truck flow rate the regression results provide an expected or average value of passenger car speeds.* This is not simply an average over a single 2-min sample, but is an average of a large number of similarly drawn samples. Individual 2-min samples can have higher or lower values.

In order to construct a comparable average from simulation results, it is necessary to form and employ samples drawn randomly from the truck population observed at the field site. In brief, although the truck population is well defined by the field data, every truck whose speed was measured in a multihour period does not appear in each short time sample. Also, since the lowest performance trucks have the greatest effect on traffic flow it is important to note that the lowest performance truck observed over a several hour period should not appear in each short sampling period.

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* Also, the influence of campers and trailers, which were found to have marginally significant correlations, were not explicitly included. Consequently, any influence from the campers and trailer combinations is reflected in the average provided by regression results.

The simulation results and the field data (regression results) were compared at six conditions listed below:

Total Flow Rate (vph)	Average Camper and Trailer Combination Flow	Truck Flow Rate (vph)
1,400	9.7% of total	0
1,400	9.7% of total	40
1,400	9.7% of total	80
1,800	9.7% of total	0
1,800	9.7% of total	40
1,800	9.7% of total	80

For each condition the design guides (simulation results) were applied to 30, 3-min samples. The procedure for selecting the samples and evaluating the flow characteristics is now described.

The flow of campers plus trailer combinations was treated as a random arrival process (Poisson).* The number in each sample of vehicles was determined stochastically using the Poisson distribution and a random number table. The on-grade speed of each camper or trailer combination was assigned stochastically using the distribution of speeds measured from field observations and a random number table. This last step was in preparation for treating campers plus trailer combinations as part of the truck population when simulation results were employed.

Because the flow rate of trucks is explicit in the regression results, it is consistent to treat as fixed the number of trucks in each sample. However, in each sample the speeds of individual trucks were assigned stochastically using the distribution of speeds observed in the field together with a random number table.

The next step in processing each sample was to locate the lowest speed truck (or camper if lowest) in the sample. The linearized weight factors (see Figure 51) were then applied to adjust the "percent trucks" in that sample to the reference population basis.

The estimated average passenger car speed for each sample was then obtained as follows: Implied capacity was read from Figure 52 at the speed of the lowest truck and the adjusted percent trucks. The percent of

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* Since only the average flow rate is employed, the actual rate in each short sample period may vary from the mean. The assumption of random arrivals and the use of the Poisson distribution is suggested by the small values of the correlation coefficients for successive minute flows.

capacity was calculated and used in a figure similar to Figure 49 to read passenger car speed. (The figure employed has passenger car average speed instead of operating speed vs. percent of capacity.)

The simulation results for each of the 30 samples at the same flow condition were averaged. The results are compared with the field data averages (regression results) in Figures 58 and 59. The agreement is acceptable. The major difference occurs at zero truck flow rate where the speed predicted by simulation exceeds the field data value. Apparently, the weight factors and design charts slightly underestimate the speed-depressing influence of the campers and trailer combinations when no trucks are present.

The simulation results and regression results (field data) in Figures 58 and 59 were treated as grand means and were compared using the t-statistic. The results are shown in Table XXIV. For testing the hypothesis of equal means, the critical t value is 1.96 for a confidence level of 95%. The simulation speed results for no truck flows are seen to be high (the hypothesis of equality is rejected). At 40 and 80 truck/hour flows, one t-value exceeds the critical value slightly. (At a confidence level of 96% the hypothesis of equal means would not be rejected.)

In view of the extensive effort required to employ the simulation results in an assembly of samples, one must inquire what speeds would be estimated using the standard reference truck population and the design charts. The estimated speeds would be 2 ft/sec (0.6 m/s) to 6 ft/sec (1.8 m/s) higher than those obtained from the stochastically selected and weighted samples. The weighting plays a large role in this difference since the truck population at the 6% grade field site was dominated by harvest trucks with very low performance. Fifty percent of the observed trucks had speeds on the grade less than 17 mph (27 km/h). Most truck populations should correspond more closely to the reference population than did the sample from the field site used.

The weighting factors derived from simulation results provide a method for adjusting truck samples to the reference truck population. However, this simple adjustment is appropriate for short period (3-min) samples. Samples were assembled in the foregoing to estimate a grand mean for passenger car speeds. However, since traffic characteristics on grades are subject to several strong sources of variance, it may be necessary to consider more than the long period mean. The sources of variation are discussed in the next section.

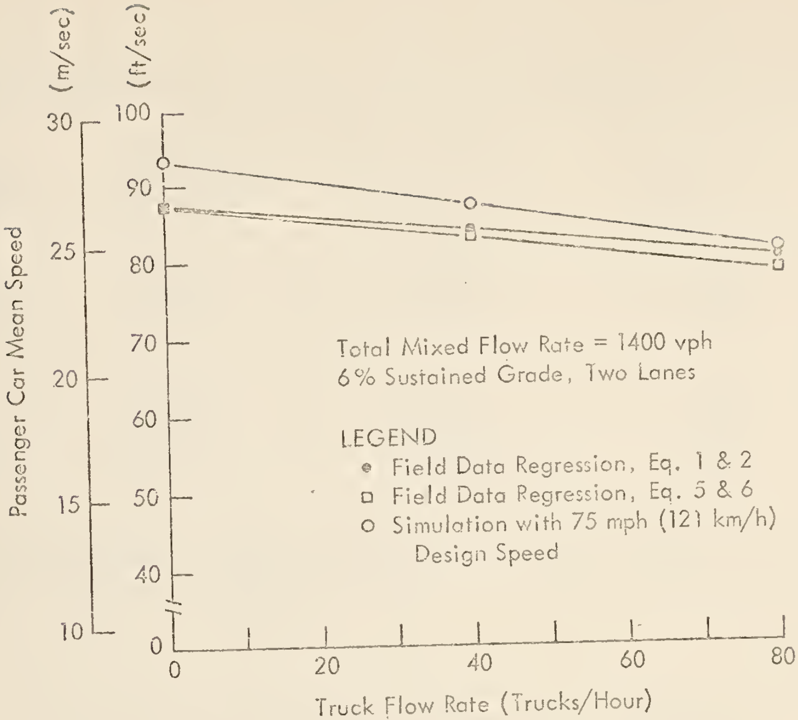

Figure 58 - Passenger Car Mean Speeds Versus Truck Flow Rate

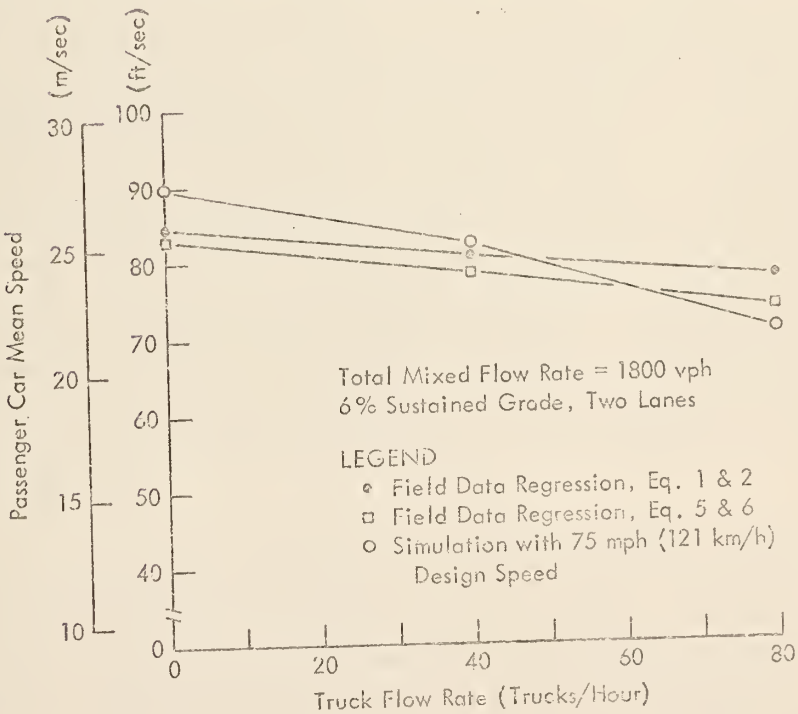

Figure 59 - Passenger Car Mean Speeds Versus Truck Flow Rate

TABLE XXIV

TESTS ON GRAND MEANS FROM SIMULATION RESULTS AND FIELD DATA

Flow (vph)		Car Mean Speeds (ft/sec)		Difference	
Total	Truck	Field[a/]	Simulation	(ft/sec)	t-Value
1,400	0	84.79	93.47	5.98	2.74
	40	83.04	87.44	4.40	2.00
	80	78.51	81.53	3.02	1.36
1,800	0	83.03	89.87	6.84	3.13
	40	78.42	82.45	4.03	1.81
	80	73.76	70.48	-3.28	-1.36

a/ Regression equations 5 and 6 accounting for the fractions of small and large trucks in measured flows.

H. Variations of Flow Characteristics with Time and Length

The data collected on grades and the observation of the flows suggests that 2 to 3 min is a suitable time period for relating the flow characteristics to the flow rate and vehicle population. Longer periods will average over characteristics which may be noticeably different. This short period is at variance with the hourly rates and volumes which are normally used in design or evaluation. However, short-term demands have been recognized as being important for flows on freeways and expressways, and the 5-min interval peak has been employed. These "peak hour factors" are used to account for the mean maximum demand during 5-min periods of peak hours. When the period is shortened to 3 min, the peaking will be slightly more severe. However, on grades (especially on sustained grades) there are additional sources of variance, some of which may be more important than the increased peaking in flow rate. The sources of variance over time are now discussed.

The design hour volume for a facility, together with the percent of trucks, may be the basis for design or evaluation. A peaking factor may be employed to account for total flow variations and to estimate the mean maximum flow rate. On a sustained grade, however, the variation of truck flow rates between 3-min intervals may be the source of equal or greater variation in traffic characteristics. In addition, the samples of trucks which arrive in individual 3-min periods may have performance capabilities which are different than the truck population sampled over long periods.

The simulation results and the comparisons with field data indicate that the size and character of the truck sample should have a strong effect on the short-period flow characteristics. Neither of these types of sample-to-sample variations has a pronounced effect on flow characteristics in level terrain.

There is an additional source of variation for the on-grade flow arising from the presence or absence of disruptive events in the flow. The disruptive events are usually associated with truck-passing-truck maneuvers. This means that the flow characteristics might vary noticeably between different 3-min samples even though each contained exactly the same set of trucks. The simulation results have been used to estimate this variance and also to evaluate any bias in the design charts.

The simulation runs have been analyzed just as though the results (flows) were field data for which the design charts were to be applied to estimate passenger passenger car speeds. (In this case, the performance characteristics of the trucks are known and can be employed in the weighting factors.) The operating speeds estimated with the design charts do not, of course, agree exactly with each operating speed measured in the simulation flow <u>even though the design charts were based on simulation results</u>. This difference, simulation operating speed - estimated operating speed, was analyzed.

Tables XXV and XXVI present the statistical properties of the speed differences for cases where the design speed is 75 mph (121 km/h)

In Table XXV the standard deviation, σ , refers to variations between operating speeds for 3-min intervals in which exactly the same trucks traverse the test section of 1,000 ft (300 m), and is an estimate of the influence of "disruptive incidents" in flows which are otherwise alike. (Because some of the variance may be due to imperfections in the weighting procedure, the σ values are upper bounds for the influence of disruptive incidents.)

In Table XXVI the mean of differences, μ , indicates the average amount by which simulated operating speeds differ from the design chart predictions. Ideally, the μ could be reduced to zero by repeated interative improvements to the weighting values and to the design charts. The design chart values were intentionally made slightly conservative* ($\mu > 0$) because they are based on results from "on-grade" flows. However, on the feet of 2% grades a slightly unconservative bias is obtained.

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* The conservative bias means that operating speed will be underestimated by the design charts.

TABLE XXV

STANDARD DEVIATIONS OF THE DIFFERENCES BETWEEN SIMULATION OPERATING SPEED AND ESTIMATED OPERATING SPEED[a/] FOR 75 MPH (121 KM/H) DESIGN SPEED

Region of Grade	Grade (%)	σ (ft/sec)	Lower Confidence Limit (ft/sec)	Upper Confidence Limit (ft/sec)
Foot transition	2	2.538	1.875	3.923
	4	5.724[b/]	4.228	8.859
	6	7.736[b/]	5.715	11.974
On sustained grade	2	5.229[b/]	3.863	8.094
	4	4.573[b/]	3.378	7.077
	6	10.434	7.708	16.149

a/ Estimated operating speeds were obtained by using the weight factors and design charts.

b/ These values were found to constitute a homogeneous set.

TABLE XXVI

MEANS OF THE DIFFERENCES BETWEEN SIMULATION OPERATING SPEED AND ESTIMATED OPERATING SPEED[a/] FOR 75 MPH (121 KM/H) DESIGN SPEED

Region of Grade	Grade (%)	μ, Mean of Differences (ft/sec)	Lower Confidence Limit (ft/sec)	Upper Confidence Limit (ft/sec)
Foot	2	-3.713	-5.065	-2.361
	4	1.067[b/]	1.982	4.116
	6	-0.085[b/]	-4.207	4.037
Sustained grade	2	0.900[b/]	-1.886	3.686
	4	2.050[b/]	-0.386	4.486
	6	5.725	0 168	11.282

a/ Estimated operating speeds were calculated using the weight factors and design charts.

b/ These values were found to be a homogeneous set and the value of the combined set is not significant, i.e., not statistically disguishable from zero.

In addition to grade feet, another set of sections on the grade regularly exhibits a negative (unconservative) bias. These sections follow the climbing lane addition and precede the lane drop. The bias is estimated to be about 8 ft/sec (2.4 m/s). The benefits of the climbing lane are not fully realized in the first 800 to 1,000 ft (240 to 300 m). Likewise, the benefits are not fully retained during the last 1,000 to 1,400 ft (300 to 425 m). The numerics here are based on simulation results. The underlying traffic behavior is also observed in the field.

Statistical tests on the values in Tables XXV and XXVI are now described.

The individual variance values (σ^2 in Table XXV) were separated into like and unlike groups using--

1. Bartlett's test for the homogeneity of a set of variances;

2. Cochrans test for testing, one extreme number from a set of variances; and

3. The F-test for equality between two variances.

All confidence intervals and hypotheses were set at the 95% confidence level.

As shown in Table XXV, four of the variance values were found to constitute a homogeneous set with a combined standard deviation $\sigma = 5.93$ ft/sec (1.81 m/s). The μ for this set was tested by a one-way analysis of variance and found to be homogeneous with respect to bias. The combined μ estimate for the four is +0.98 ft/sec (0.30 m/s) which is not distinguishable from zero.

The variances for the 2% foot and 6% on-grade cells were found to be statistically lower and higher, respectively, than the others. These same cells have different (Mann-Whitney U tests), and non-zero biases.

I. Concluding Remarks Concerning Use of Design Charts

The design charts presented in Appendix B may be used to estimate average conditions (speeds and service levels) on either sustained grades or in rolling terrain. The chart-determined speeds may be a few feet per second conservative (low) for most situations with the underestimate increasing with grade. In transition regions (feet and crests) the estimate may be a few feet per second high.

As in any other traffic flow situation, it may be of interest to know more than just average conditions of on-grade flows. Peaking factors are more involved and more drastic on grades than they are on level terrain. Peaking happens on grades not only because of fluctuations in total flow rates, but also because of fluctuations in truck flow rates, in the mix of truck performances, and in the occurrence of truck-truck interactions. The latter factors alone, even for traffic made up of the identical set of vehicles, can result in speed standard deviations of 5 to 10 ft/sec (1.5 to 3 m/s) between 3-min intervals.

The estimates discussed for operating speed and the sources for variance with time are appropriate for short sections of highway (1,000 ft or 300 m). However, if a sustained grade is extended for an additional distance, there is a greater likelihood that at any given time there will be a region of seriously suppressed service somewhere on the grade. This follows from the fact that there are more sections in which extremals can develop. Second, when a serious disruptive event does occur, it may lead to a spot of congested flow that does not dissipate, but remains with the slow vehicles that triggered it. On a sustained grade the spot of congestion will influence overall service for a time proportional to the remaining grade length. The persistent spot of congestion has been observed in the simulated flows. Temporary spots of congestion were observed numerous times in the simulation flows and at the 6% grade field site.

For design and traffic engineering purposes, it may be more informative to know the distribution of operating speeds (with each value being an average operating speed during a short period of peak hour or design flows) rather than estimates of the mean and variance. Obviously, the low service extremals are most important. There are two obvious alternatives for obtaining this information.

Speed distributions over 1-hr periods could be obtained by simulating hour periods of time, and individual operating speeds be taken as averages over 3-min invervals. It would be much more economical, however (even with a faster running simulation), to use the design charts repetitively with stochastically assembled vehicle samples. The design charts and weight factors can be used to process short period samples and obtain speed distributions. A computer program, which employs Monte Carlo methods for sample solutions, has been outlined and is recommended for use.

VI. RECOMMENDATIONS

It is recommended that the design charts in Appendix B be employed to estimate speeds and service for mixed flows on facilities with two or three unidirectional lanes up significant grades.

With the 55-mph (89-km/h) speed limit in force, the 70-mph (131-km/h) design speed with the 60-mph (97-km/h) speed limit is appropriate for most facilities. Facilities having poor cross section geometrics and located remotely from urban areas may operate more nearly in accord with the 65-mph (105-km/h) design speed with a 60-mph (97-km/h) speed limit.

It is further recommended that consideration be given to the formulation of two computer programs to assist the design chart user. The first program would select truck samples and calculate associated speed characteristics for mixed flows. The intent is to determine the variance of flow characteristics which may occur during a design hour flow. Emphasis would be placed on identifying the distribution of serious service depressions. (An initial outline for this program has been formulated and provided to FHWA.)

The second computer program would calculate truck speeds over terrain specified by the user. These speeds would facilitate the use of the design charts when the complexities of vertical alignment make it difficult to select a single appropriate grade.

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APPENDIX A

CHANGES TO SIMULATION LOGIC

A. Initial Changes (Made Before Any Production Runs On This Contract)

The priming logic was altered so that vehicle types which are very uncommon could be "forced" into the priming set. Basically, placement of primed vehicles is determined by effectively integrating a local density function for each vehicle type over the various road sections (from the downstream end upstream) until the integral is 1. Then a vehicle of the given type is put in place. The logic originally had each integration include an 0.5 vehicle bias. If a vehicle is so uncommon that the average distance between vehicles of its type is twice the length of the simulated road, none would be primed. The change in logic allowed a variable, GPINIT, to be read in if the user wishes to override the value 0.5, which was made the default value. The data code for reading GPINIT is 20(28).

Two changes were made in the logic controlling lane changes of commercial vehicles. One of these changes simply gave commercials a 50% larger initial acceptable risk level for evaluating lane change opportunities due to a tendency to move right.

The other change reduced the tendency for commercials to form lane change plans which contained a large loss in speed. The program determined the minimum speed which a vehicle can use as the terminal speed of a lane change, SPDMIN, by solving a quadratic equation involving risk level and lane change reason. The equation was the same for passenger and commercial vehicles. The change takes effect for commercials only when:

1. The maximum sustained speed which the vehicle could maintain on the local grade (PSPD) is 45 ft/sec or less, and

2. The reason for the lane change is either to improve progress or to move right.

When these conditions are satisfied, a flag is set in subroutine PLAN (IL is set to -1) which causes an alternate path to be taken through subroutine ADJPER so that the value for SPDMIN determined from the quadratic is superseded. The following are calculated:

1. 0.8 times the maximum speed which the vehicle could maintain on the local grade (i.e., 0.8 PSPD), and

2. 0.8 times the maximum speed the vehicle could reach at the end of the time interval being projected for lane change execution (i.e., 0.8 PERXD1).

If XDN, the current vehicle speed, is greater than both of the above, then the minimum speed considered for lane change plans is 0.8 PERXD1. Otherwise, the current speed is used.

B. Changes Effective With Run V45

On 10 September 1971, the program was modified to allow a specified fraction of platooned vehicles to operate at a risk level of -2 to -3 ft/sec^2 instead of at the normal, zero risk level. For this purpose two new parameters, KLOSE and VFKLOS, were added with data codes 23(1) and 22(2) respectively. KLOSE is the number of tenths of the vehicle population which will "close follow" in platoons. Its default value is zero; consequently, none of the vehicles simulated will accept increased risk while they are in platoons unless a data card is read containing a positive value for KLOSE. VFKLOS, with default value 0.07, is a velocity factor which sets the strength of the close-following tendency.

Subroutine FOLSTD calculates a value for XDDNEW, the tentative acceleration of the current vehicle, based on normal following logic and independent of any motivation to change lanes. This value is returned to the calling routine unless all the following conditions are met:

1. XDDNEW is a deceleration less than or equal to half of ACCLIM, where ACCLIM is the most severe deceleration which permits the vehicle to continue in accommodation mode,

2. XDDNEW must be less than 1,

3. The packed table index of the vehicle in process must have its last digit less than KLOSE (allowing random but permanent assignment of close followers), and

4. The acceleration of the leader of the current vehicle must be dictated by his leader (meaning, in effect, that the first two vehicles in a platton would not use close-following logic). (This requirement was deleted beginning with Run V51.)

If the four conditions above are met, then an increment for XDDNEW is computed as

$$\frac{\text{VFKLOS} \cdot \text{XDN}}{1. + 0.04\ (\text{XDN} - \text{VL})^2}, \quad \text{XDN} > \text{VL}$$

where XDN is the speed of the vehicle in process and VL is the speed of his leader. When XDN is not greater than VL, the increment to XDDNEW is just VFKLOS · XDN. This increment is restricted further in that it is not allowed to exceed -0.045 times ACCLIM, and when XDDNEW is incremented by the amount determined, the result must not exceed 1. The first of these restrictions is to prevent jitter in steady following which would occur if VFKLOS · XDN > ACCLIM/2.

C. Changes Effective With Run V51

In October 1971, the logic for close following was extended to apply to the second vehicle in any platoon as well as the third through the last. A correction was also made in the computation of the maximum acceleration possible for commercial vehicles based on performance limitations. On previous runs, the value calculated had contained an encoding error. As a result, the maximum acceleration capability of commercial vehicles did not take correct account of the diminution in capability as speed increased during the (1 sec) interval.

In November 1971, prior to run V51, two changes were made to the priming logic. The first of these corrected the notation for the frequency with which the four types of commercial vehicles appeared in the traffic population. The error was such that the frequency of some vehicle types could have been interchanged. On runs through V48 the commercial population was such that Types 7 and 10 (and Types 8 and 9) were equally likely so the encoding error had not showed up or influenced the runs.

The other change had to do with the number of passenger vehicles in the simulation. All vehicles assigned to the median lane were assumed to be passenger vehicles in summing to get total passenger flow. This overlooked the high performance type of commercials, which made up 3.625% of median lane flow. Runs made prior to the correction had a small difference in distribution to lane at entrance to the simulation.

D. Changes Effective With Run V52

On 20 November 1971, a change was made in the logic for evaluating projected delay. This change forced at least one vehicle within sight distance to be evaluated as a potential cause of delay. Prior to this change, if no vehicle was near enough so that his relative velocity could be perceived, the program would erroneously use results from the previous vehicle reviewed in deciding whether the current vehicle would be delayed. The change enabled the current vehicle to make positive use of the "negative" finding--that the vehicle ahead had no apparent relative velocity.

The change described above was inadvertently incorporated into the program such that all vehicles within sight (2,000 ft) were evaluated, whether their relative speeds could be perceived or not. Two runs were made with this error, which had only a small effect due to associated logic. It was corrected prior to run V54.

E. Changes Effective With Run V67

During the traffic observations at climbing lane sites in California it was noticed that numerous lane changes were made from the middle to the median lane in anticipation of merges from the climbing lane, which was about to end. These lane changes clearly did not arise from impeding traffic ahead in the middle lane. These anticipatory changes were made by relatively high speed traffic in the region back to 1,350 ft before the lane drop.

To reflect the effect of this anticipatory lane changing, which can be quite important in the vicinity of the lane drop, the simulation logic controlling lane change motivation was changed. Subroutine DLAY now determines whether potential mergers will be considered by the vehicle in process. They will be considered provided that the vehicle in process:

1. Has a driver type 4,*

2. Is either a passenger vehicle or a commercial vehicle of the highest performance type (i.e., vehicle code is seven or less),

3. Has lanes on both sides, and

4. Is within 1,500 ft from the end of the climbing lane.

When all four conditions above are met, subroutine DLAY conveys this fact to subroutine PDELAY by reversing the sign on the subroutine argument corresponding to the position of the vehicle in process. Subroutine PDELAY examines this argument and, if it is negative, sets a switch (IMERG) causing some of the vehicles in the lane to the right LNE-1 to be treated as occupants of lane LNE. The vehicles so selected will be those which:

1. Will not be overtaken within 3 sec, and

2. Have either a plan or motivation to change lanes to the left. (This is equivalent to having a value for KLAN greater than 1 in the regional table since the vehicle is in the right most lane). After subroutine PDELAY uses the sign flag to set IMERG, it replaces the position argument by its absolute value.

F. Changes Effective With Run V70

On 25 May 1972, two program changes were made to improve upon the results of run V69. Because of the very light flow rates used, V69 revealed that delayed vehicles were not motivated to move into a new lane which is completely vacant ahead of them. This occurred because there were no vehicles within sight (2,000 ft sight distance) and the routine which evaluates alternate lanes returned a code signifying "no information." The program erroneously concluded the current lane was better. This difficulty was corrected with a change to subroutine PDELAY.

The other change was made to prevent vehicles from oscillating from one lane to another where the move left was to improve progress and the move right was because of the tendency to move right. A change was made in subroutine TTMR to minimize this by using the time until deceleration would be called for rather than the time to overtake in estimating the delay that would be encountered after moving right.

* Type 4 drivers, which constitute nearly half the driver population, are assigned the higher desired speeds.

G. Changes Effective With Run V72

A continuing investigation of the abnormal tendency to move right, first noted on run V69, finally disclosed an error in subroutine PACK which packs parameters from the regional table into the packed table. The error caused the packed table parameter ASMOVR, the accumulated contribution to the tendency to move right, to be packed as its maximum possible value whenever EXCSSL was zero or greater. EXCSSL is the excess of the gap ahead of the vehicle in process over the gap required to change lanes by the front unprocessed vehicle in the left adjacent lane. Thus, EXCSSL would be negative unless the gap ahead is large enough that a vehicle, with speed not necessarily optimum for the gap, could enter it. At high to moderate flow rates, this would often be the case, and no packing error would have resulted. However, when very low flow rates were used, e.g., 750 vehicles/hr in run V69, the values for EXCSSL would often be positive and would result in an erroneously large value for ASMOVR. This vehicle, then, would have a false motivation to move right. If there were many opportunities to move right, as would also exist at low flow rates, excessive lane changes would result and the fraction of traffic using the right-hand lane would be too high.

H. Changes Effective With Run V73

The final change in program logic was made on 8 June 1972. Subroutine TTMR was modified to prevent lane changes, where tendency to move right was the motive, and simultaneously the time to delay in the new lane was less than 30 sec. The original program logic obtained this exclusion in most cases. The change caused it to be explicit for all cases.

Changes made after Run V73 are fully discussed in Section III-B.

APPENDIX B

DESIGN CHARTS AND BASIC FLOW CHARACTERISTICS

This appendix contains design chart sets for two and three unidirectional lanes with design speeds of 65 mph (105 km/h), 70 mph (115 km/h) and 75 mph (121 km/h). With the 55-mph (89-km/h) speed limit in effect, the 70-mph (113-km/h) charts with 60-mph (97-km/h) speed limit are recommended for most applications.

Examples of design chart use are presented in Sections V-B and V-C of the report body.

The user is cautioned that capacity is not a practical capacity and that during short periods of a peak hour flow the service and speed on sustained grades are likely to vary significantly from the mean.

The user is also cautioned that the full benefits of a climbing (third) lane may not be realized immediately after the lane addition and in the approach to the lane drop. The passenger car speeds in these regions may be about 8 ft/sec (2.4 m/s) below the value indicated for three lanes. The lower-than-normal speeds should end about 1,000 ft (300 m) after the lane addition and begin again about 1,000 to 1,400 ft (300 to 425 m) from the lane drop.

The design charts are based on a reference vehicle population described in Tables XXI and XXII. The reference truck population contained a large proportion of low-performance trucks. Figure 78 in this appendix provides weight factors which can be used to convert other truck populations to the reference. An example was presented in Section V-C.

This appendix also contains figures of the basic flow characteristics and the speeds of the reference truck population on grades.

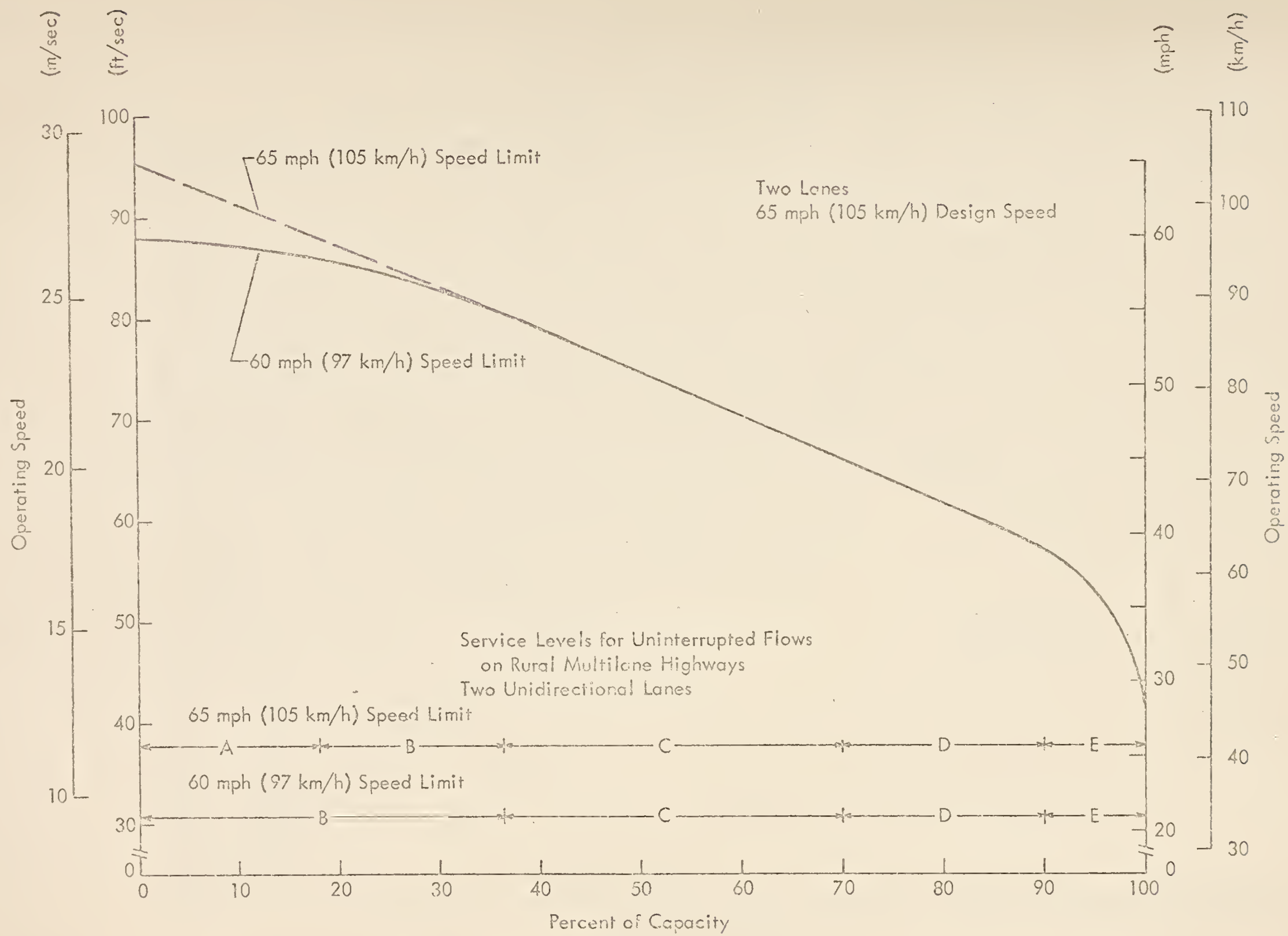

Figure 60 - Operating Speed Versus Percent Capacity, Two Lanes, 65 mph (105 km/h) Design Speed

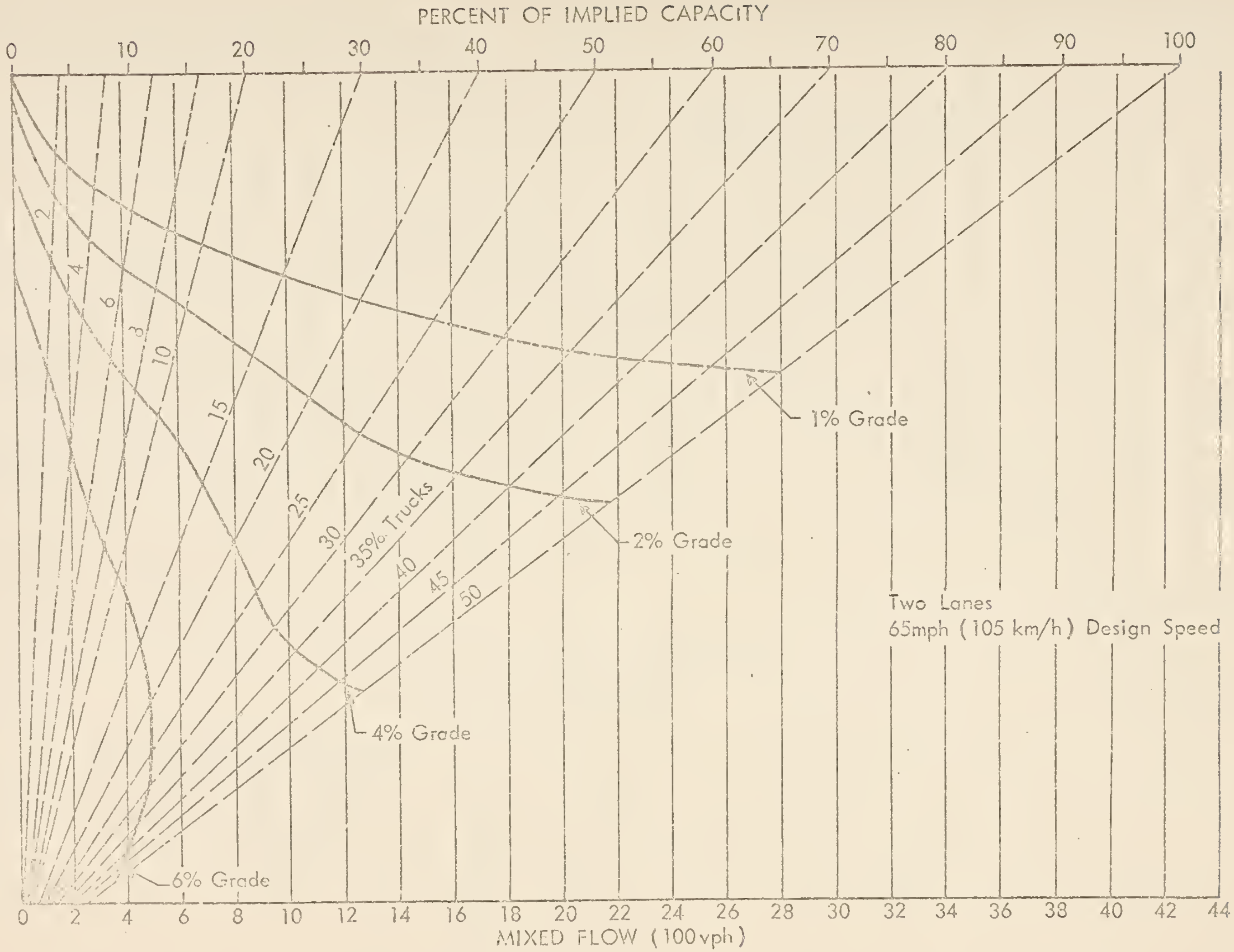

Figure 61 - Implied Capacities Versus Percent Trucks and Sustain Grade, Two Lanes, 65 mph (105 km/h) Design Speed

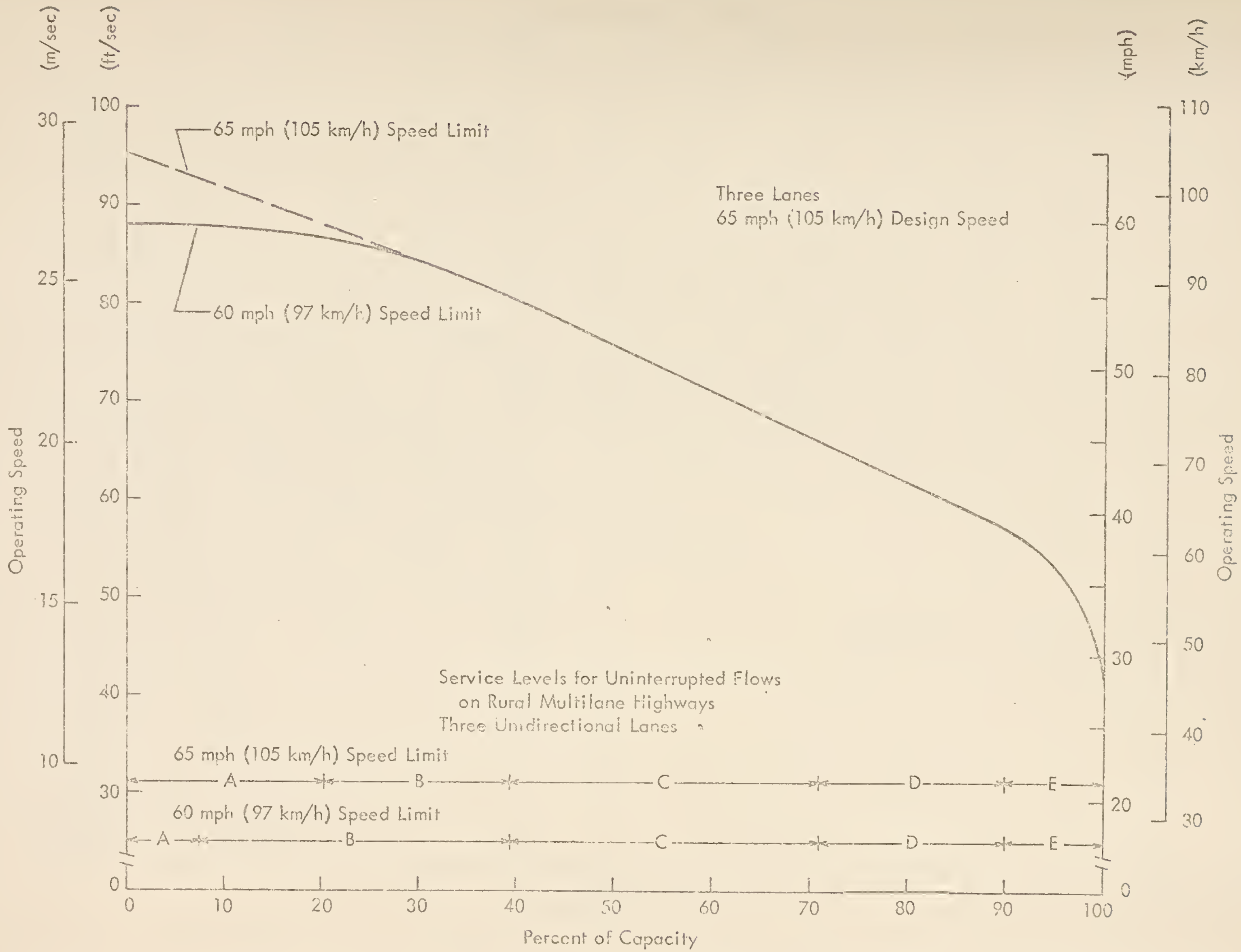

Figure 62 - Operating Speed Versus Percent Capacity, Three Lanes, 65 mph (105 km/h) Design Speed

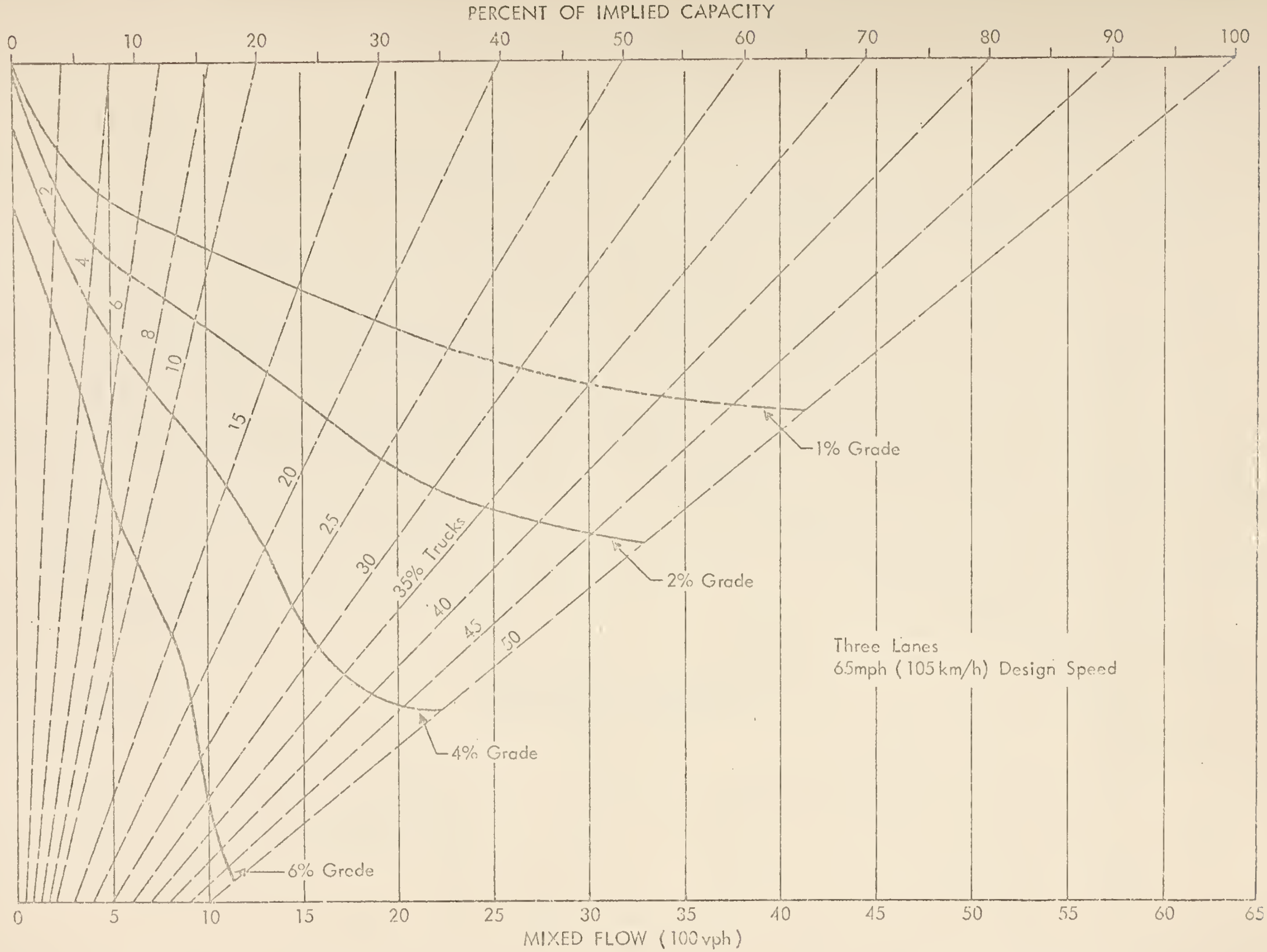

Figure 63 - Implied Capacities Versus Percent Trucks and Sustained Grade, Three Lanes, 65 mph (105 km/h) Design Speed

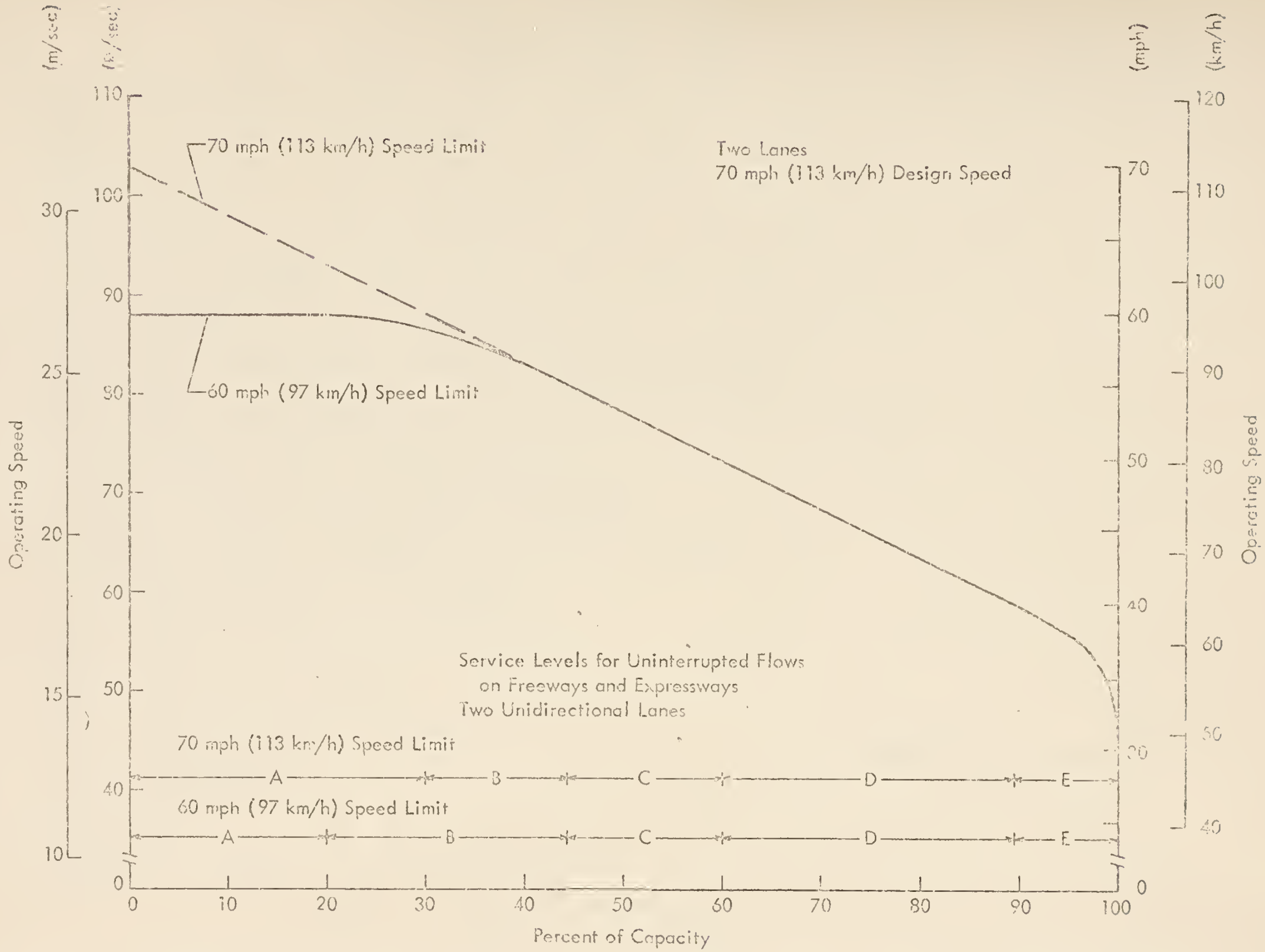

Figure 64 - Operating Speed Versus Percent Capacity, Two Lanes, 70 mph (113 km/h) Design Speed

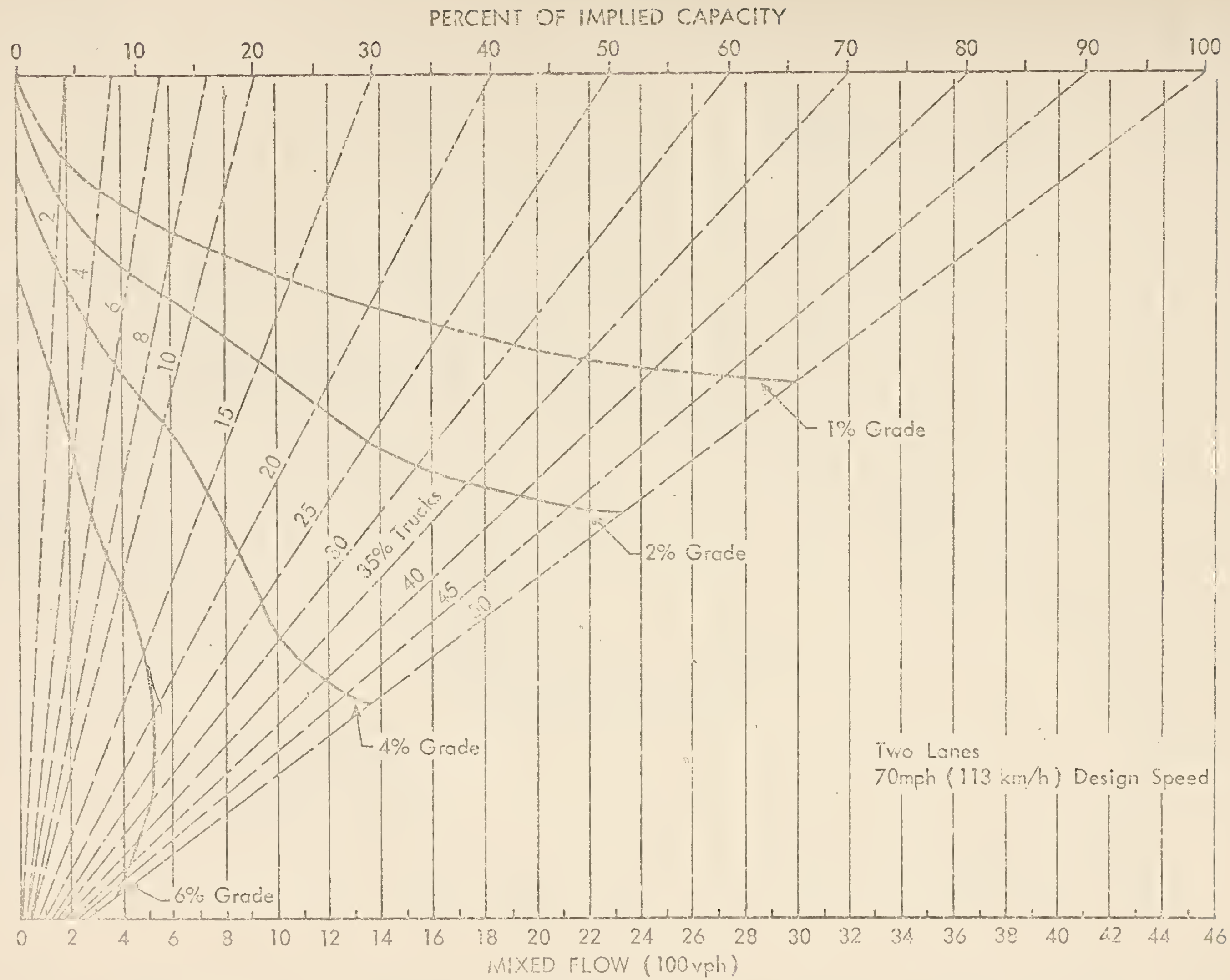

Figure 65 - Implied Capacities Versus Percent Trucks and Sustained Grade, Two Lanes, 70 mph (113 km/h) Design Speed

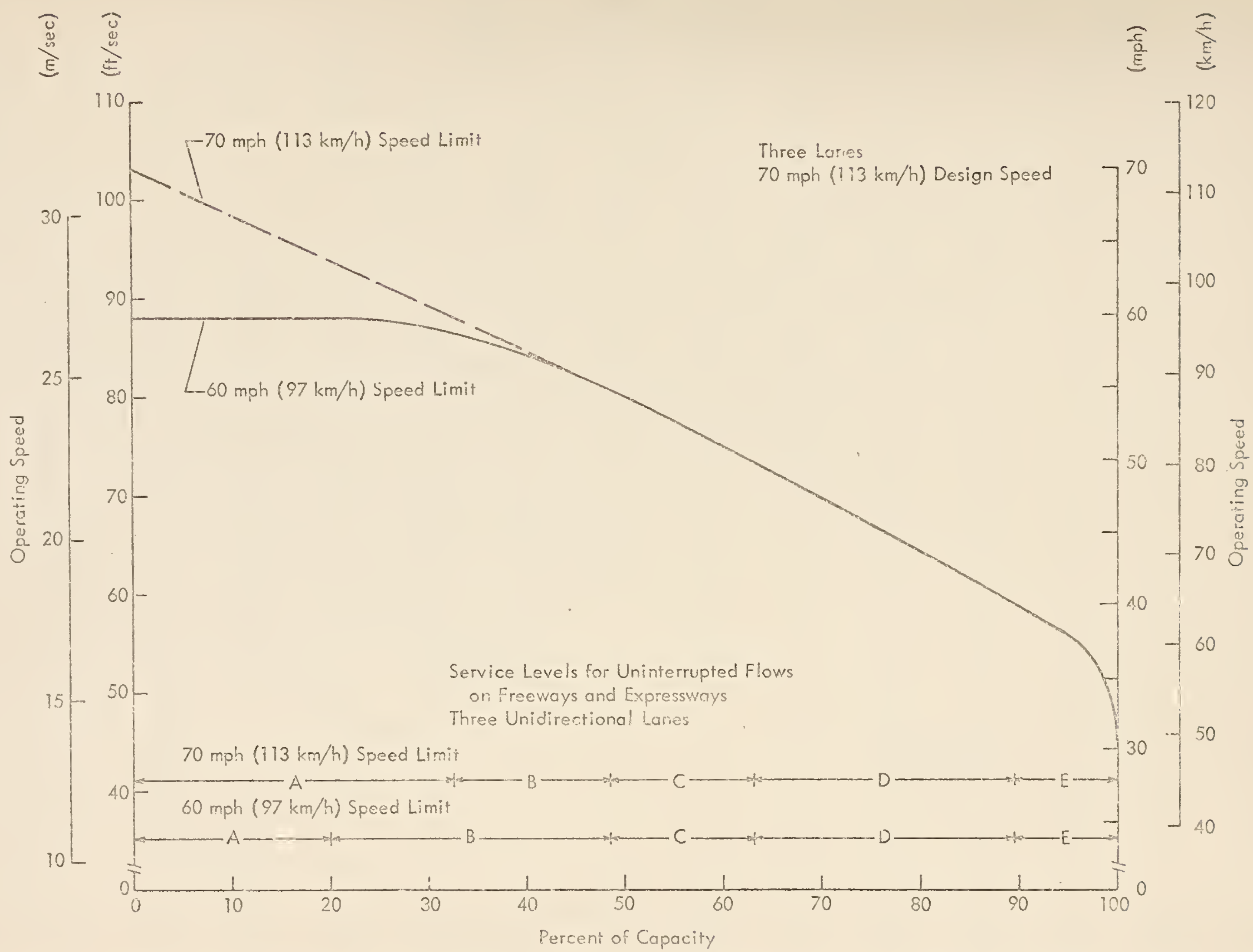

Figure 66 - Operating Speed Versus Percent Capacity, Three Lanes, 70 mph (113 km/h) Design Speed

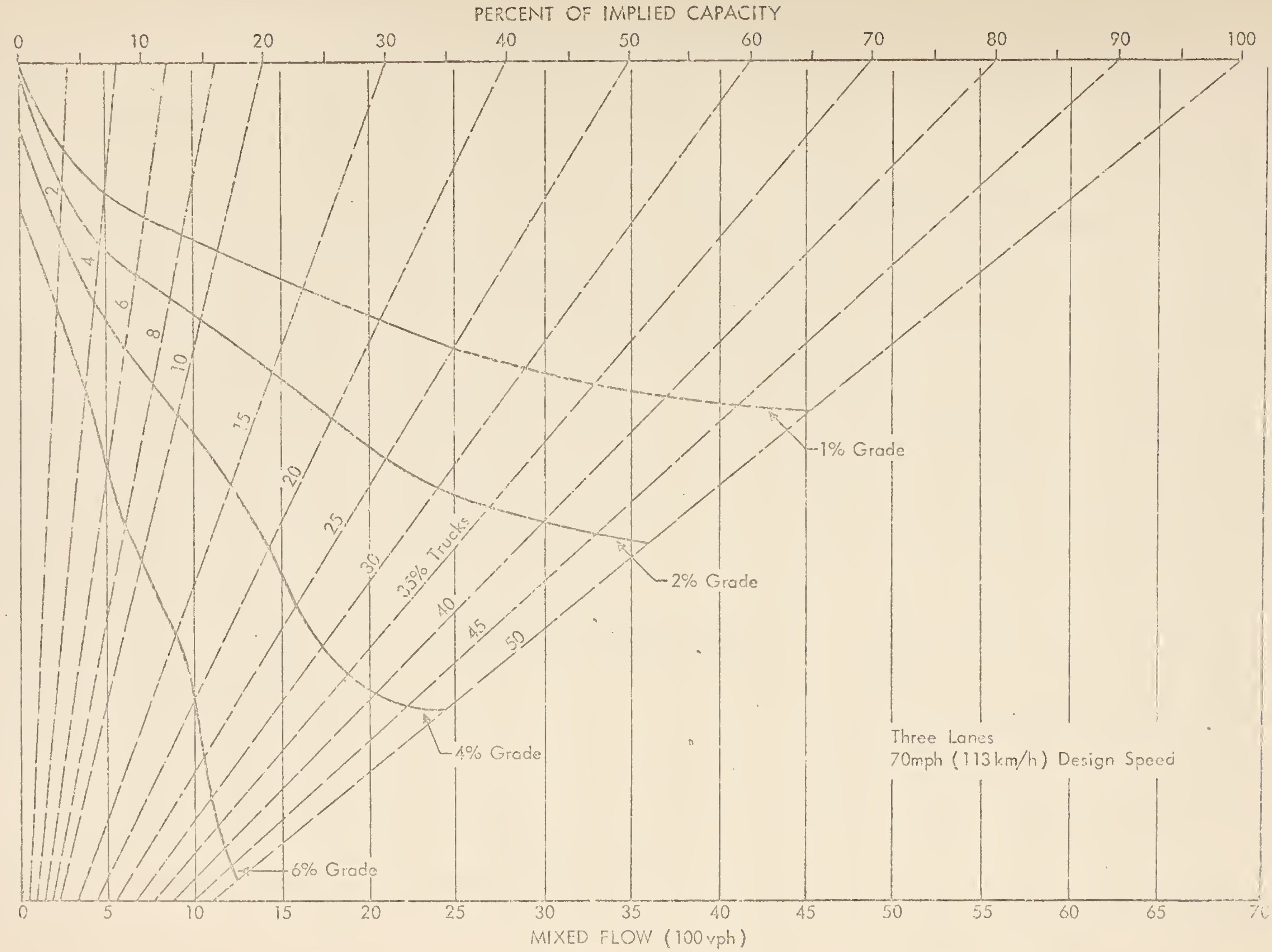

Figure 67 - Implied Capacities Versus Percent Trucks and Sustained Grade, Three Lanes, 70 mph (113 km/h) Design Speed

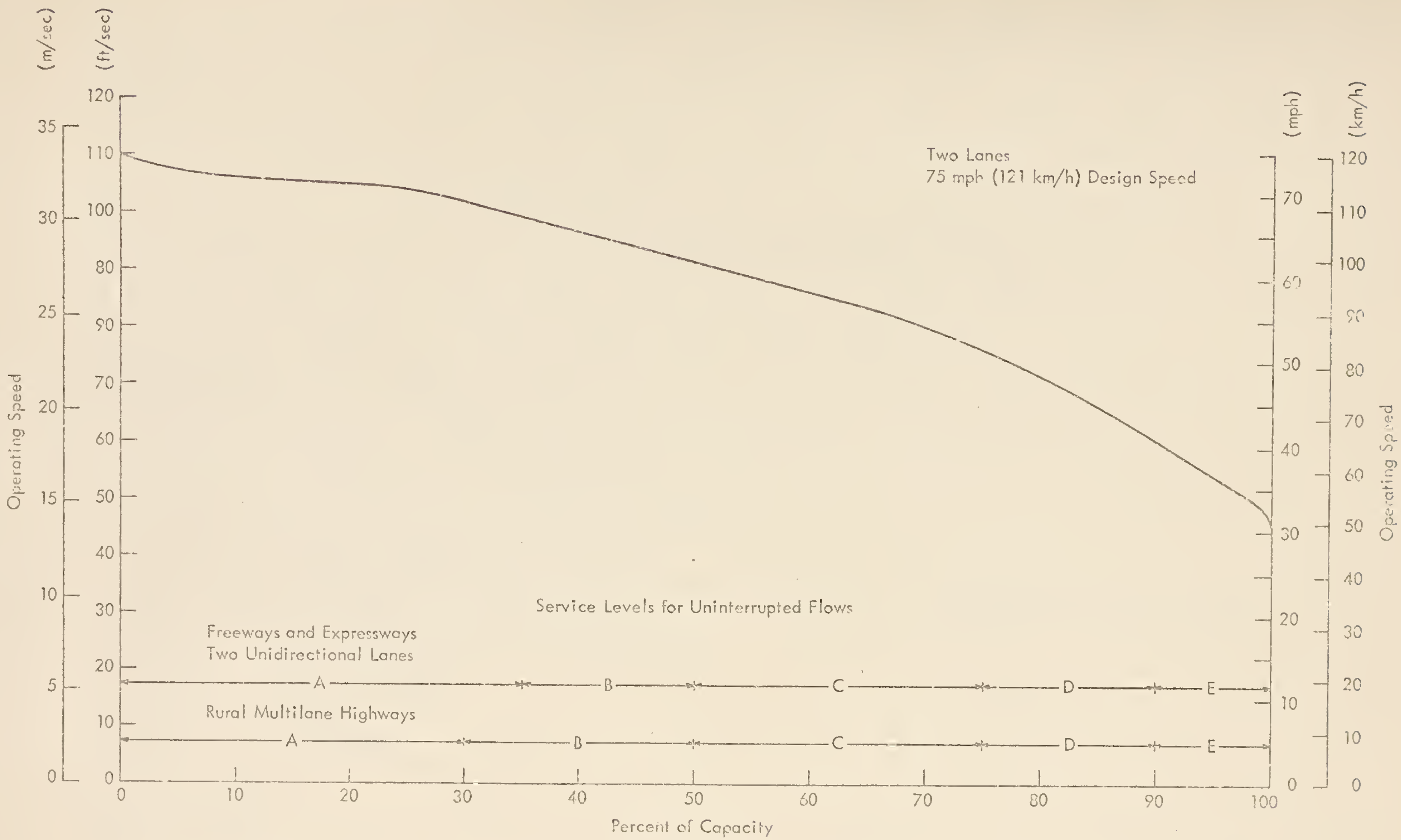

Figure 68 - Operating Speed Versus Percent of Capacity, Two Lanes, 75 mph (121 km/h) Design Speed

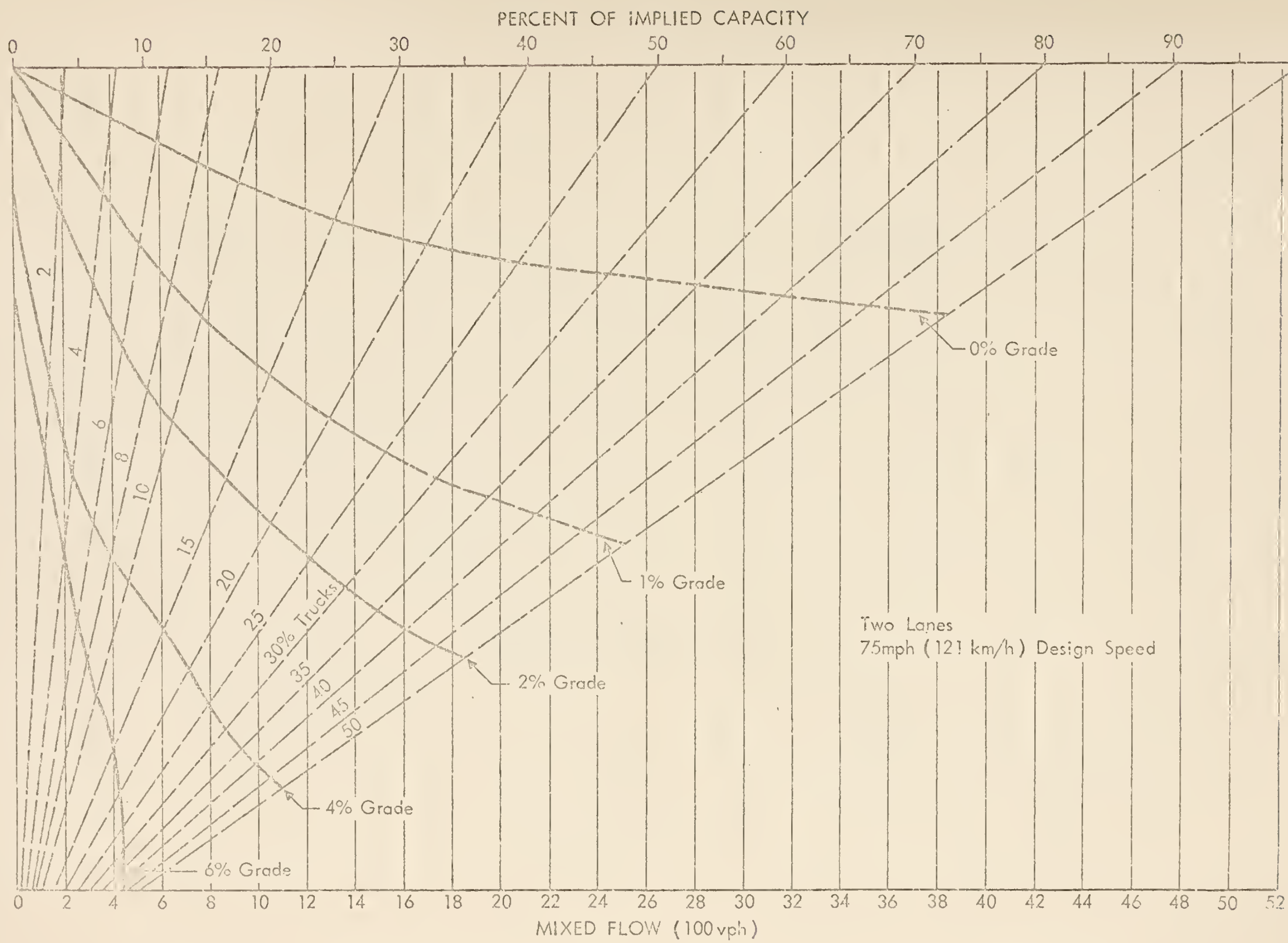

Figure 69 - Implied Capacities Versus Percent Trucks and Sustained Grade, Two Lanes, 75 mph (121 km/h) Design Speed

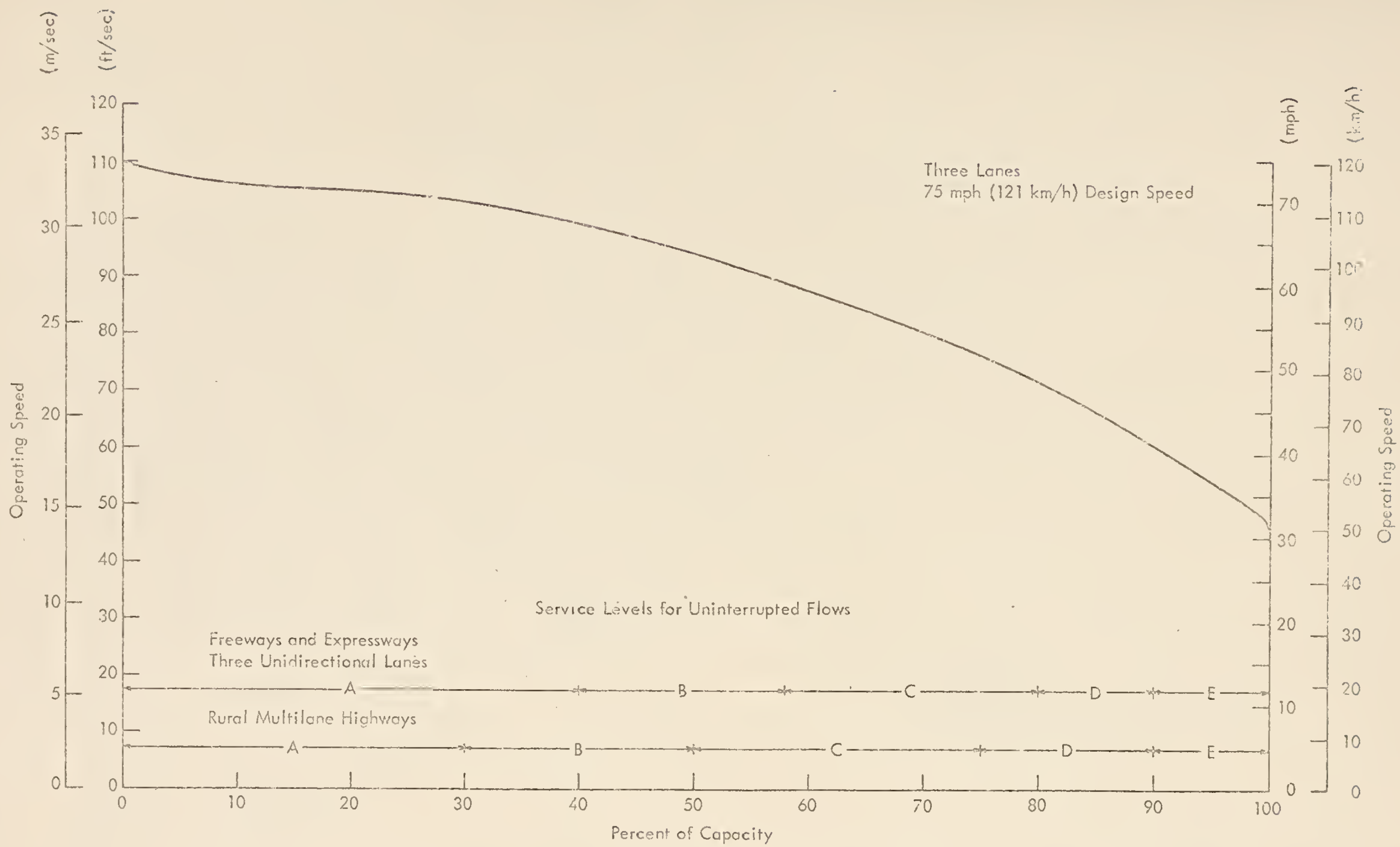

Figure 70 - Operating Speed Versus Percent of Capacity, Three Lanes, 75 mph (121 km/h) Design Speed

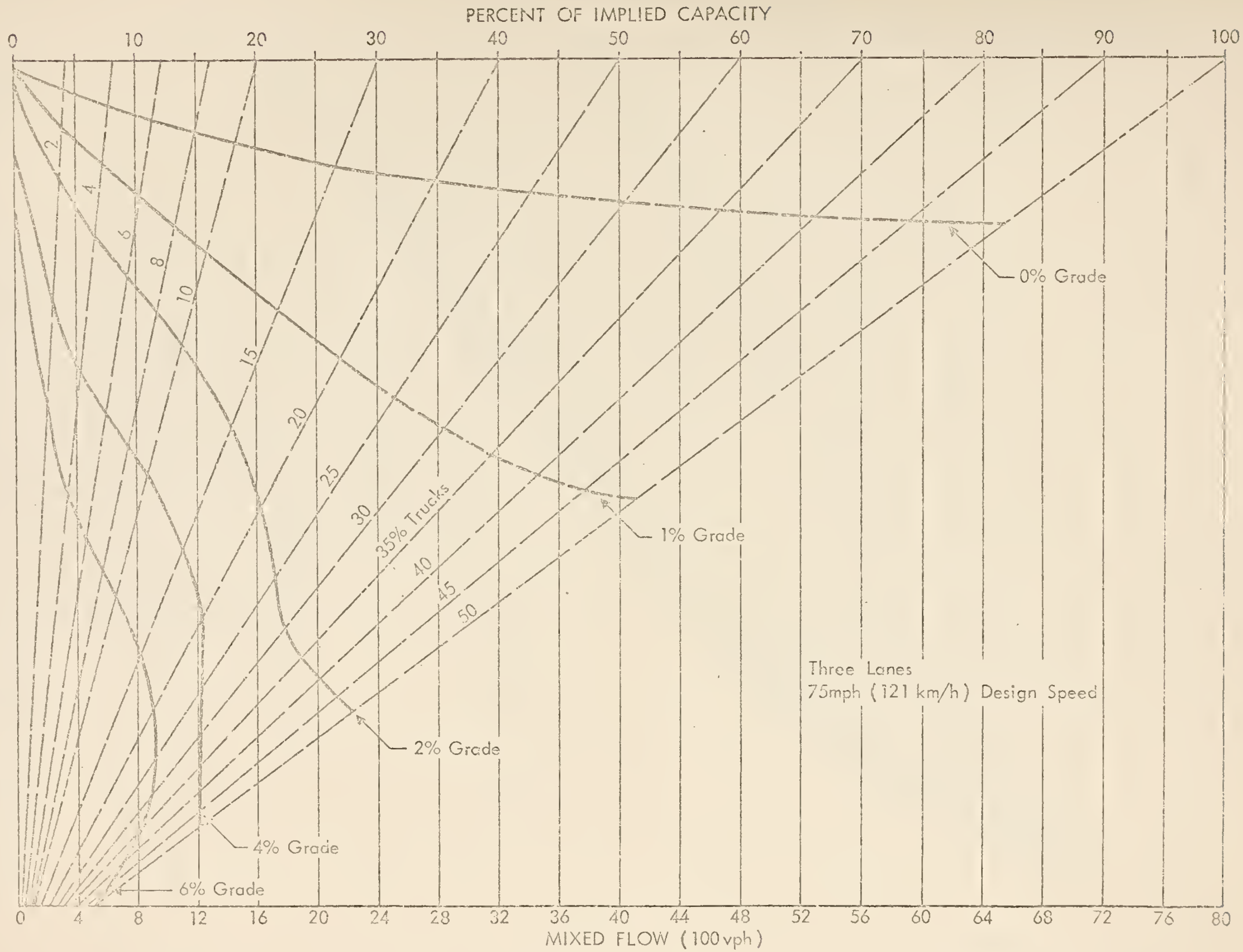

Figure 71 - Implied Capacities Versus Percent Trucks and Sustained Grade, Three Lanes, 75 mph (121 km/h) Design Speed

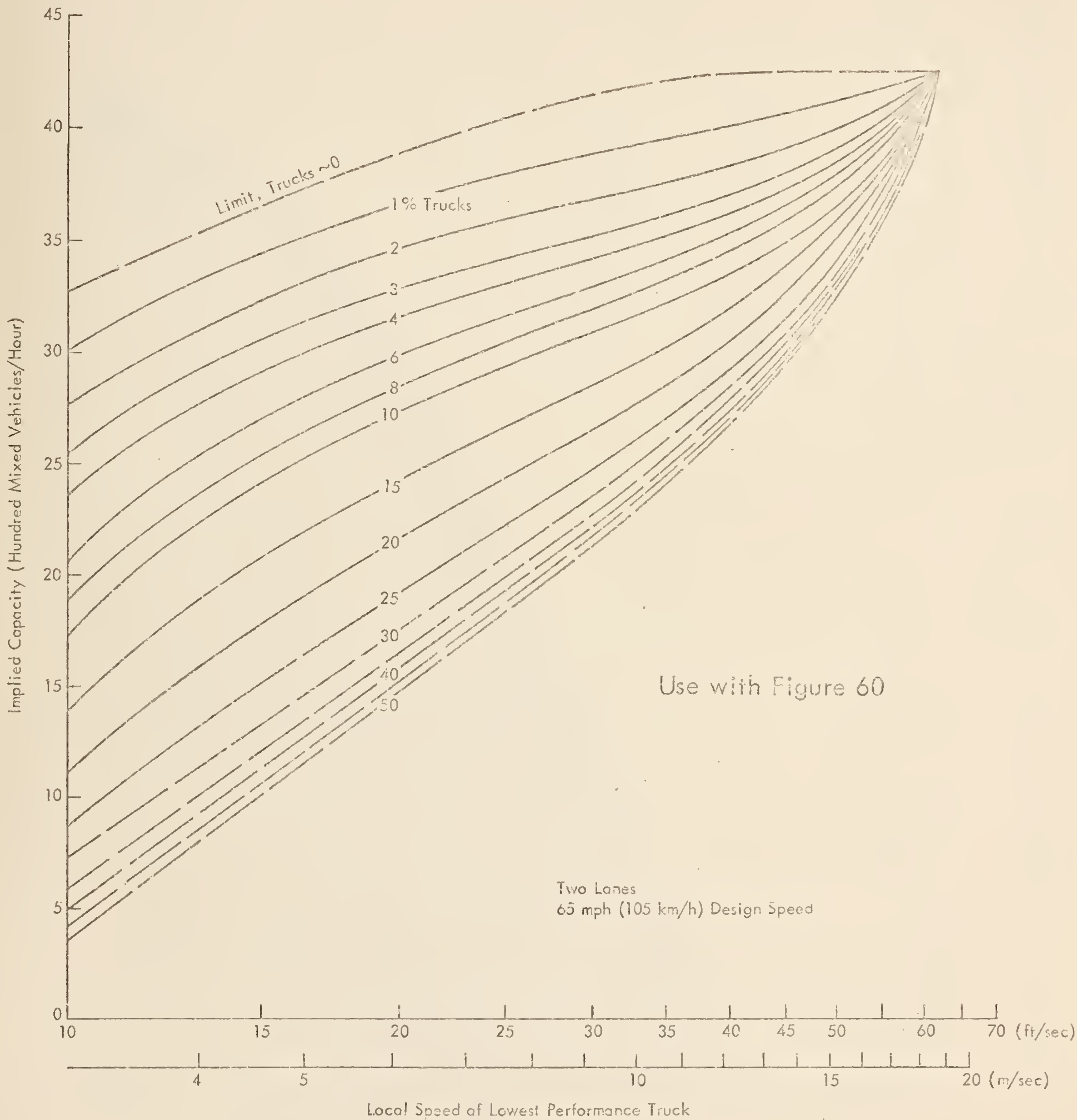

Figure 72 - Implied Capacity Versus Speed of Slowest Truck and Percent Trucks, Two Lanes, 65 mph (105 km/h) Design Speed

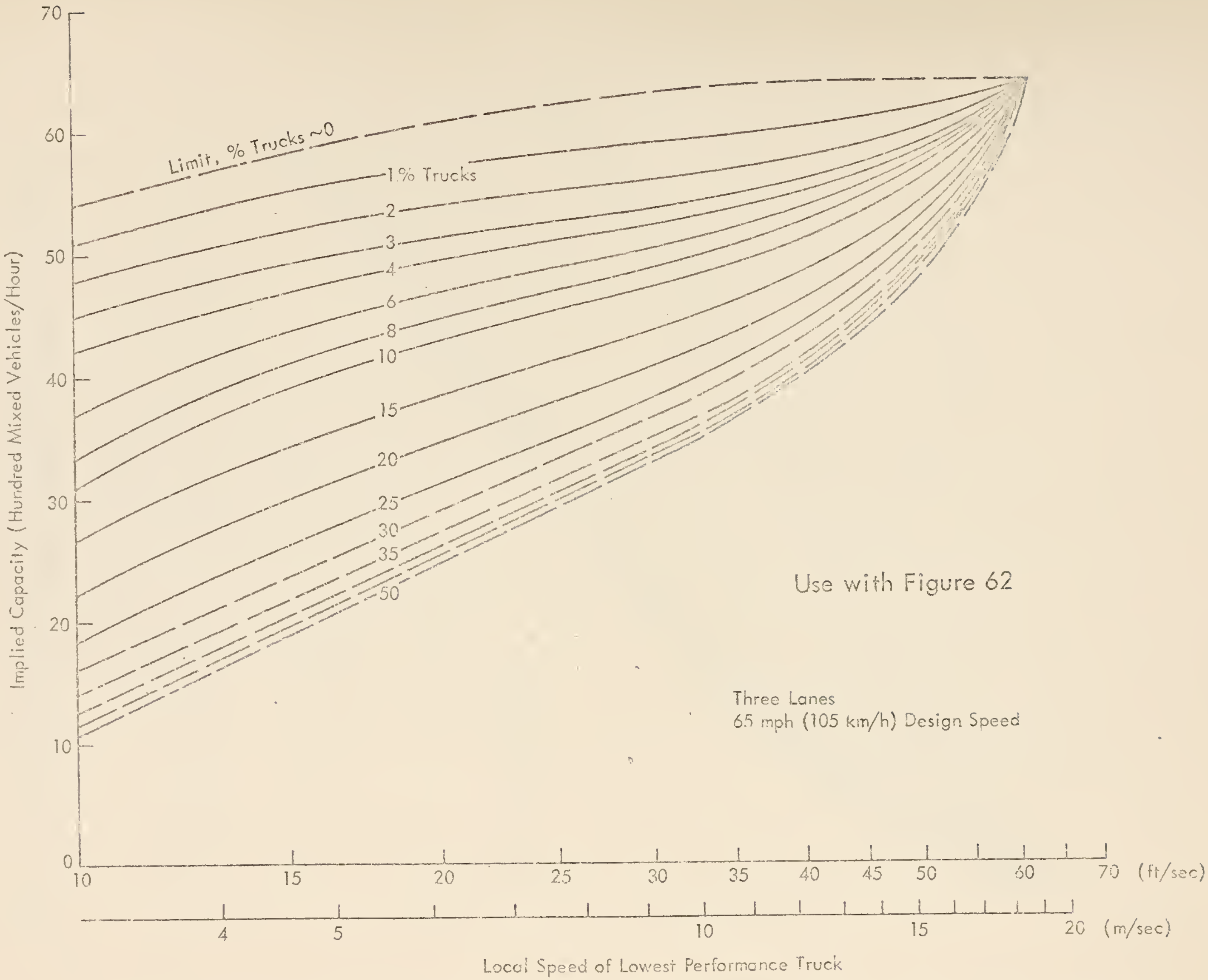

Figure 73 - Implied Capacity Versus Speed of Slowest Truck and Percent Trucks, Three Lanes, 65 mph (105 km/h) Design Speed

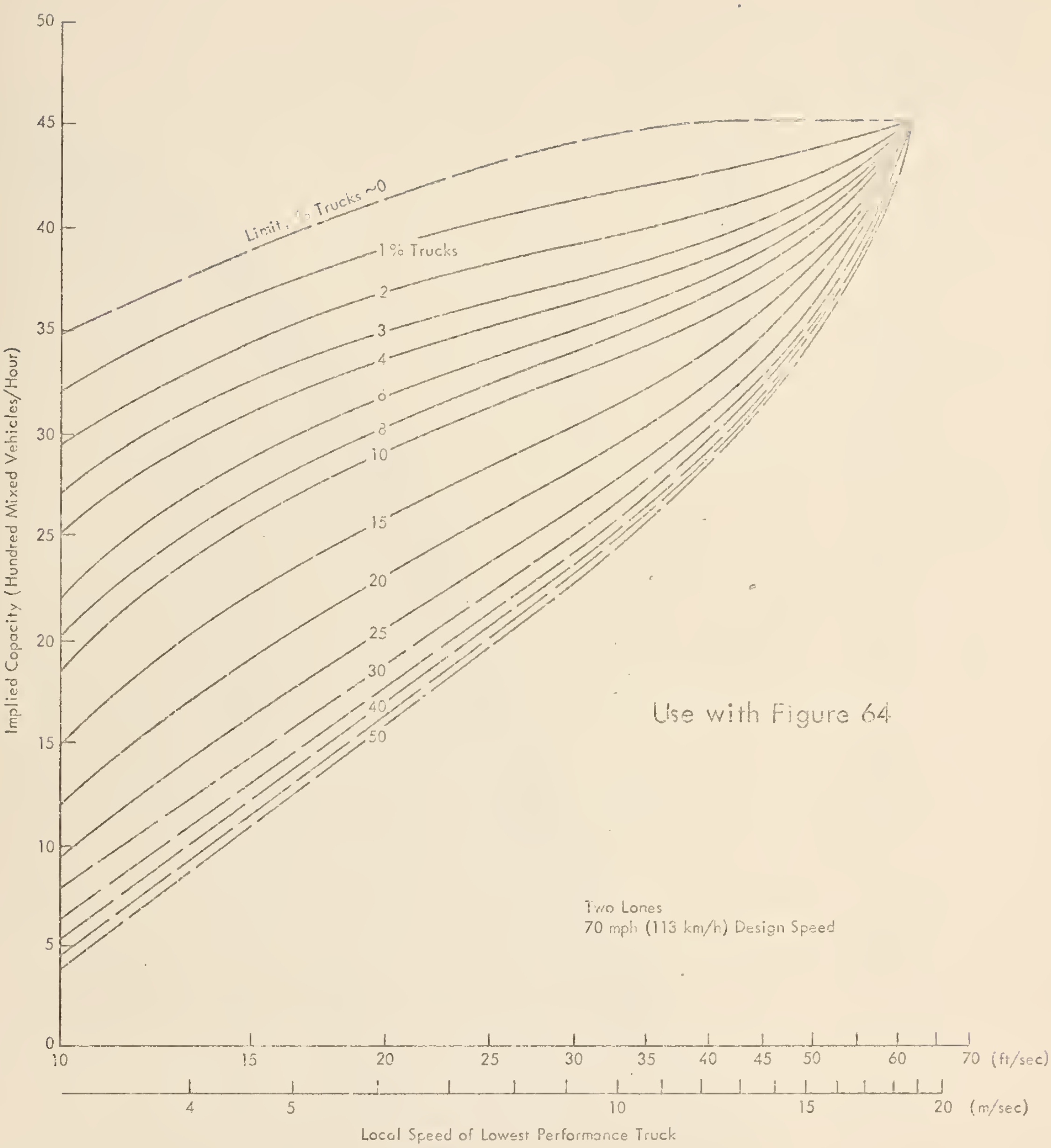

Figure 74 - Implied Capacity Versus Speed of Slowest Truck and Percent Trucks, Two Lanes, 70 mph (113 km/h) Design Speed

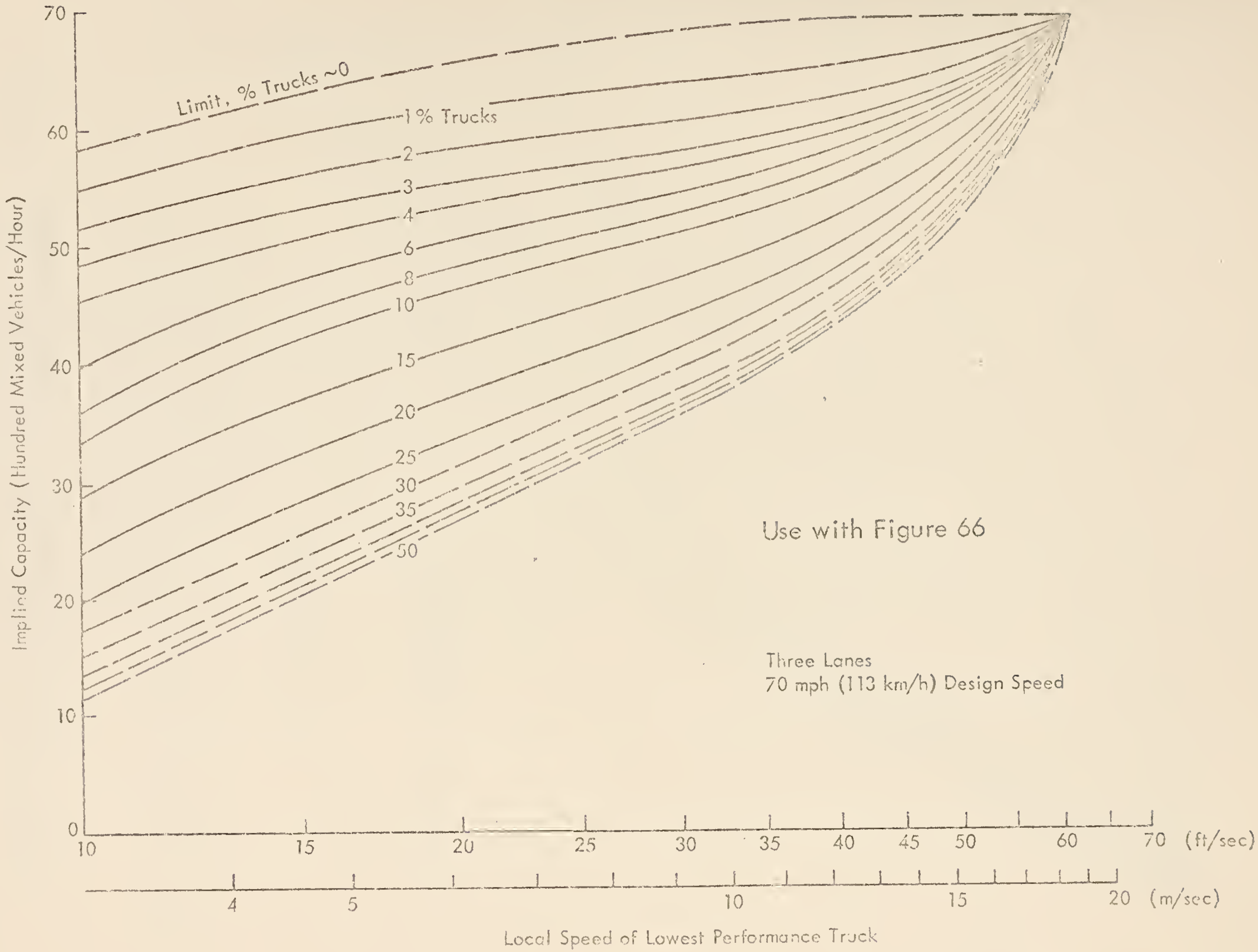

Figure 75 - Implied Capacity Versus Speed of Slowest Truck and Percent Trucks, Three Lanes, 70 mph (113 km/h) Design Speed

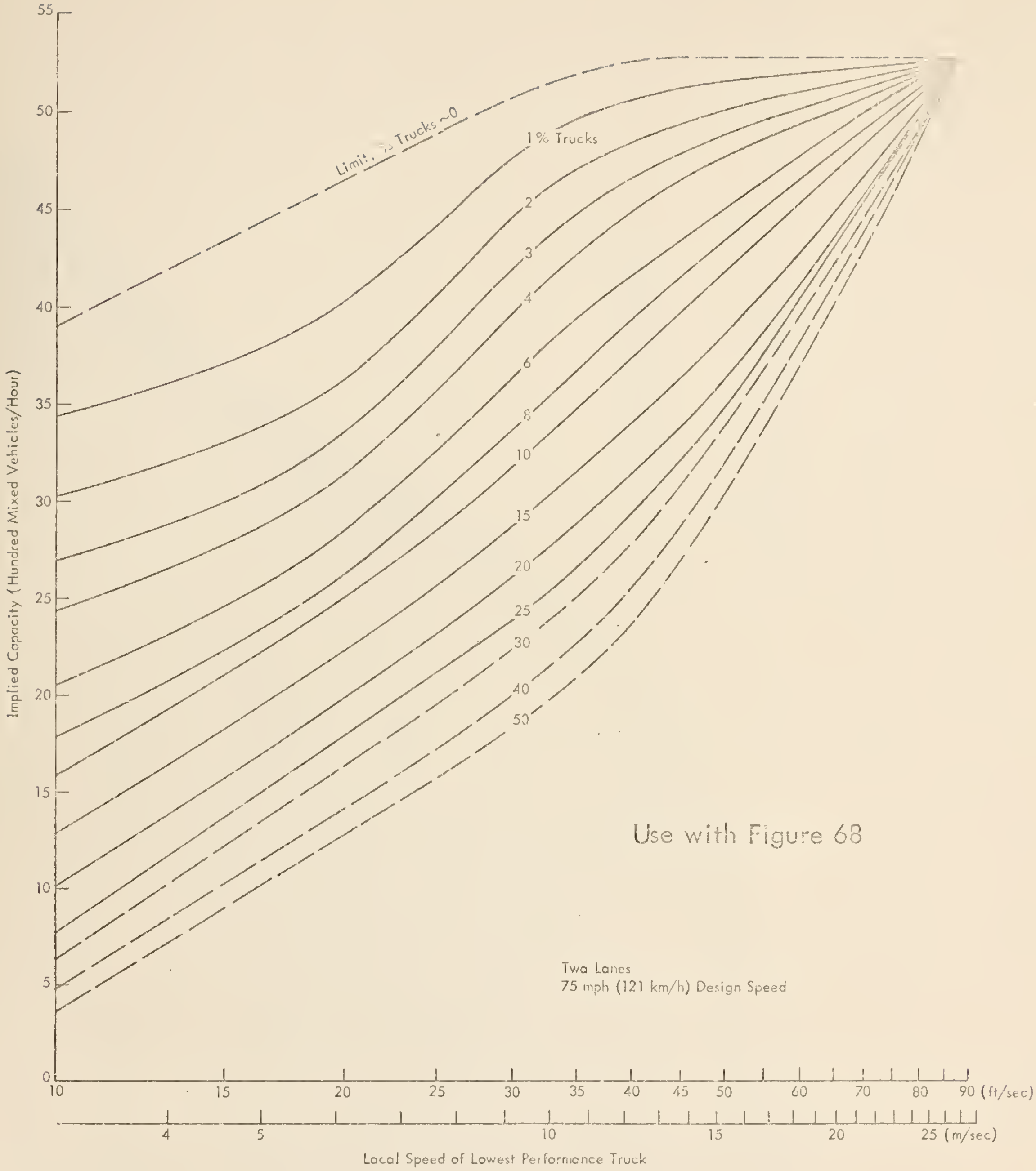

Figure 76 - Implied Capacity Versus Speed of Slowest Truck and Percent Trucks, Two Lanes, 75 mph (121 km/h) Design Speed

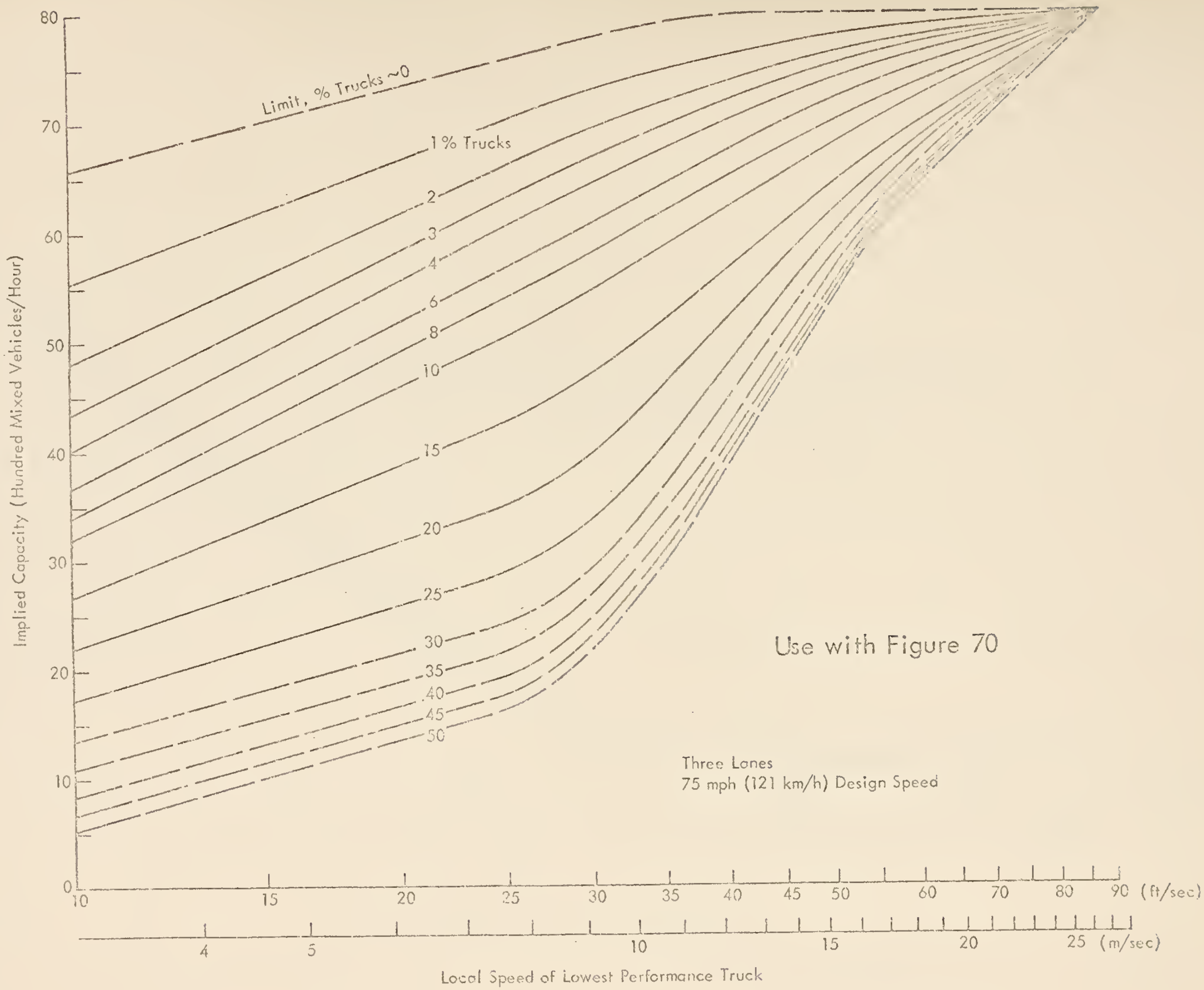

Figure 77 - Implied Capacity Versus Speed of Slowest Truck and Percent Trucks, Three Lanes, 75 mph (121 km/h) Design Speed

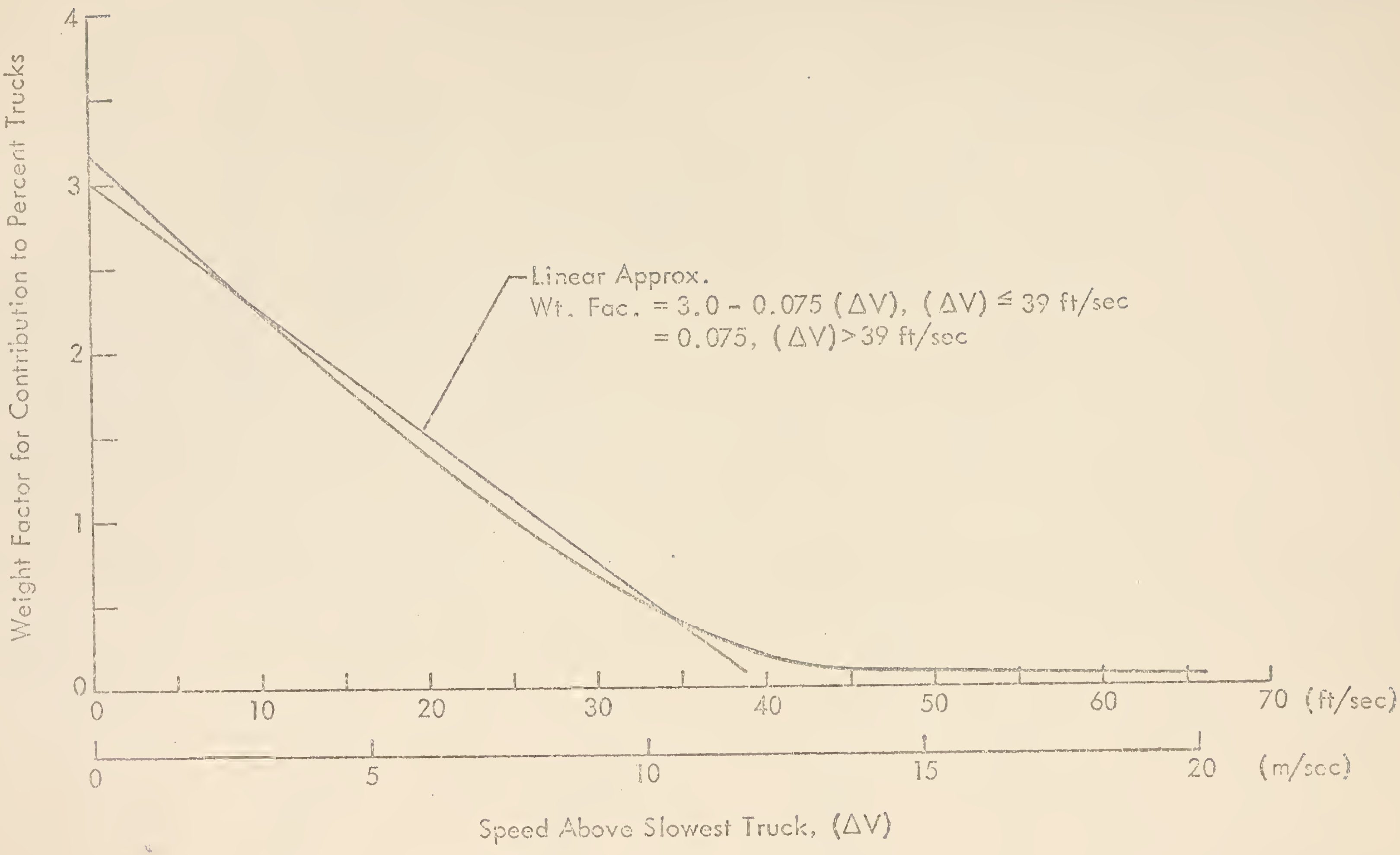

Figure 78 - Weight Factors for Trucks Versus Speed Difference

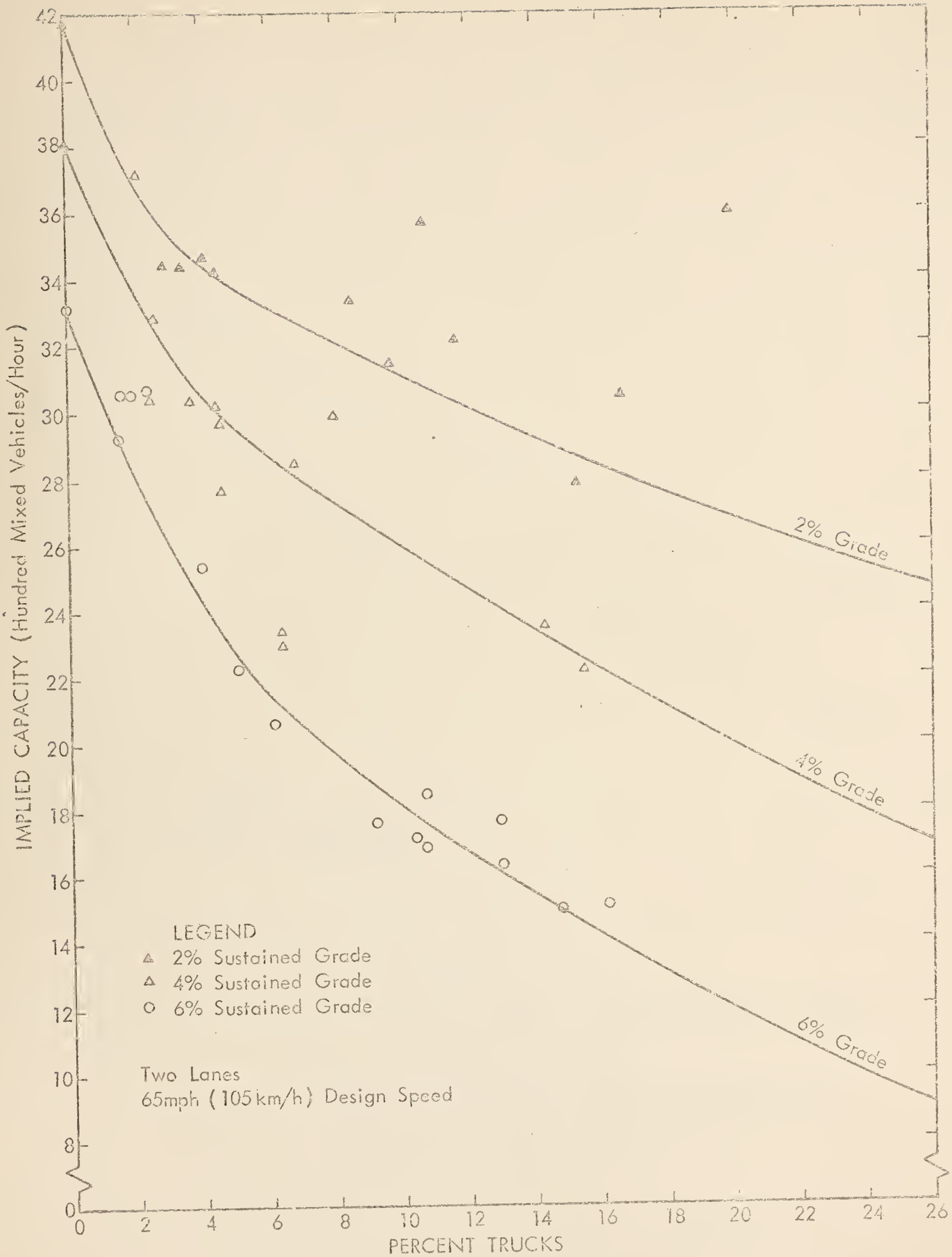

Figure 79 - Implied Capacities on Two Upgrade Lanes, 65 mph (105 km/h) Design Speed

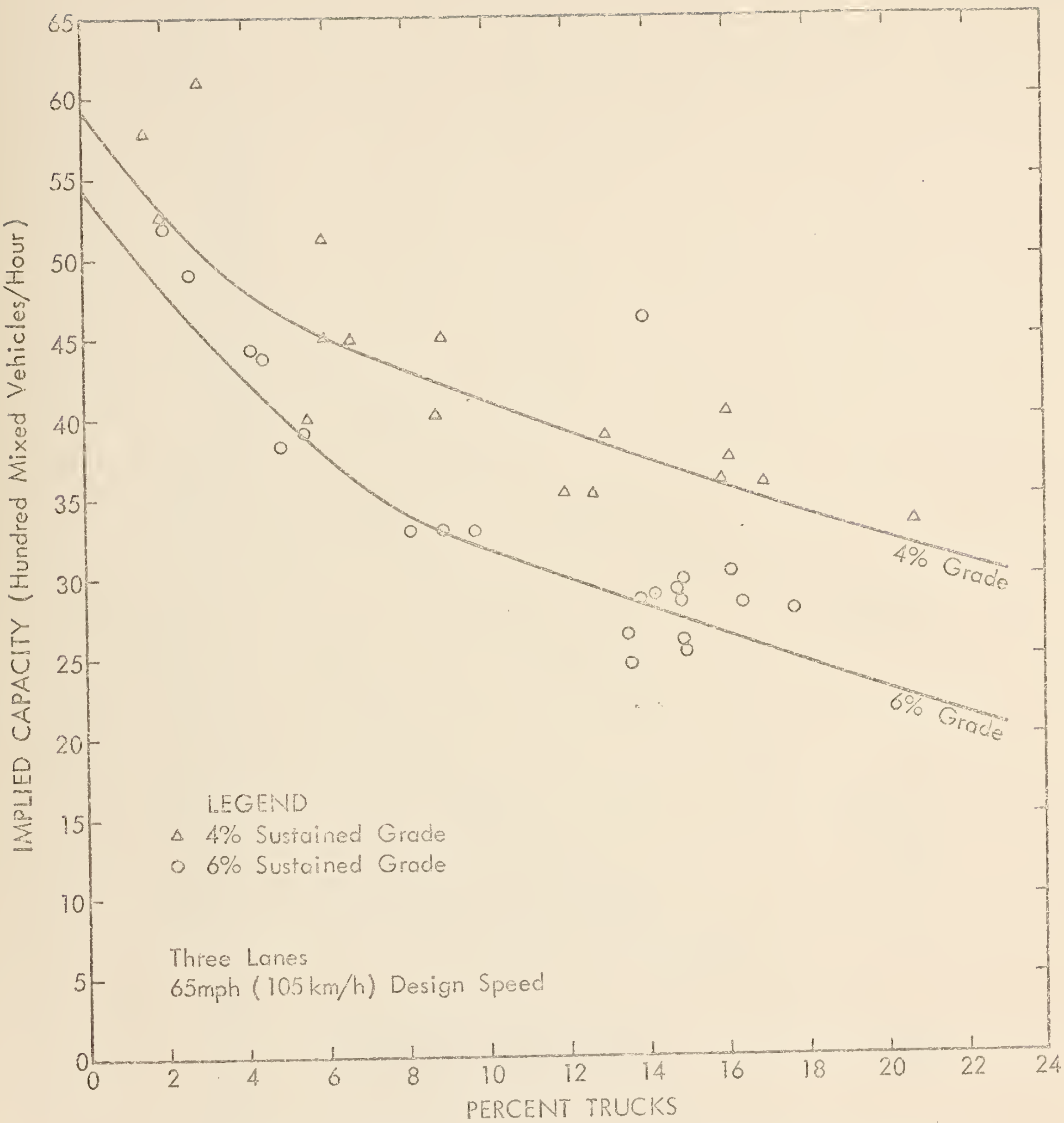

Figure 80 - Implied Capacities on Three Upgrade Lanes, 65 mph (105 km/h) Design Speed

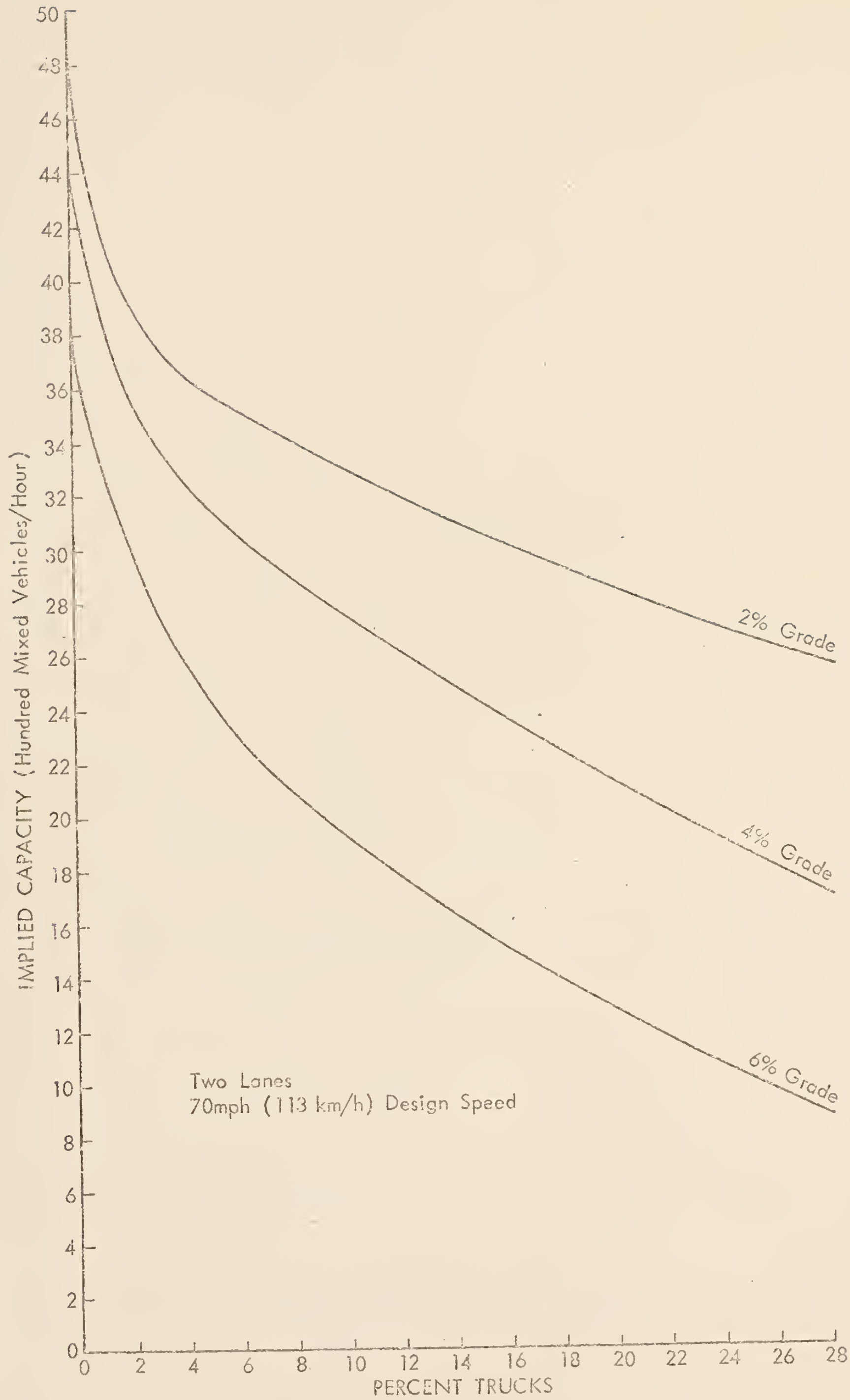

Figure 81 - Implied Capacities on Two Upgrade Lanes, 70 mph (113 km/h) Design Speed

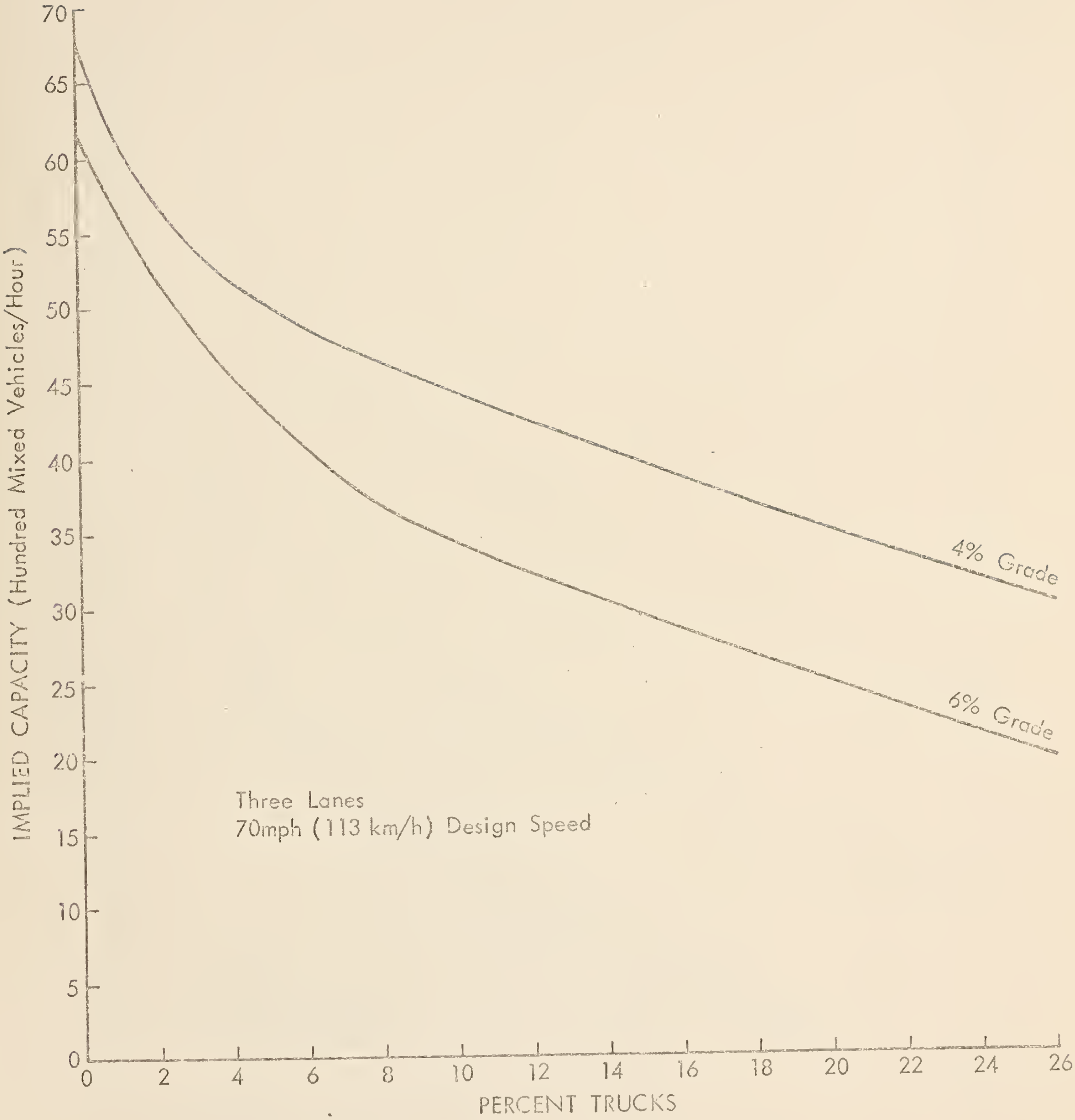

Figure 82 - Implied Capacities on Three Upgrade Lanes, 70 mph (113 km/h) Design Speed

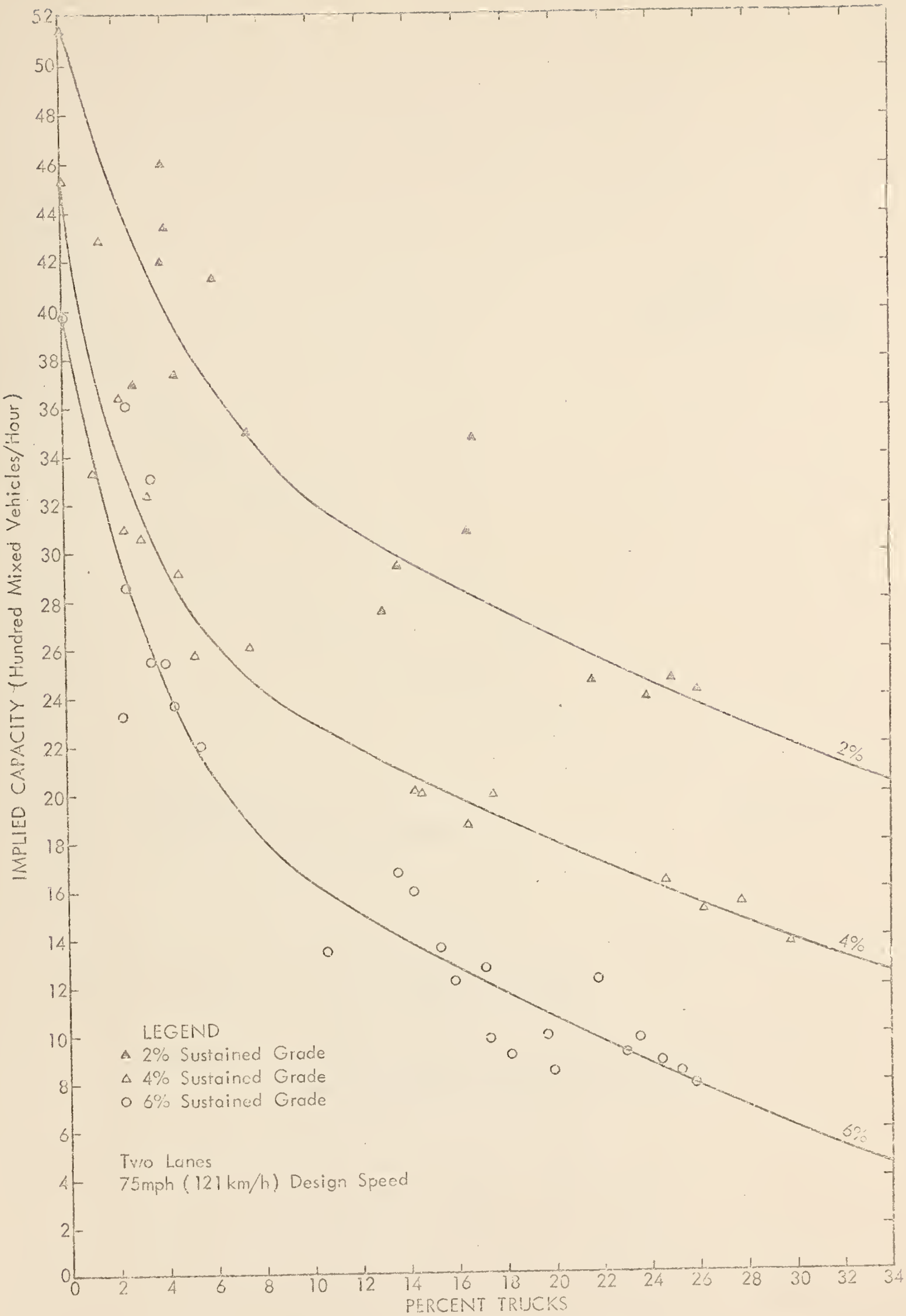

Figure 83 - Implied Capacities on Two Upgrade Lanes, 75 mph (121 km/h) Design Speed

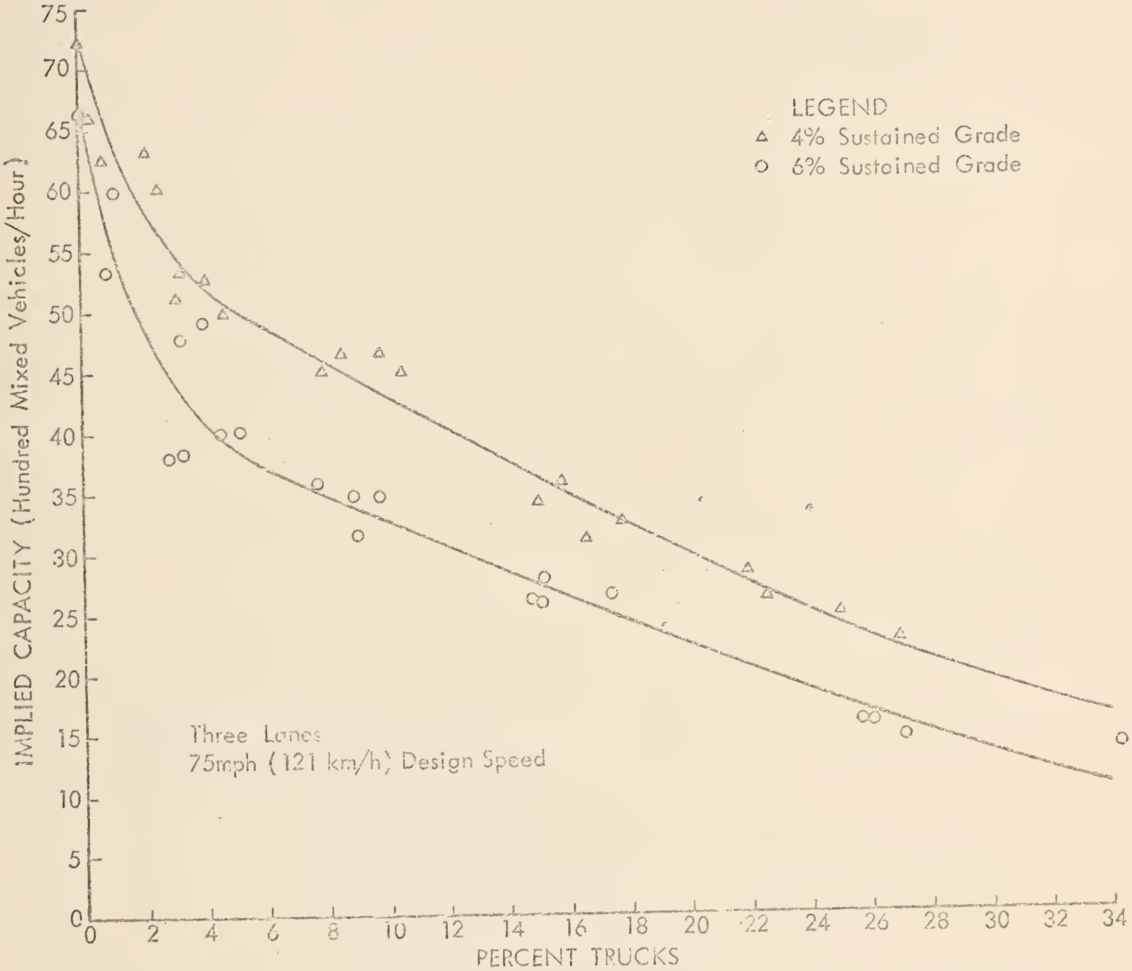

Figure 84 - Implied Capacities on Three Upgrade Lanes, 75 mph (121 km/h) Design Speed

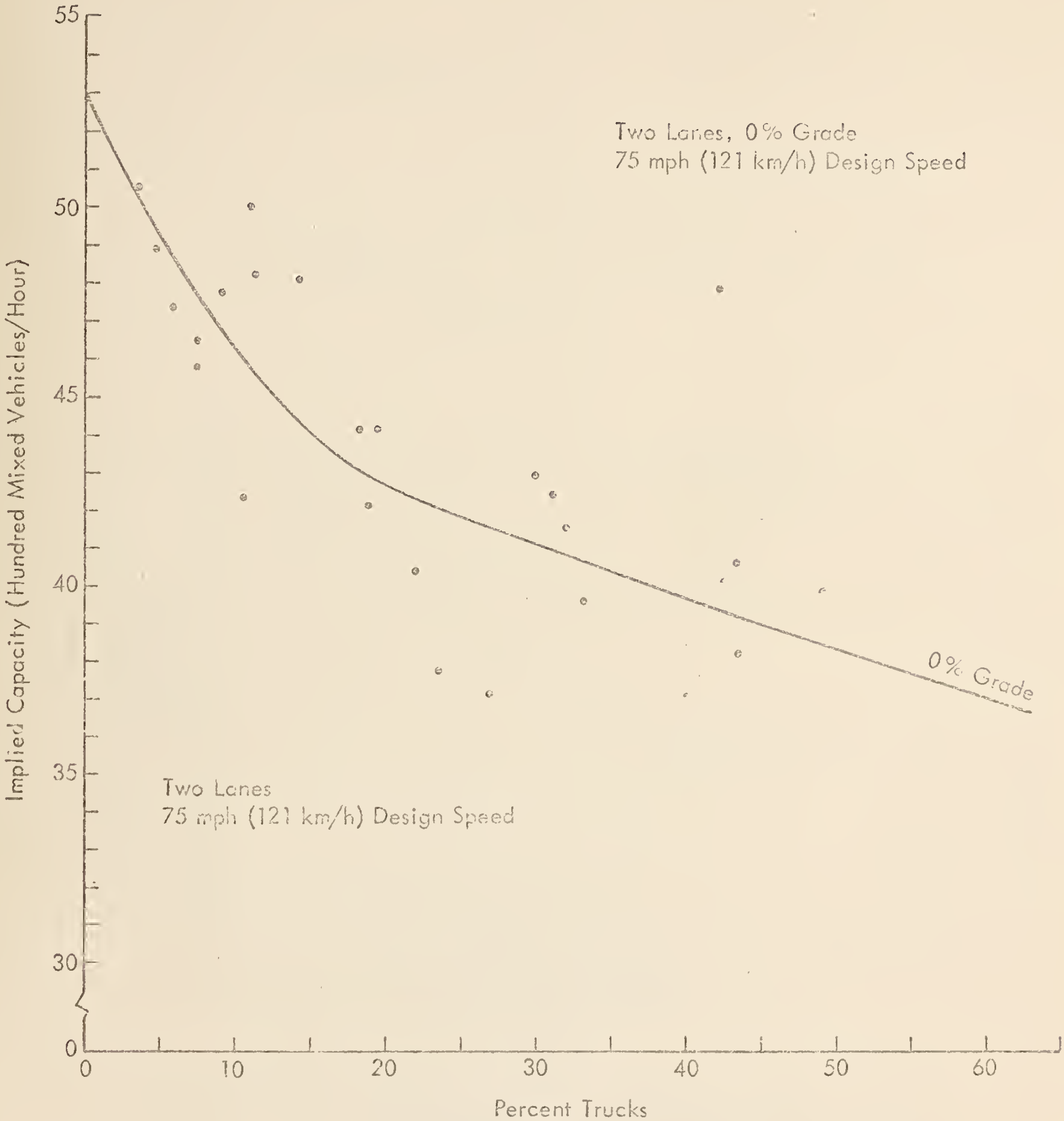

Figure 85 - Implied Capacities on Two Lanes, 0% Grade, 75 mph (121 km/h) Design Speed

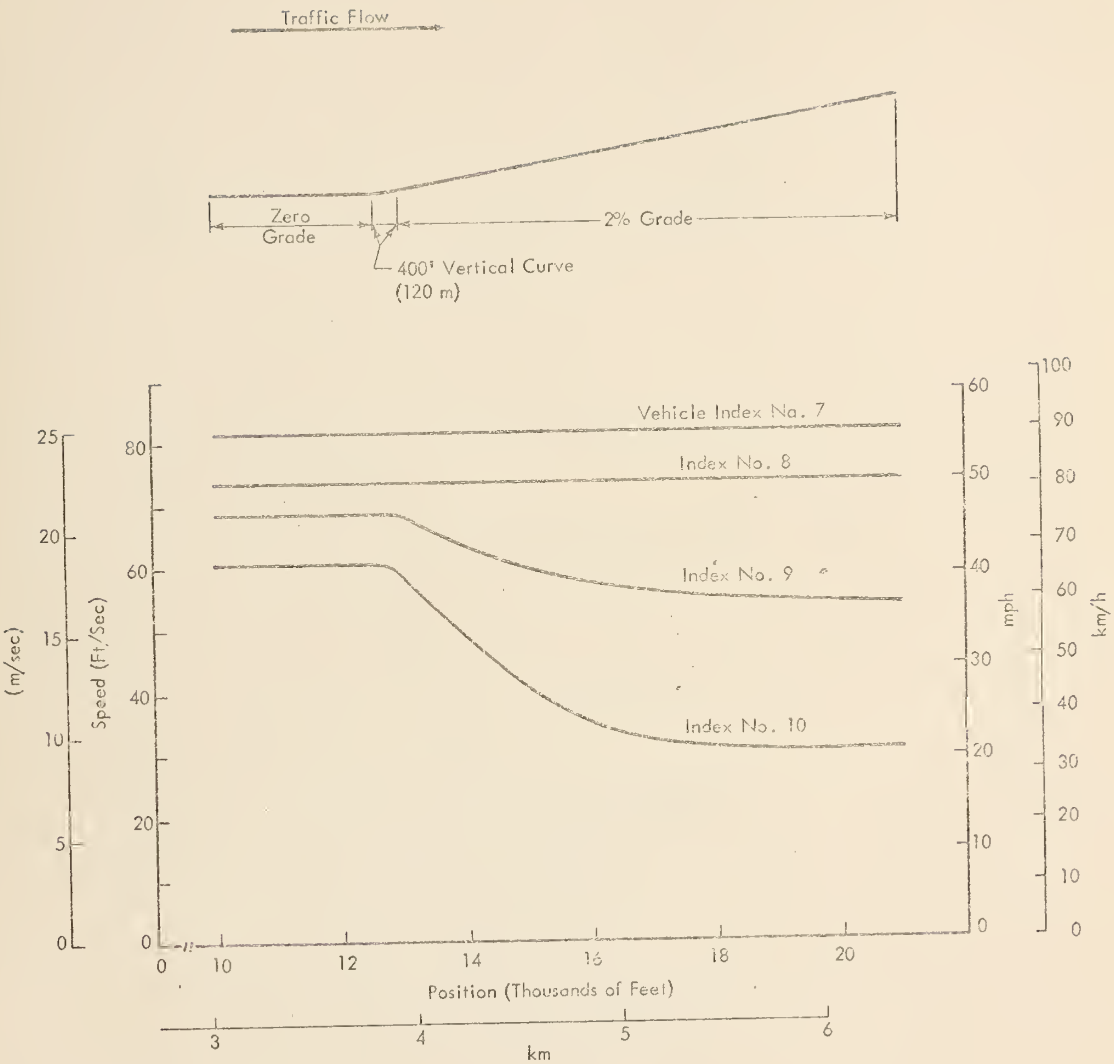

Figure 86 - Performance and Preference-Limited Speeds of Four Commercial Vehicles, 2% Grade

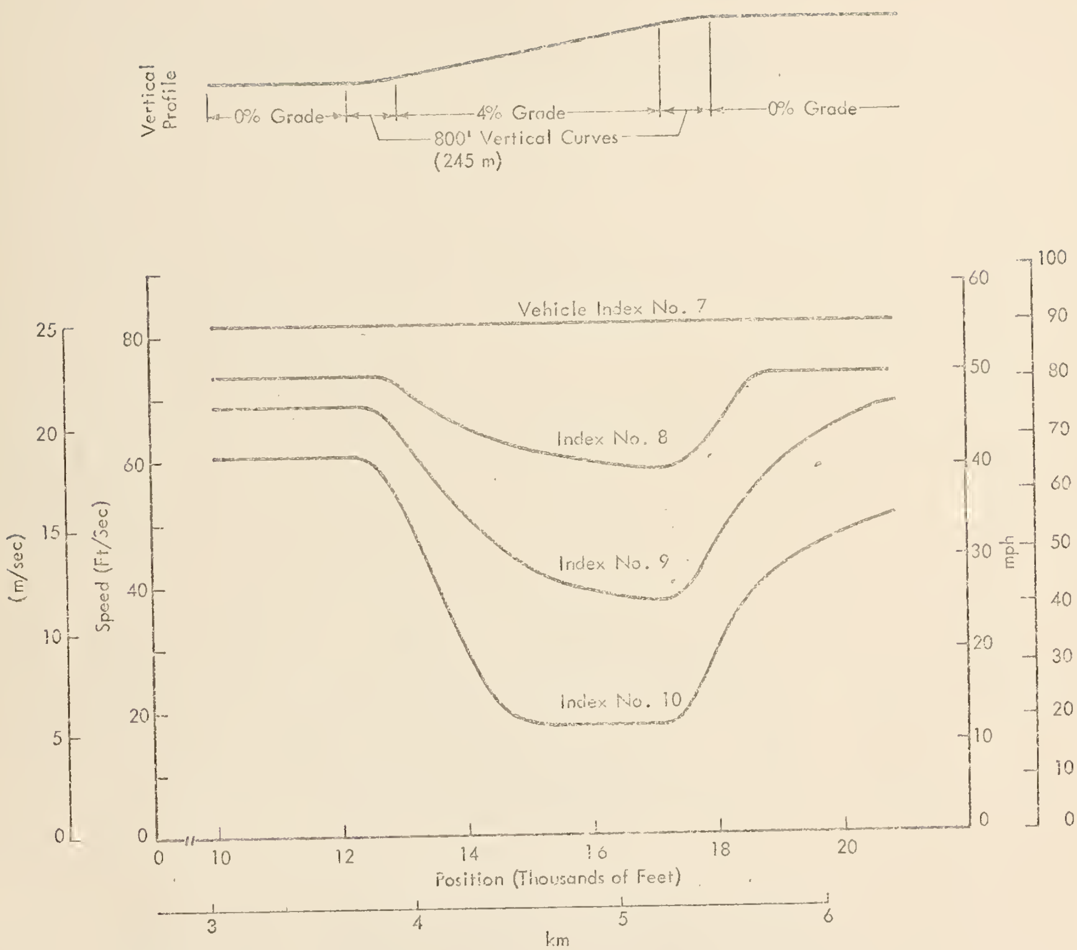

Figure 87 - Performance and Preference-Limited Speeds of Four Commercial Vehicles, 4% Grade

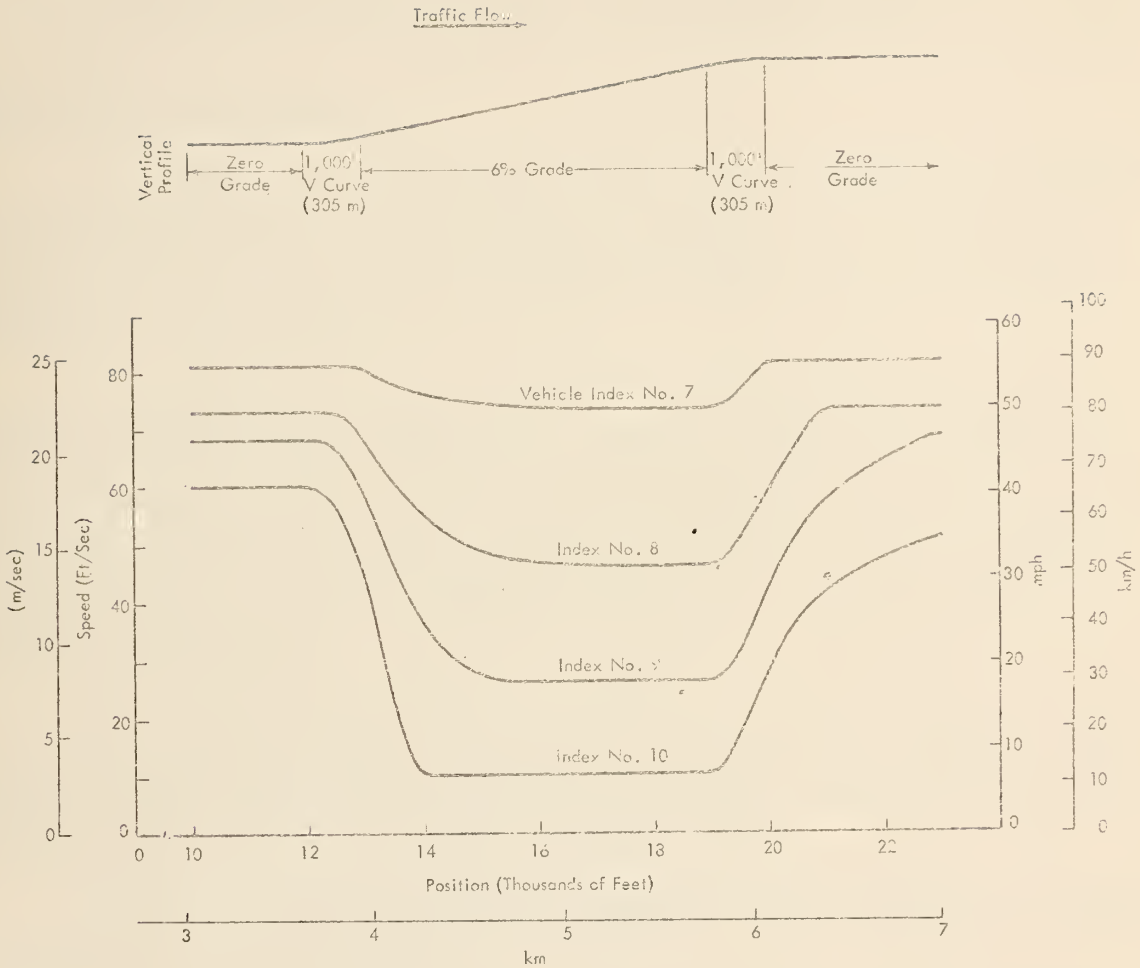

Figure 88 - Performance and Preference-Limited Speeds of Four Commercial Vehicles, 6% Grade

APPENDIX C

COMPUTER REQUIREMENTS AND SIMULATION RUNNING TIMES

General Program Description

The program for simulating highway traffic in mountainous terrain was written in FORTRAN IV and was initially debugged on a Control Data Corporation 6400 using the SCOPE 3.1.6 operating system. Core requirements are 31,200 (74,000 octal) words on the CDC 6400 and a partition of about 170 K bytes on the IBM 360.

The computer program is divided into three main parts, called Program I, Program II and Program III. Program I reads cards specifying the simulation to be run. It also initializes the system and primes it by placing a suitable number of vehicles on the simulated road with velocities and spacings designed to provide the user specified flow and to minimize start-up transients. Finally, Program I builds a file of vehicles which will enter the system after the simulation has begun--that is, during the process of simulation.

Program II performs the actual simulation for the required length of time, prints out periodic displays of the status of the simulation and generates three intermediate files containing events occurring during the simulation which will be summarized in Program III.

Program III reads the three intermediate files produced by Program II and produces printed reports.

Throughout all three programs the following units are used unless otherwise specified:

Time - seconds (review periods)*

Length - feet

Speed - ft/sec

Acceleration - ft/sec^2.

* A review period is the time between updates of the vehicle positions, speeds, and lane placements, and is equal to 1 sec.

Estimates of Running Time on the CDC 6400

Running time for the simulation program depends on program input. It is clear that running time increases if the number of vehicles or the length of time being simulated increases. For this reason, running times are described in terms of computer seconds required per simulation vehicle second (i.e., per simulated vehicle review period where the review period is 1 sec).

The number of vehicle seconds in a run can be determined by multiplying the average number of vehicles in the system by the number of seconds to be simulated. The average number of vehicles in the system can be estimated from estimated vehicle density and the length of simulated road.

Running times for Program I should not and do not depend markedly on the number of vehicle reviews to be simulated. There may be a slight dependence on the road length and the number of vehicles placed there in priming. The estimate shown in Table XXVII is for road lengths of about 2 miles and vehicle densities associated with maximum flow. Since running time for Program I is small compared with that for Program II, it can be neglected when running both programs as parts of the same job.

Table XXVII gives running time estimates based on runs made at total flow rates ranging from 1,800 to 3,200 vehicles/hour.

TABLE XXVII

RUNNING TIME ESTIMATES FOR CDC 6400

Program	Estimated Central Processor Time
I	4 to 6 sec
II	0.0095 to 0.0110 sec/vehicle sec
III-1,2,3	0.0016 to 0.0022 sec/vehicle sec

Running Times on the CDC 6600

During the current project the simulation program has been run on the CDC 6600 computer, and running times have been improved by reducing printed output and by blocking the output to intermediate tapes. Examples of running experience on the CDC 6600 are shown in Table XXVIII.

TABLE XXVIII

EXAMPLES OF SIMULATION RUNNING TIMES ON THE CDC 6600 COMPUTER

Run No.	Description: Road Length	Description: Geometrics	Description: Flow Rate (vph)	Time Simulated (min)	Central Processor (min)
145	8,000 ft (2,400 m)	0% grade; 2 lanes	500; 0% trucks	7	0.58
146			1,330; 0% trucks	4	0.79
147			2,600; 0% trucks	4	1.63
149		0% grade; 3 lanes	1,350; 0% trucks	4	0.77
151	14,000 ft (4,300 m)	2% grade with foot and crest; 2 lanes	3,050; 2% trucks	4	4.18
152			2,450; 3% trucks	4	3.20
153			2,350; 10% trucks	4	2.99
154			2,070; 25% trucks	4	2.83
155		4% grade with foot and crest; 2 lanes	2,600; 1% trucks	4	3.88
156			2,200; 3% trucks	4	3.06
157			1,800; 12.5% trucks	4	2.45
163		4% grade with climbing (3rd) lane on grade	4,100; 1.5% trucks	4	6.10
159		6% grade with foot and crest; 2 lanes	2,300; 2% trucks	4	3.09
160			1,700; 4% trucks	4	2.25
173			900; 11% trucks	4	1.21
168		6% grade with foot and crest; climbing (3rd) lane on grade	2,850; 4% trucks	4	3.98
169			2,250; 13% trucks	4	3.25