Passing Experiment on Two-Lane Rural Highways

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The major purpose of this study was twofold: (a) investigate the physical components of the overtaking maneuver on two-lane rural highways and the relationship between these components, and (b) evaluate whether current practices in highway design are adequate. Data for the study were collected by two instrumented vehicles driven simultaneously along two rural-road sections: the first car, the impeder, was overtaken by the second, faster car. Findings regarding the initial maneuver distance and time, space and time gap at encroachment onto opposing lane, distance traveled and time in opposing lane, space and time gap on completion of maneuver, speed differences, and acceleration characteristics are evaluated and discussed. Comparison of the findings with AASHTO values is presented, and it is concluded that the values given by AASHTO may be somewhat conservative. It is concluded that the passing maneuver should be studied more extensively, with the intention of re-reviewing current road-design guidelines.

The overtaking maneuver is perhaps one of the most complicated tasks that drivers have to perform when traveling on two-lane rural roads. It involves lane-change maneuvers, possibly some acceleration and deceleration actions, and estimation of the relative speed of the overtaking and overtaken vehicles. The overtaking drivers have to go through certain decision-making processes in order to accept or reject gaps presented to them in the oncoming traffic stream and to determine whether passing is justified under the constantly changing road and traffic conditions. In spite of the complexity of this maneuver and despite the continuous research efforts that have been directed at almost all aspects of transportation engineering, the overtaking maneuver has not been investigated extensively. However, the distances and speed relationships involved in the maneuver constitute a major input in highway design and sight-distance requirements.

Furthermore, the importance of the overtaking maneuver has implications for overall road safety. A likely assumption is that accidents involving overtaking on rural roads are much more severe than other types of rural accidents. Recent statistics on road-traffic accidents *(1)* show that rural head-on collisions account for 2.3 percent of rural road accidents and 7 percent of the fatalities. The percentage of fatalities and major injuries in the head-on category is about 43 percent, which is considerably higher than the overall average of about 17 percent for the equivalent consequences of all road accidents on rural roads.

The major purpose of the study reported here was twofold: (a) to investigate the physical components, both individually and in combination, constituting the overtaking maneuver on two-lane rural roads and the relationships between these elements; and (b) based on the study findings, to evaluate whether current practices in highway design are adequate and recommend amendments if needed. There were two other, secondary objectives: one was to compare the extent of similarity in the overtaking maneuver in two different countries—specifically, Israel and South Africa; the second was to compare methods of data collection and to deduce the advantages, disadvantages, and adaptability of each method according to a predetermined set of conditions.

The research on which this paper is based was conducted as a joint effort of the Transportation Research Institute of the Technion in Israel and the National Institute for Transport and Road Research in South Africa. The analysis and findings of the two major objectives are presented; those of the two secondary objectives will be reported in due course.

STUDY BACKGROUND

The study of overtaking practices by Holmes *(2)* and Normann *(3)* constituted perhaps the first comprehensive research of passing practices. They examined a total of 1,635 overtakings by placing more than 100 pneumatic tubes on the road surface at 50-ft intervals. Normann's analysis provided details of the gaps accepted by overtaking drivers, but not of the gaps rejected. In a study of drivers who wanted to overtake on two-lane rural roads in Australia, Miller and Pretty *(4)* conducted observations from test vehicles being driven at constant speeds of 30, 35, and 40 mph on two straight, level road sections near Melbourne. They differentiated between two extreme groups of drivers: those who will not overtake, regardless of gap size, and those who will overtake even when there is no gap in the oncoming traffic, thus forcing both the overtaken and oncoming vehicles onto the shoulders. The authors note, however, that rational drivers will make their decision of whether or not to overtake based on the available gap, sight distance, the speed of their vehicle, as well as that of the overtaken vehicle, and the estimated speed of the oncoming traffic.

Miller and Pretty also discussed a common bias in gap acceptance studies; namely, that the proportion of drivers who will accept a given gap size is greater than the proportion of gaps of that size that are accepted. This difference was probably first pointed out by Raff *(5)* and quantified by Ashworth *(6)*. Although a sufficiently large sample could not be obtained in either case, each researcher fitted a log-normal distribution to the set of accepted gaps and found that the estimated mean critical gap increases with the increase in the speed of the overtaken car. In another Australian investigation of sight-distance requirements for overtaking maneuvers, Troutbeck et al. (7) fitted a log-normal distribution of critical sight distances to the data and used maximum likelihood techniques to estimate the parameters. They found that a small percentage of drivers would accept extremely small sight distances for over-

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taking. Lieberman *(8)*, in the United States, developed a theoretical model for calculating safe passing distances on two-lane rural roads. His model was based on the hypothesis that a point exists in the passing maneuver that can be identified as the critical position at which the decision to complete or abort the maneuver will provide the same factor of safety relative to the oncoming vehicle. The model locates this critical position and, following a series of sensitivity analyses, suggests that the current sight-distance criteria in highway design may be adequate from the safety standpoint. Lieberman argued that this supposition particularly holds for high-speed passing maneuvers and for passing vehicles that are low-powered subcompacts.

Several other studies have addressed the adequacy, over the years, of the sight-distance criteria for passing. Turner *(9)*, who studied line markings for restricting overtaking on curves, suggested that the more closely line-marking standards approach a practice that is acceptable to a driver, the more likely the marking will command his respect. Field investigations of completed and aborted overtaking maneuvers were conducted on an automobile racetrack where the observations of overtaking distances and times were compared with theoretical calculations based on the acceleration characteristics of the assumed vehicle. The findings suggested that the full overtaking sight-distance values were generally lower, by approximately 10 percent, than the equivalent values proposed by the American Policy on Highway Design *(10)*. A different approach toward this policy was later taken by Khasnabis and Tadi *(11)*, who reevaluated crest vertical-curve-length requirements and, based on a series of assumptions, showed that the resulting stopping sight distances may be considerably higher than those currently set forth in the AASHO policy *(10)*; they also maintained that the vertical-curve-length requirements may have to be increased significantly.

Somewhat more recently, Saito *(12)* conducted a theoretical analysis of minimum passing sight-distance requirements for aborting the passing maneuver. He found that the desired sight distance would be greater than current U.S. standards when the 85th percentile speed was more than approximately 40 mph.

Overtaking behavior on Australian two-lane rural highways was studied by Troutbeck *(13)*, who used a research vehicle fitted with video cameras, radar speedmeter, and a set of mirrors to record traffic flow in four directions simultaneously. The duration of events in his study could be determined to a greater degree of accuracy than could the distances traveled by vehicles; his analysis, therefore, gave more emphasis to time measures. When large coefficients of skewness with overtaking times and distance distributions were revealed, Troutbeck fitted log-normal distributions to the data. Conclusions included the following: (a) overtaking times generally increased with speed [see also Turner *(9)*], (b) being delayed did not affect drivers' overtaking times, and (c) overtaking times were significantly correlated with the size of the accepted gap.

In another paper, Troutbeck *(14)* presented a method of estimating the rate with which faster vehicles catch up to slower vehicles; he also related catch-up and overtaking rates. His model, however, was only applicable to roads with very low traffic flows where catch-up rates can actually be equated with overtaking rates. Troutbeck suggested using the catch-up rate to evaluate passenger car equivalents (pces), but the method proposed only accounted for the expected overtaking rate and did not take into consideration the difficulty of the overtaking maneuver. Craus et al. *(15)* had earlier suggested a more realistic method of evaluating pces with the ratio of the number of actual overtakings of a truck to the number of actual overtakings of a passenger car, taking into consideration the effects of the oncoming traffic.

Briefly, it can be said that there have been a limited number of passing studies since the major ones conducted in the United States in the late 1930s and early 1940s. The study reported in this paper was based on a rather different approach, as well as on a unique method of data collection and analysis.

DATA COLLECTION

The data collection for this study was carried out near Pretoria on two tangent, level, two-lane rural-road sections with practically unlimited sight distance: Silverton and Pretoria West. The traffic volume on the first road was rather low, the average hourly volume was approximately 100 vehicles per hour (vph); at the second site the volume was higher, approximately 200 vph. Both sites had about 20 percent trucks. The gap presented to overtaking drivers were somewhat long, though mostly shorter at the second site. There were no other important differences between the two sites.

Data on overtaking maneuvers were collected by two instrumented vehicles, driven simultaneously along each section. The first car, the impeder, was overtaken by the second, faster car. The overtaken vehicle was driven at a range of steady speeds along each section: 37.5, 43.8, 50.0, and 56.3 mph (60, 70, 80, and 90 km/hr). The overtaking driver was instructed to perform the passing maneuver at a self-chosen free speed to suit his natural driving behavior, and not to exceed the safe speed for the appropriate road and traffic conditions during the time of the maneuver.

The two vehicles were each equipped with a multipurpose data acquisition and processing system *(16)*, called the Traffic Engineering Logger (TEL). These computerized recording systems produced highly accurate, synchronized time and distance diagrams of the overtaken and overtaking vehicles, as shown in Figure 1, and thus enabled an analysis of the paths and speeds of both vehicles at any given instant. A team of two men, a driver and a TEL operator, were responsible for each instrumented car. Before logging, the operator had to initialize the system with such information as date, time, and calibration constant. The unique feature of the TEL system, its two separate, real-time, synchronized clocks, was of great importance to the accuracy of the measurements. The clocks are physically linked during the initialization and pace verification phases. The link is then removed and the survey can proceed without any obstruction. Whenever the logging function is activated, all the transducers are scanned and the pulses received counted and stored in the system memory. The data recorded include time, distance, speed, and events. [Details of the TEL system are presented by Skowronski *(16)*].

The definitions of the beginning and end of the overtaking maneuver are shown in Figure 2, along with the relevant designations of the distance between the overtaking and overtaken vehicles. Because of the relatively short time taken by the maneuver, distance measurements were logged continuously and recorded at 0.125-sec intervals. The TEL system's built-in

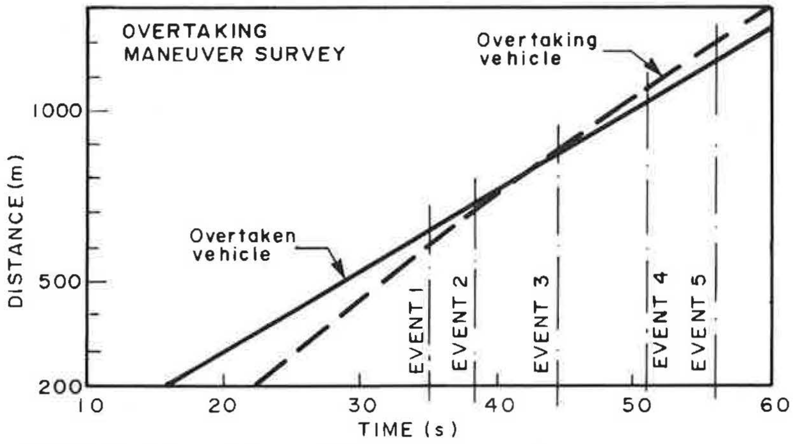

FIGURE 1 A typical time and distance diagram of the overtaking maneuver, with the events marked.

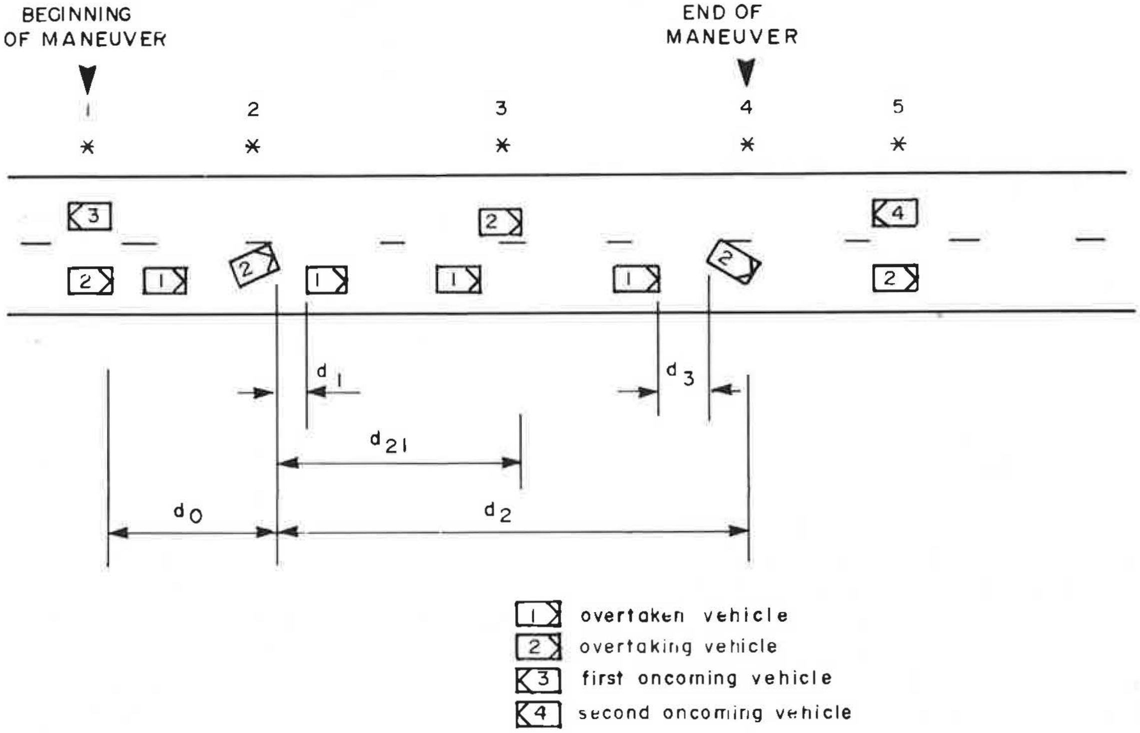

FIGURE 2 Overtaking maneuver and relative distances between vehicles.

event marker was used to identify five events (note Figures 1 and 2): Event 1, when the overtaking vehicle met the last oncoming vehicle and the passing maneuver was about to start; Event 2, when the overtaking vehicle encroached on the centerline toward the opposite lane; Event 3, when the rear of the overtaking vehicle was in line with the front of the overtaken vehicle; Event 4, defined as the end of the maneuver, when the overtaking vehicle had returned completely to its lane; and Event 5, when the overtaking vehicle met the next oncoming vehicle. In addition, the operator of the overtaken vehicle also activated the event marker to identify oncoming-vehicle arrivals and thus record exact gap sizes.

Following the synchronization of time and distance references for both cars, the measured parameters were obtained with an accuracy in time of a fraction of a second and in distance of about 1 m. It was recognized, nevertheless, that some error might have been introduced because the operator's judgment had to be relied on for the exact instant of each event. It was decided, therefore, to reduce the variability involved by using the same two TEL operators on the two instrumented vehicles throughout the entire experiment. In order to introduce some variability in driver behavior, eight different drivers, one for each day of data collection, were employed to drive the overtaking vehicle throughout the entire speed range. All drivers—seven men and one woman—had at least 3 years of driving experience (the range being 3 to 20 years). It was observed that some drivers behaved more cautiously than others; the assumption, therefore, was that they represented a typical cross section of the driver population.

Overall, 320 overtaking maneuvers were recorded. The steady speeds of the overtaken vehicle were established at 37.5, 43.8, 50.0, and 56.3 mph (60, 70, 80, and 90 km/hr); 40

overtaking maneuvers, 10 at each speed, were performed daily for 8 days when the weather was dry and clear. During the analysis, the data were reduced by eliminating erroneous information resulting from obvious mistakes in judgment by the TEL operator or from electrical failure of the instruments. In the end 250 maneuvers were analyzed in detail, grouped into four categories: (a) accepted gap, (b) infinite gap, (c) accepted lag, and (d) no oncoming traffic (only 26 maneuvers).

RESEARCH FINDINGS

General

The data were extracted from the TEL memory and transferred to the mainframe computer by using the interface device developed at the National Institute for Transportation and Road Research (NITRR), then analyzed with the aid of the *Statistical Package for the Social Sciences* (SPSS) computer package *(17)*. The maneuvers were divided into two basic groups. The first group was composed of accelerative overtakings, which for computing purposes were defined as occurring when the initial overtaking and overtaken speeds differed by not more than 6.2 mph (10 km/hr); the maneuver, therefore, had to start with some acceleration after the gap-acceptance decision was made. The gaps were considered regular (between two oncoming vehicles) or infinite (when the second oncoming vehicle—Vehicle 4 in Figure 2—was not present). The second group was composed of flying overtakings, when the speed difference between the vehicles was larger than 6.2 mph (10 km/hr); usually, the maneuver had started after a lag was accepted by the overtaking driver. The first oncoming vehicle (Vehicle 3 in Figure 2) did not prevent the fast vehicle from continuing its journey at the desired speed. Further data breakdown according to the four speed groups was performed when necessary.

The discussion of the findings will be presented in the relative order of occurrence during the passing process, starting with the initial-maneuver distance and time. The results will be compared to those previously published, particularly the AASHO *(10, 18)* recommendations. The analysis of the relative relationships between several related variables, such as the distance traveled in the opposing lane and the speed, will also be reported.

Initial-Maneuver Distance

This distance (d_0) is defined as that traversed during the perception and reaction time and during the initial acceleration to the point of encroachment onto the opposing lane (or the same as AASHO d_1). The average value of d_0 for a total sample size of 112 was 151 ft (46 m), with a standard deviation of 125 ft (38 m). The 85th percentile was 222 ft (68 m). A breakdown according to accelerative and flying overtakings and according to two extreme speed groups is given in Tables 1 and 2.

TABLE 1 INITIAL MANEUVER DISTANCE BY TYPE OF MANEUVER AND TYPE OF GAP ACCEPTED

Maneuver	Type of Gap Accepted	Average d_0 (ft)	Standard Deviation (ft)	Sample Size	Overall d_0 (ft)
Accelerative	Accepted	153.5	105.3	18	163.1
	Infinite	184.4	103.7	8	
Flying	Accepted	138.8	117.8	66	146.6
	Infinite	173.5	160.0	20	

NOTE: 1 ft = 0.3 m.

TABLE 2 INITIAL MANEUVER DISTANCE RELATED TO SPEED OF OVERTAKEN VEHICLE AND TYPE OF GAP ACCEPTED

S_1 Speed Group (mph)	Type of Gap Accepted	Average d_0 (ft)	Standard Deviation (ft)	Sample Size	Overall d_0 (ft)
37.5	Accepted	96.1	59.7	31	107.3
	Infinite	191.9	85.9	4	
56.3	Accepted	124.0	51.2	16	158.1
	Infinite	218.8	149.2	9	

NOTE: 1 ft = 0.3 m.

The following prominent observations can be made. First, as might be expected, d_0-values are considerably smaller with the accepted gaps than with the infinite gaps. Second, there is a slight increase in d_0 with speed, although it is not statistically significant at the 5 percent level; this observation was verified by the scattergram of the initial-maneuver distances over the entire speed range.

Initial-Maneuver Time

The time t_0 is that needed for the overtaking vehicle to traverse the relevant distance, d_0. The overall average value of t_0 for the sample size (112) was 1.74 sec with a standard deviation of 1.35 sec. The 85th percentile was 2.59 sec. A breakdown of these values according to accelerative and flying overtakings is given in Table 3. The following conclusions can be drawn. First, the values of t_0 for a maneuver in which the gap was accepted are slightly smaller than those in which the gap was infinite. Second, t_0-values for accelerative maneuvers are larger than those for flying maneuvers; the difference is statistically significant at the 5 percent level. An attempt was made to calibrate t_0-values against the initial speed of the overtaking vehicle, SI_2; however, no strong correlation could be established ($r = 0.18$ for flying maneuvers and $r = -0.07$ for accelerative maneuvers). It was concluded that t_0 is independent of SI_2.

Space and Time Gap at Encroachment onto Opposing Lane

The distance d_1 is defined as the space gap between the overtaken and overtaking vehicles at the moment of the latter's encroachment onto the opposing lane. This value was obtained by calculating the difference in relative distance at the moment of Event 2 (note Figure 1). The overall average value of d_1 for a sample of 106 accepted and infinite gap maneuvers was 78 ft (23.7 m), with a standard deviation of 37 ft (11.4 m). The 15th percentile was 46 ft (14.1 m), and the 85th percentile was 117 ft (35.7 m). Regression of d_1 on the initial speed of the overtaken

TABLE 3 INITIAL MANEUVER TIME BY TYPE OF MANEUVER AND TYPE OF GAP ACCEPTED

Maneuver	Type of Gap Accepted	Average t_0 (sec)	Standard Deviation (sec)	Sample Size	Overall t_0 (sec)
Accelerative	Accepted	2.12	1.38	18	2.20
	Infinite	2.36	1.27	8	
Flying	Accepted	1.52	1.25	66	1.60
	Infinite	1.88	1.60	20	

vehicle, SI_1, was inconclusive. Furthermore, no statistically significant difference at the 5 percent level was found between accepted and infinite gap cases in all four speed groups.

The time difference t_1 is the relevant time for distance d_1. Its average value for a sample size of 107 was 0.95 sec, with a standard deviation of 0.46 sec. The 15th percentile was 0.60 sec and the 85th percentile was 1.38 sec. The rather small d_1- and t_1-values indicated some bad driving habits, particularly in passing: the overtaking vehicle would approach the overtaken vehicle too closely, thus creating the risk of a rear-end collision, and also causing the overtaking driver to lose some of the sight distance needed to assess the situation ahead properly. This bad driving practice, however, can be rectified by proper education.

Distance Traveled in Opposing Lane

The distance traveled by the overtaking vehicle in the opposing lane, d_2, is probably the most significant element of the passing maneuver. It has a direct bearing on the safety and convenience of flow on two-lane roads and, therefore, has obvious importance for the design of such roads. In this research, the overall average of d_2 for a sample size of 176 was 735 ft (224 m), with a standard deviation of 256 ft (78 m). The 85th percentile was 963 ft (294 m). The breakdown of d_2 according to the speed of the overtaken vehicle, S_1, is given in Table 4.

The regression of the distance d_2 against the average speed of the overtaken vehicle, $\bar{S}_1$, showed a significant increase in distance with the increase in speed. This is represented as

$$d_2 = 17.14 + 2.60\ \bar{S}_1 \qquad r = 0.54 \tag{1}$$

where the independent and dependent variables are as defined previously and r is the correlation coefficient. The units are meters and kilometers per hour. No statistically significant differences were found between the cases of accepted gap, infinite gap, and accepted lag.

TABLE 4 DISTANCE TRAVELED IN OPPOSING LANE BY SPEED OF OVERTAKEN VEHICLE

S_1 Speed Group (mph)	Average d_2 (ft)	Standard Deviation (ft)	Sample Size
37.5	573	137	57
43.8	721	178	52
50.0	880	388	31
56.3	887	186	36

NOTE: 1 mph = 1.6 km/hr; 1 ft = 0.3 m.

Further investigation explored whether the distance traveled in the opposing lane was related to the average speed difference, ΔS, between the overtaking and overtaken vehicles during the former's occupation of the opposing lane. This was the model calibrated:

$$d_2 = 257.09 - 1.81\ \Delta S \qquad r = -0.24 \tag{2}$$

where all variables are as defined earlier, and the units are meters and kilometers per hour.

A slight reduction in d_2 is observed with the increase in ΔS. The lack of statistical significance, however, suggests a contradictory effect: as the speed difference increases, the overtaking driver performs the encroachment onto and return from the opposing lane with a larger space gap in relation to the overtaken vehicle (distances d_1 and d_3), which increases distance d_2 (note Figure 2); on the other hand, less time is required to stay in the opposing lane, which in turn reduces d_2.

The distance traveled in the opposing lane was also found to increase with the average speed of the overtaking vehicle, $\bar{S}_2$. The following model was calibrated:

$$d_2 = 28.72 + 1.80\ \bar{S}_2 \qquad r = 0.34 \tag{3}$$

where the variables are as previously defined, and the units are meters and kilometers per hour.

An analysis of the distance traveled in the opposing lane to the point of no return—that point from which it will be safer for the overtaking driver to complete the passing process rather than to abort it—yielded the relationships given in Table 5 and in Equation 4. This distance, d_{21}, was measured at the point at which the rear of the overtaking vehicle was aligned with the front of the overtaken vehicle (note Figure 2).

TABLE 5 RELATIONSHIP BETWEEN DISTANCE TRAVELED IN OPPOSING LANE UP TO POINT OF NO RETURN AND TOTAL DISTANCE

Type of Gap Accepted	Average Distance of d_{21} (ft)	Average Distance of d_2 (ft)	Ratio d_{21}/d_2
Accepted and lag	389	731	0.53
Infinite	459	735	0.62

NOTE: 1 ft = 0.3 m.

$$d_{21} = -17.30 + 0.621\ d_2 \text{ for } d_2 > 27.8 \qquad r = 0.85 \tag{4}$$

where all the variables are as defined previously, and the units are in meters.

Time of Travel in Opposing Lane

The time t_2 corresponds with the time traveled on distance d_2. The overall average value of t_2 for a sample size of 176 was 8.00 sec, with a standard deviation of 2.60 sec. The 85th percentile was 10.14 sec. The breakdown of t_2 according to the speed of the overtaken vehicle is given in Table 6. The regres-

TABLE 6 TIME TRAVELED IN OPPOSING LANE BY SPEED OF OVERTAKEN VEHICLE

S_1 Speed Group (mph)	Average t_2 (sec)	Standard Deviation (sec)	Sample Size
37.5	6.9	1.7	57
43.8	8.1	2.1	52
50.0	9.0	4.3	31
56.3	8.6	1.9	36

NOTE: 1 mph = 1.6 km/hr.

sion of t_2 against the average speed of the overtaking vehicle, $\bar{S}_2$, showed that t_2 was independent of $\bar{S}_2$.

Space and Time Gap on Completion of Maneuver

The space and time gap between the overtaking and overtaken vehicles on the former's return to a lane were termed d_3 and t_3, respectively (see Figure 2). The overall average of d_3 was 97 ft (29.7 m), with a standard deviation of 30 ft (9.0 m) for the sample size, 139. The 15th and 85th percentiles were 70 ft (21.3 m) and 127 ft (38.6 m), respectively. The overall average of t_3 was 1.52 sec, with a standard deviation of 0.58 sec for the sample size, 144. The 15th and 85th percentiles were 0.99 sec and 2.07 sec, respectively. The breakdown of the averages according to the type of gap is given in Tables 7 and 8.

Speed Difference

The maximum speed difference between the overtaking and overtaken vehicles, ΔS_{max}, is an important feature of the overtaking process. As such, it is considered in passing models and has been discussed in a number of previous studies [e.g., AASHTO *(18)*, Lieberman *(8)*, Troutbeck *(13)*]. The average maximum speed difference found in this study was 19 mph (30.67 km/hr). Further investigation determined, as expected, that a slight negative correlation existed between the maximum speed difference and the speed of the overtaken vehicle. The general form of the relationship is expressed as

$$\Delta S_{max} = 51.99 - 0.28\ \bar{S}_1 \qquad r = 0.44 \tag{5}$$

where the variables are as defined previously, and the units are in kilometers per hour.

TABLE 7 VALUE OF DISTANCE GAP BETWEEN OVERTAKING AND OVERTAKEN VEHICLES ON COMPLETION OF PASSING MANEUVER

Maneuver	Type of Gap Accepted	Average d_3 (ft)	Standard Deviation (ft)	Sample Size
Accelerative and flying	Accepted	90	26	83
	Accepted lag	109	30	56

NOTE: 1 ft = 0.3 m.

TABLE 8 VALUE OF TIME GAP BETWEEN OVERTAKING AND OVERTAKEN VEHICLES ON COMPLETION OF PASSING MANEUVER

Maneuver	Type of Gap Accepted	Average t_3 (sec)	Standard Deviation (sec)	Sample Size
Accelerative and flying	Accepted	1.37	0.46	83
	Accepted lag	1.74	0.65	61

The speed variability of the overtaking vehicle during the process was also analyzed, and led to two major findings. First, for accelerative maneuvers, when the initial speed was low, the final speed was higher, and vice versa. Second, for flying maneuvers, the initial speed was not significantly different, at the 5 percent level, from the final speed. For all maneuvers, the speed of the overtaken vehicle was almost constant throughout the overtaking process.

Acceleration Characteristics

An analysis of the acceleration characteristics of the passing vehicles was conducted separately for accelerative and flying maneuvers owing to the obvious difference between these two processes. The results are given in Table 9. Accelerative passing is a process whereby the speed difference between the overtaking and overtaken vehicles was assumed to be equal to or less than 6 mph (10 km/hr) at the beginning of the maneuver. When this difference was greater, it was defined as a flying maneuver.

The overall mean of the initial acceleration, a_1, of the accelerative passing maneuver (based on 25 cases) was found to be 3.24 ft/sec^2 (0.99 m/sec^2), with a standard deviation of 1.15 ft/sec^2 (0.35 m/sec^2). The 15th and 85th percentiles were 2.23 ft/sec^2 (0.68 m/sec^2) and 3.70 ft/sec^2 (1.13 m/sec^2), respectively. A breakdown of the initial acceleration by speed group is given in Table 10. It can be observed that the average acceleration decreases by about 17 percent with an increase in speed from 37 mph (60 km/hr) to 56 mph (90 km/hr).

The maximum acceleration of the overtaking vehicle while traveling in the opposing lane, a_2, was also investigated. The overall average was found to be 1.74 ft/sec^2 (0.53 m/sec^2), with a standard deviation of 0.89 ft/sec^2 (0.27 m/sec^2) for the sample

TABLE 9 INITIAL ACCELERATION BY MANEUVER TYPE AND TYPE OF GAP ACCEPTED

Maneuver	Type of Gap Accepted	Average a_1 (mph/sec)	Standard Deviation (mph/sec)	Sample Size
Accelerative	Accepted and infinite	2.23	0.79	25
Flying	Accepted and infinite	1.69	0.59	83
Flying	Accepted lag and no oncoming traffic	1.08	0.54	65

NOTE: 1 mph/sec = 0.447 m/sec^2.

TABLE 10 VALUES OF AVERAGE INITIAL ACCELERATION RELATED TO SPEED OF OVERTAKEN VEHICLE

S_1 Speed Group (mph)	Average a_1 (mph/sec)	Standard Deviation (mph/sec)	Sample Size
37.5	1.98	0.58	33
43.8	1.78	0.63	33
50.0	1.62	0.56	17
56.3	1.64	0.52	24

NOTE: 1 mph = 1.6 km/hr; 1 mph/sec = 0.447 m/sec^2.

TABLE 11 VALUES OF AVERAGE ACCELERATION WHILE IN OPPOSING LANE RELATED TO SPEED OF OVERTAKEN VEHICLE

S_1 Speed Group (mph)	Average a_2 (mph/sec)	Standard Deviation (mph/sec)	Sample Size
37.5	1.19	0.50	33
43.8	1.19	0.54	33
50.0	0.92	0.32	17
56.3	1.13	0.45	24

NOTE: 1 mph = 1.6 km/hr; 1 mph/sec = 0.447 m/sec^2.

of 134. This value was considerably lower than the average initial acceleration. The breakdown by speed groups is given in Table 11.

COMPARISON OF FINDINGS WITH AASHTO VALUES

Only the two lower speed groups in this study are comparable with the two higher AASHTO *(18)* speed groups because of the incompatibility of the speeds of the overtaking vehicle in the remaining speed groups. The relevant comparisons are given in Table 12. There is no indication in the AASHTO document as to which of the values given are averages, 85th percentiles, or 15th percentiles. The comparison is made on the assumption that the time and distance values are 85th percentiles, the acceleration is a 15th percentile, and the speed difference is an average.

It is clear from Table 12 that the initial maneuver distance and time are much shorter than the AASHTO values. This also applies to the distance traveled in the opposing lane and to its corresponding time. These results are supported by the observed speed difference between the overtaking and overtaken vehicles, which is much higher than the AASHTO assumed value. The logical conclusion is that the acceleration should also be much higher, which surprisingly is not confirmed if the 15th percentile value of the initial acceleration is compared to the AASHTO values. The average initial acceleration, as given in Tables 9 and 10, is, however, much higher than the AASHTO values.

The ratio of the distance traveled in the opposing lane up to the point of no return to the total distance traveled in the opposing lane (see Table 5) differs from the value of 1/3 assumed by AASHTO. The comparison, however, appears meaningless because the relative position of vehicles in the AASHTO documents is not well defined; from the figure given, it seems to differ from the point of no return defined in the present study.

Distance d_2 against the average speed of overtaken vehicle, $\bar{S}_1$, a plot of the best-fit model, and the AASHTO line for d_2 are shown in Figure 3. The increase in d_2 with speed is noticeable. It can also be seen that the AASHTO values are higher by about 25 percent, and that the absolute difference increases with speed.

The distance, d_2, as a function of the average speed of the overtaking vehicle, $\bar{S}_2$, is shown in Figure 4: again, the AASHTO line is also shown. As with $\bar{S}_1$, the findings suggest that the distance traveled in the opposing lane is shorter than the recommended AASHTO values. This supports the AASHTO statement that ". . . the minimum passing sight distances given . . . are generally conservative for modern vehicles . . . ." The authors of the present study postulate, however, that a design based on the AASHTO values may carry an unnecessarily high safety factor and that more research work leading to a possible reduction of these values should be carried out. It is contended, though, that automobiles driven in

TABLE 12 COMPARISON OF STUDY FINDINGS WITH AASHTO VALUES

S_1 Speed Group (mph)	$\bar{S}_2$ Average Passing Speed (mph)	Variable	85th Percentile	AASHTO
37.5	57.8	Initial maneuver distance (ft)	151	290
		Initial maneuver time (sec)	2.15	4.3
		Initial acceleration[a] (mph/sec)	1.64	1.47
		Distance in opposing lane (ft)	690	825
		Time in opposing lane (sec)	8.42	10.7
		Speed difference[a] (mph)	18.7	10
43.8	61.2	Initial maneuver distance (ft)	170	370
		Initial maneuver time (sec)	1.94	4.5
		Initial acceleration[a] (mph/sec)	1.73	1.50
		Distance in opposing lane (ft)	853	1,030
		Time in opposing lane (sec)	10.44	11.3
		Speed difference (mph)	16.0	10

NOTE: 1 mph = 1.6 km/hr; 1 mph/sec = 0.447 m/sec^2.

[a] The acceleration values are 15th percentiles. The speed difference is the average.

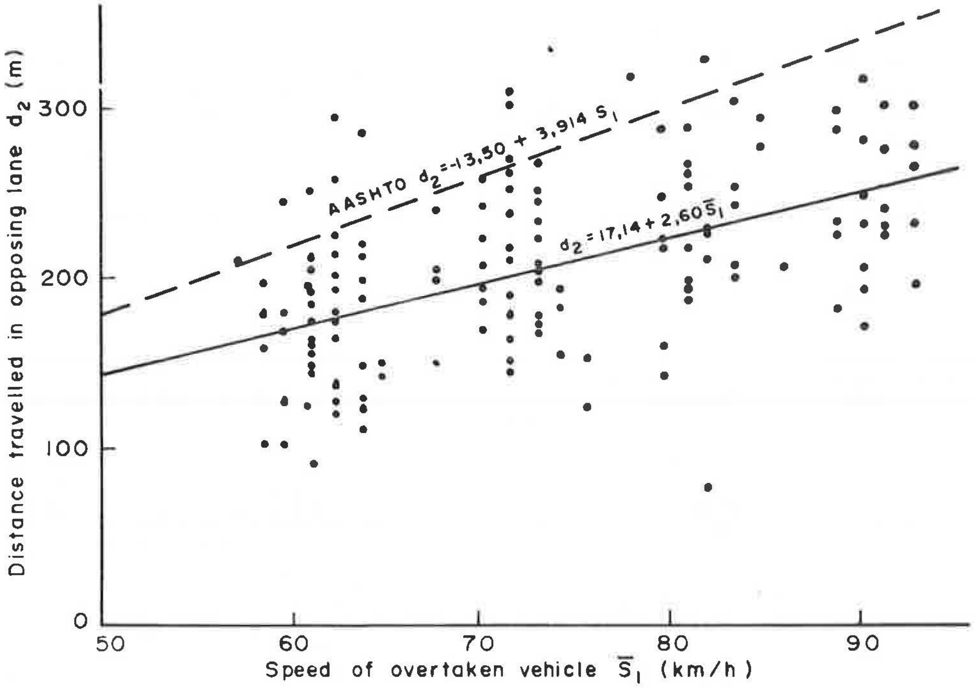

FIGURE 3 Distance traveled in opposing lane as a function of S_1.

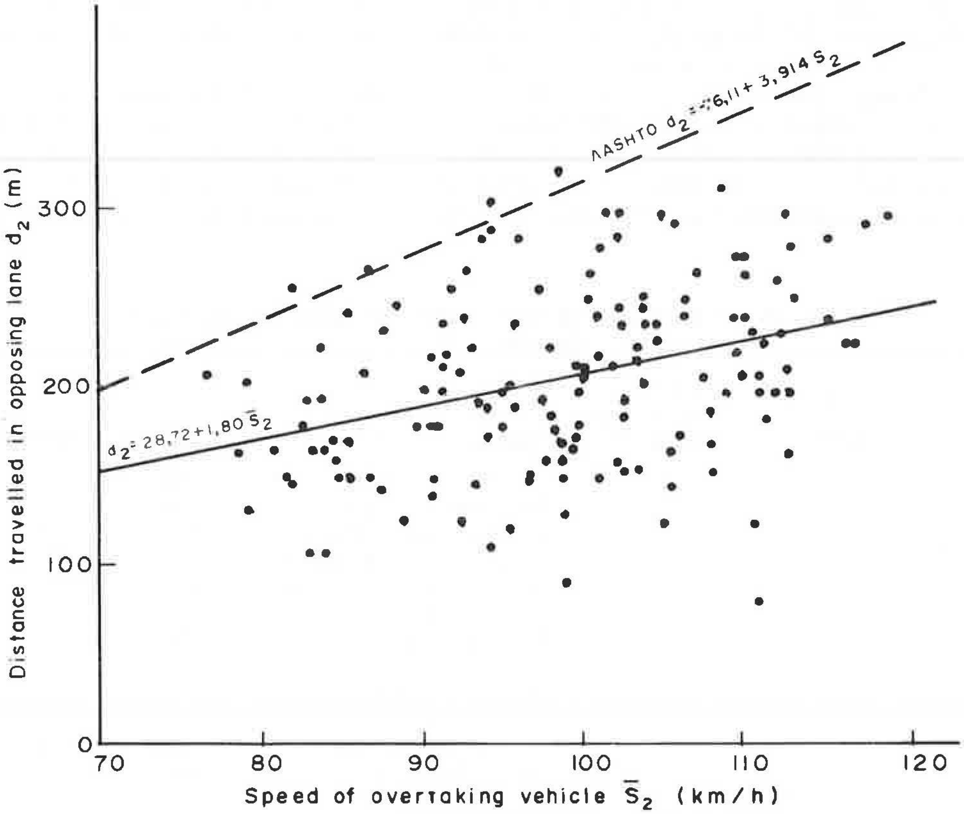

FIGURE 4 Distance traveled in opposing lane as a function of S_2.

South Africa, where the observations were made, are somewhat smaller than those in the United States. The present trend in the United States is, however, toward smaller passenger cars.

CONCLUSIONS

A study of the passing maneuver was conducted on two-lane rural highways. The data were collected by two passenger cars instrumented with coordinated (on a time and distance basis) Traffic Engineering Loggers. The overtaken vehicle was driven at a constant speed in one of four speed groups. The observations were made for accelerative and flying maneuvers. Two phases of the passing maneuver were studied: (a) the initial maneuver; that is, from the perception–reaction time until encroachment onto the opposing lane [average distance was 151 ft (46 m), the 85th percentile was 222 ft (68 m), and average time was 1.74 sec, the 85th percentile was 2.59 sec]; and (b) travel of overtaking vehicle in the opposing lane [average distance was 735 ft (224 m), the 85th percentile was 963 ft (294 m), and average time was 8.00 sec, the 85th percentile was 10.14 sec]. Other variables recorded were (a) space and time gap between the overtaking and overtaken vehicles at the moment of encroachment onto the opposing lane, (b) space and time gap between the vehicles on completion of the maneuver, (c) speed difference between the overtaking and overtaken vehicles, and (d) initial acceleration of the overtaking vehicle.

The findings indicate that the values given by AASHTO *(18)* may be somewhat conservative. It is the opinion of the authors that the passing maneuver should be studied more extensively, with the intention of reviewing current road-design guidelines.

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