TTI-2-18-81-292-2

TEXAS
TRANSPORTATION
INSTITUTE

STATE DEPARTMENT
OF HIGHWAYS AND
PUBLIC TRANSPORTATION

COOPERATIVE
RESEARCH

CONTROLLING SPEEDS IN HIGHWAY WORK ZONES

in cooperation with the
Department of Transportation
Federal Highway Administration

RESEARCH REPORT 292-2
STUDY 2-18-81-292
TRAFFIC AT WORK ZONES

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-84/58+292-2		

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code / 8. Performing Organization Report No.
Controlling Speeds in Highway Work Zones	5. Report Date: February 1984 6. Performing Organization Code: 8. Performing Organization Report No.: Research Report 292-2
7. Author(s): S. H. Richards, R. C. Wunderlich, and C. L. Dudek	
9. Performing Organization Name and Address: Texas Transportation Institute Texas A&M University College Station, TX 77843	10. Work Unit No. (TRAIS): 11. Contract or Grant No.: Study No. 2-18-81-292
12. Sponsoring Agency Name and Address: Texas State Department of Highways and Public Transportation; Transportation Planning Division P.O. Box 5051 Austin, TX 78763	13. Type of Report and Period Covered: Interim Report (Sept. 1981-Feb. 1984) 14. Sponsoring Agency Code:

15. Supplementary Notes

Research performed in cooperation with DOT, FHWA
Study Title: Handling Traffic in Work Zones

16. Abstract

The objective of the research was to determine or develop effective methods of slowing traffic to an acceptable speed in work zones. Factors considered in the study included cost, motorist and worker safety, institutional constraints, and probability of success in obtaining the desired speed.

Field studies were conducted to evaluate the short-term effects of several candidate treatments of four methods of speed control: 1) flagging, 2) law enforcement, 3) changeable message signs, and 4) lane width reduction. Studies were conducted on 2-lane, 2-way rural highways. Results from studies sponsored by the Federal Highway Administration on an undivided multilane urban arterial, an urban freeway, and two rural freeways were incorporated into the report.

The results indicated that flagging and law enforcement were very effective methods of speed control in work zones. An innovative flagging approach, MUTCD flagging, police traffic controller, and stationary patrol car were found to be very effective treatments on most highway types. A circulating patrol car was found to be an ineffective approach. The results are inconclusive with respect to changeable message signs since they were not studied at the 2-lane, 2-way highway sites where the largest speed reductions were generally observed for the other methods.

Implementation of work zone speed control measures are also discussed.

17. Key Words	18. Distribution Statement
Speed Control, Highway Work Zone Maintenance, Construction, Law Enforcement, Changeable Message Signs, Flagging, Rumble Strips, Transverse Striping, Narrow Lanes	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	99	

ACKNOWLEDGEMENTS

The authors wish to thank Blair Marsden and Lewis Rhodes (D-18T, SDHPT) for their constructive comments and suggestions during the course of the research documented herein. The research direction was guided by a Technical Advisory Committee. The contributions of this Committee, whose members are listed below, are gratefully acknowledged:

Benjamin W. Bohuslav, Supervising Maintenance Engineer, District 13
Walter Collier, District Maintenance Engineer, District 15
Billie E. Davis, District Maintenance Engineer, District 2
Milton Dietert, Assistant Chief Engineer of Safety and Maintenance Operations, D-18
Herman Gadeke, District Traffic Engineer, District 15
Hunter Garrison, District Maintenance Engineer, District 12
Henry Grann, Supervisory Traffic Engineer, District 18
Herman Haenel, Supervisory Traffic Engineer, D-18T
Bobby Hodge, Supervisory Traffic Engineer, District 2
Steve Levine, Traffic Management Supervisor, District 12
Blair Marsden, Traffic Engineer, D-18T
Silas M. Prince, District Maintenance Engineer, District 11
Lewis Rhodes, Traffic Engineer, D-18T
Russell G. Taylor, Engineering Technician V, District 14
Milton Watkins, District Maintenance Engineer, District 18
John Wilder, District Maintenance Engineer, District 14

EXECUTIVE SUMMARY

Excessive speeds in highway construction and maintenance work zones can adversely affect the safety of the work crew and motorists. Unfortunately, motorists do not always slow down to posted speed limits in work zones.

The objective of the research reported herein was to determine or develop effective methods of slowing traffic to acceptable speeds in work zones. In addition to their effectiveness in reducing speeds, other factors such as cost, motorist and worker safety, and institutional constraints were also considered.

Candidate speed control methods for work zones were identified through a literature search and recommendations from the Study 292 Technical Advisory Committee.

Following a limited number of proving ground studies, plans were made to conduct field studies at work sites on two 2-lane, 2-way highways to evaluate the short-term effects of four methods of speed control: flagging, law enforcement, changeable message signs, and effective lane width reduction. Unfortunately, changeable message signs were not available and could not be evaluated at the 2-lane highway sites.

A companion research project, sponsored by FHWA, evaluated flagging, law enforcement, changeable message signs, and effective lane width reduction on three types of highways: 1) undivided multilane arterial, 2) rural freeway, and 3) urban freeway. The results of this research were incorporated into Research Report 292-2.

Several variations (treatments) of the four speed control methods were tested. The speed control methods and treatments studied included:

1. Flagging
   a. MUTCD Flagging
   b. Innovative Flagging (one side)
   c. Innovative Flagging (both sides)
2. Law Enforcement
   a. Stationary Patrol Car
   b. Police Traffic Controller
   c. Circulating Patrol Car
   d. Stationary Patrol Car - Lights On
   e. Stationary Patrol Car - Radar On
3. Changeable Message Sign
   a. CMS - Speed Messages Only
   b. CMS - Speed and Informational Message
   c. CMS - Speed and Informational (Alternative Location)
4. Effective Lane Width Reduction
   a. Lane Width Reduction - 11.5 Feet with Cones
   b. Lane Width Reduction - 12.5 Feet with Cones

The results indicated that flagging and law enforcement were very effective methods of speed control. The best flagging treatment at each site reduced speeds an average of 19% and the best law enforcement treatment reduced speeds an average of 18%. In contrast, the best changeable message sign and effective lane width reduction (with cones) treatments evaluated reduced speeds by only 7% each. However, because they were not available, changeable message signs were not studied at the 2-lane, 2-way rural highway sites where the greatest speed reductions were observed for the other methods. It is quite likely that the performance of the changeable message signs, in terms of reductions in average speeds, would have improved had they been tested at the 2-lane, 2-way highway sites.

An innovative flagging approach (MUTCD alert and slow signal enhanced by special hand signals and eye contact with approaching motorists), MUTCD flagging, police traffic controller, and stationary patrol car were found to be very effective treatments on most highway types, whereas the circulating patrol was found to be an ineffective approach.

The innovative flagging treatment developed as part of this research resulted in larger average speed reductions than MUTCD flagging at 5 of the 6 study sites but the differences were small. For example, on one rural 2-lane, 2-way highway the innovative flagging treatment reduced the average speed by 16 mph (30%), while MUTCD flagging reduced the mean speed by 12 mph (23%). Although the differences were statistically significant, the differences were in the magnitude of only 2-4 mph.

The various flagging treatments studied produced the greatest average speed reductions at the 2-lane, 2-way rural highway sites (8-16 mph) and urban arterial sites (11-13 mph). They generally resulted in smaller average speed reductions at the freeway sites (3-7 mph), particularly the urban freeway site (3-4 mph). The results also indicated that flagging effectiveness may be improved on freeways by having a flagger on both sides of the travel lanes.

The police traffic controller reduced average speeds between 9-13 mph at the sites studied. The average speed reduction for a stationary patrol car ranged between 4-12 mph. The stationary patrol car with emergency lights or radar on performed only slightly better than without lights or radar. The circulating patrol car treatment was only tested on the 2-lane, 2-way highway sites and was found to be the least effective of all the law enforcement treatments studied, reducing mean speeds by only 2-3 mph.

Although the research did not specifically address the issue of when speed control should be implemented at a particular work zone, several important considerations were identified by the authors. One consideration is the harmful effect of speed control abuse and misuse at work zones. If unreasonably low speed limits are used or if reduced speed limits are left in place after the work activity is removed, the credibility of work zone speed reduction efforts in general is damaged. This concern and other issues are discussed in Chapter 5.

Also in Chapter 5, the authors recommend maximum speed reductions for work zones by type of highway, as follows:

Rural 2-Lane, 2-Way Highway	10-15 mph
Rural Freeway	5-15 mph
Urban Freeway	5-10 mph
Urban Arterial	10-20 mph

CONTENTS

1. INTRODUCTION

Background

The issue of speed control through highway work zones has been a topic of concern for several years (1, 2). Excessive work zone speeds can adversely affect the safety of the work crew and motorists. In an attempt to control work zone speeds, highway agencies have followed standard signing practices, but drivers do not always slow down in response to posted speed limits.

Besides signing, other methods (e.g., changeable message signs (CMSs), flagging, rumble strips, transverse striping, lane width reductions (funneling) and law enforcement) have been used in an effort to reduce speeds through work areas to the desired level. Some of these methods have been successful in reducing speeds and others have been ineffective. The question addressed in this study was: when required, how can speeds through highway work zones be reduced?

Objective and Scope

The objective of the research was to determine or develop effective methods of slowing traffic to an acceptable speed in work zones. Factors considered in the study included cost, motorist and worker safety, institutional constraints, and likelihood of success in obtaining the desired speed.

Research Approach

Through an extensive literature search, a set of candidate speed control methods for work zones was identified. The candidate approaches were reviewed, critiqued, and refined by the Study 292 Technical Advisory Committee (TAC). Proving ground studies were then conducted to screen some of the candidates.

Based on the results of the proving ground studies, literature review and TAC input, four basic approaches of speed control were selected for field evaluation on 2-lane, 2-way highways in this research effort:

1. Flagging
2. Law Enforcement
3. Changeable Message Signs
4. Lane Width Reduction (Funneling)

Conventional speed signing was also selected for evaluation as the base condition.

Attempts to locate CMSs for evaluation at the 2-lane highway work sites were unsuccessful. Therefore, CMSs could not be evaluated at 2-lane highway sites. In addition, initial plans to include rumble strips as one of the alternative speed control methods were deleted because of the poor results obtained at the first 2-lane highway site and the problems experienced while installing rumble strips at the second site.

Field studies were also conducted as part of a companion research effort (3) sponsored by the Federal Highway Administration (FHWA) in which several of the speed control methods and variations within the methods were tested on an undivided multilane arterial, two rural freeways, and an urban freeway.

2. CANDIDATE SPEED CONTROL METHODS

Literature Review

A review of work zone and speed control literature was conducted to identify and evaluate candidate speed control methods applicable to work zones. A secondary purpose of the literature review was to determine the extent and nature of the work zone speed problem. Identification of pertinent literature was aided by an HRIS file search.

The available literature revealed that there are two schools of thought regarding work zone speed control (1). One group contends that work zone speeds should be similar to normal speeds (i.e., before work began) in order to minimize speed differentials and thus accident potential. The other group argues that, since work zones generally contain many hazardous elements, it is desirable to reduce traffic speeds in the interest of safety. Although these two philosophies appear to contradict one another, in practice they do not. In fact, the philosophies may be merged to establish a basic approach to work zone speed control.

> **Every effort should be made to design work zones to safely accommodate traffic at normal speeds. When it is impossible or impractical to accomplish this goal, safe, effective and economical means should be used to reduce speeds to the appropriate level.**

Several studies have concluded that work zone speed control is a critical problem. Based on a review of rural work zone accidents in Ohio, Nemeth and Migletz (4) found that excessive speed was cited 5 1/2 times more frequently than any other accident-producing factor. Richards and Faulkner (5) observed that speed violations contributed to 27 percent of the work zone accidents in Texas compared to 15 percent of non-work zone accidents. Humphreys et. al. (2) visited 103 work zones in several states and concluded that unsafe speeds within work zones and ineffective attempts at speed reduction are primary causes of work zone accidents.

Numerous speed control approaches have been considered and/or evaluated for work zones in the United States and abroad:

1. Regulatory and Advisory Signing - SDHPT guidelines for posting regulatory and advisory speed signs at work zones are set forth in the Department's "Procedures for Establishing Speed Zones-1976." However, previous studies indicate that conventional speed signing generally has no effect on work zone speeds, but may increase work zone conflicts (1,6). Drivers respond to perceived work zone conditions regardless of any posted speed limits, and they may not reduce their speeds if there is no perceived danger. Furthermore, there is no evidence that reduced speed zoning at work zones reduces accidents (1).

2. Changeable Message Signs - Studies conducted by Hanscomb (7) and Webb (8) found that CMSs, used for advance warning at lane closure work zones, reduced average traffic speeds up to 7 mph. Changeable message signs have generally been ineffective as a speed control device in non-work zone applications (9,10).

3. Traffic Activated Signing - This approach has had mixed success in reducing speeds at small towns, built-up areas, curves and school zones (11,12).

4. Flashing Lights - Flashing lights used to supplement static signing have failed to reduce work zone speeds (1). Some agencies are using flashing overhead signals to warn of particular hazards at work zones (e.g., in advance of a detour). The effects of these installations on speeds are undocumented.

5. Traffic Signals and Stop Signs - These traffic control devices will reduce speeds over a short section (13), but have very limited work zone applications.

6. Iowa Weave Section - Brewer (14) reported modest speed reductions, without adverse effects on safety, using this strategy at a freeway lane closure work zone.

7. Colored or Textured Pavements - Both of these approaches have proven ineffective in reducing speeds on intersection approaches and at sharp curves (15). There is no documentation of their use at work zones.

8. Flagging and Pacing - These approaches are cited in several publications, however their performance was not documented.

9. Speed Bumps and Humps - Speed bumps, except at very low speeds, may cause loss of control, damage to the undercarriage of vehicles and excessive noise (16). They are generally restricted to parking lots. Speed humps, on the other hand, have been used successfully to reduce speeds and accidents on low speed streets (17,18). Their impact on safety is questionable above 30 mph.

10. Rumble Strips - Numerous studies have been conducted in the United States, Great Britain and Sweden with inconsistent results. A British study (19) found that rumble strips reduced accidents, but not necessarily speeds. Rumble strips at the Dartfort Tunnel in Berkshire, England (20) and in a Swedish study (21) reduced speeds. A Michigan study (22) concluded that rumble strips were effective when strip spacing was gradually decreased based on a deceleration rated of 3 feet/sec./sec.

11. Transverse Striping - Studies conducted in Maine (23), Ohio (24), Kentucky (25) and Great Britain (26) indicated that transverse striping can reduce speeds, and in some cases, accidents at curves, intersections and approaches to towns. A British study (26) suggests that marking effectiveness may decrease with time and may be influenced by an unfavorable previous exposure. Agent (25) concluded that transverse markings should be implemented over long sections (e.g., 1200 feet) to promote their effectiveness.

12. Lane Width Reductions - This approach, also called "funneling," has produced mixed results. At a freeway construction zone in Texas, Richards et. al. (6) found that lane narrowing to a 10-foot width reduced speeds 10 mph without adverse safety effects. A Swedish study (28) found that funneling traffic into 10-foot lanes reduced work zone speeds significantly. On the other hand, Graham et. al. (1) reported higher accident rates at work zones with reduced lane widths.

    Funneling can be accomplished even though the actual lane width is not reduced. Placement of cones or barrels at the lane lines may not necessarily physically reduce the lane width, but they do produce funnels which effectively reduce the lane width.

13. Law Enforcement - Studies (11,29) have concluded that enforcement reduces speeds by 10-15 percent depending on the strategy employed. The most effective strategies are those which are highly visible and connote the most obvious threat (e.g., stationary patrol car with lights and/or radar on). Enforcement may also reduce speed variance (30). Enforcement normally suppresses speeds for several miles upstream and downstream, and it may have "carryover" effects, suppressing speed after it is removed (31).

Technical Advisory Committee

The Study 292 Technical Advisory Committee (TAC) provided input into the development and refinement of work zone speed control approaches. Committee members contributed to the research effort by reviewing candidate speed control approaches and providing opinions on feasibility, practicality, limitations and preference. The TAC also assisted in locating appropriate field study sites and making the necessary study arrangements.

The TAC met following completion of the literature review. After identifying and discussing a wide range of speed control approaches, the Committee developed a list of nine candidate approaches for consideration. Table 1 presents the TAC's list of candidates along with a brief description of each approach.

TABLE 1. TAC CANDIDATE SPEED CONTROL METHODS

Method	Description	Comments[a]
Changeable Message Signs	Changeable message signs are installed in the work zone to display speed advisories based on real-time conditions.	Variable message speed signing has not been very effective in non-work zone situations (9, 10) and only minimally effective at work zones (7, 8).
Overhead Flashing Signals	Flashing yellow lights are suspended over the travel lanes on span wire with or without accompanying signing to warn of a hazardous condition.	This approach is relatively untested. It would seem to have certain practical limitations (e.g., long-term, point hazards).
Iowa Weave Section	Drivers are forced to negotiate a reverse curve created by cones upstream of the hazard area.	This approach will reduce speeds moderately without adverse effects on safety (14). It is complicated and costly to set up and maintain.
Flagging	A flagger, equipped with a paddle or flag, signals traffic to slow.	No data available on effectiveness. Some signals are not understood by drivers (32).
Pacing	A special pace vehicle leads a line of vehicles through the work area at a reduced speed.	This approach is effective, but expensive. Motorist delay may be excessive.
Rumble Strips	A series of raised strips are installed upstream of the hazard area.	This approach can be effective (22) but may present safety hazards to motorcyclists.
Transverse Striping	A series of colored markings (usually white) are installed on the pavement upstream of the hazard area.	A U.S. study suggests that this approach is ineffective (1). Other studies contradict this finding, however (23, 24, 25, 26).
Effective Lane Width Reduction ("Funneling")	Lane width is effectively narrowed to create a "funneling" effect.	This approach can reduce speeds (6) but may result in accidents and reduced capacity (1).
Law Enforcement	Law officers are deployed at the work zone. They may issue citations to speeders.	This approach is effective (21, 29, 30, 31), but requires police agency cooperation.

[a]Comments based on literature review and TAC input.

Proving Ground Studies

The literature review and TAC identified several candidate speed control approaches for work zones and eliminated others from consideration. At this point, a series of proving ground studies was planned to further evaluate and refine some of the approaches. It was hoped that the proving ground studies would determine which treatments within the various approaches were not appropriate for further field testing. Evaluating driver performance in a proving ground setting is not a substitute for real-world testing. It is difficult to translate drivers' performance at a proving ground to behavior on a highway. However, proving ground studies provide an effective way to further screen candidate control measures. They can, for example, indicate a "worst case" treatment which should not be tested in the field.

The proving ground studies evaluated 3 candidate speed control approaches: effective lane width reduction, transverse striping and rumble strips. For each of these approaches, 3 treatments were tested as described below:

1. Effective Lane Width Reduction -- The test track travel lanes were reduced in width from 12 feet to 9 feet using each of the following traffic control devices:

   - temporary pavement markings,
   - 28-inch traffic cones, and
   - 55 gallon drums (barrels)

2. Transverse Striping -- A series of 1-foot wide, white stripes were installed on the test track in three patterns as follows:

   - perpendicular to the travel direction and spanning the full width of the roadway,
   - perpendicular to the travel direction and spanning only to the shoulders, and
   - herringbone pattern across the full width of the roadway.

3. Rumble Strips -- A series of raised vinyl strips were placed in the wheel paths on the test track in the following patterns:

   - individual strips with the spacing between strips decreasing in the direction of travel
   - 3 clusters of 6 strips each with a 200-foot spacing between clusters, and
   - 3 clusters of 6 strips each with decreasing spacings between clusters.

Appendix A describes the studies in detail and presents the study results. Generally speaking the results were inconclusive and indicated that the simulated work zone setting had inherent limitations in assessing driver response to speed control measures. None of the treatments evaluated significantly affected driver speeds under the study conditions. Subjectively, drivers felt that certain of the treatments were more effective, but they also rated these treatments as the most hazardous.

Speed Control Methods

The proving ground studies left many questions unanswered. A decision was made, however, to abandon further proving ground work in favor of expanded (or comprehensive) field studies. The field studies were "expanded" beyond their original scope in that several different treatments of each speed control approach were evaluated in an effort to identify and refine the more effective treatments.

In selecting speed control approaches for field testing, the results of the literature review and proving ground studies, as well as TAC input, were considered. From the TAC's listing of candidate speed control methods (see Table 1), the following 5 approaches were selected: flagging, law enforcement, CMSs, effective lane width reduction, and rumble strips. In addition, conventional speed signing was studied as a base condition.

The remaining approaches cited by the TAC were not studied as a part of this research for the reasons noted:

1. Overhead Flashing Signals - This approach is limited to long-term, point hazards and would be too expensive to evaluate fully within the scope of this study.

2. Iowa Weave Section - Since there were sufficient data on this approach (14), it was omitted.

3. Pacing - The effects of this approach are very predictable without field validation. Also, this approach has very limited application because it is expensive, greatly reduces work zone capacity, requires traffic stoppage, can cause excessive motorist delays, and increases accident potential.

4. Transverse Striping - Since there were sufficient data on this approach (23-26), it was omitted.

3. FIELD STUDIES

Purpose and Scope

A series of comprehensive field studies was conducted to:

1. determine the relative and absolute effectiveness of selected speed control methods in reducing speeds at work zones on different types of highways,

2. gather information on the cost, institutional limitations and operational and safety performance of the selected speed control methods, and

3. evaluate specific speed contol treatments within the selected methods.

The studies evaluated the short-term (or immediate) effects of the selected speed control methods. It was not practical within the scope of the research to leave speed control treatments in place for extended time periods so that long-term effects could be studied. However, some of the considerations for long-term use were identified and are discussed in Chapter 5.

Study Sites

Field studies were conducted at 2 work zone sites in Texas on 2-lane, 2-way highways. In addition, companion studies were conducted at 4 work zones on 3 types of highways as part of an FHWA research project (3): undivided multilane arterial (1 site), rural freeway (2 sites), and urban freeway (1 site). Based on the results from the 2-lane highway studies, FHWA elected to omit rumble strips from further consideration. Since the FHWA studies directly complement the research, the results of these highway studies have been incorporated into this report where appropriate.

Table 2 identifies the study sites by highway and location and also summarizes prevailing site conditions including type of work activity, location of work, traffic control strategy, traffic volumes, percent trucks, and posted and prevailing speeds. The table includes information on the arterial and freeway sites for reference. Construction or major maintenance work was in progress at all of the sites during the studies.

Figures 10 through 15 in Appendix B present site layouts for each of the 6 study sites. The layouts illustrate the roadway configuration and work zone signing at each site.

TABLE 2. SITE SUMMARY

SITE NO.	LOCATION	TYPE OF ROADWAY	WORK ACTIVITY	LOCATION OF WORK ACTIVITY	TRAFFIC CONTROL STRATEGY	DIRECTIONAL TRAFFIC VOLUME, VPH AVERAGE (RANGE)	% TRUCKS	MEAN APPROACH SPEED, MPH	POSTED SPEED MPH[a]
1	FM 1960 Near Houston[b]	Urban 4-Lane Undivided Arterial With Continuous Left Turn Lane	Construction of Overhead Structure	Within Normal Travel Lanes	Detour	800 (650-950)	15	54	35 (R)
2	IH-35 Near Kyle[b]	Rural 4-Lane Freeway	Pavement Overlay	Left Travel Lane	Left Lane Closure	1150 (850-1450)	10	60	45 (A)
3	IH-35 Near Selma[b]	Rural 4-Lane Freeway	Interchange Reconstruction	Off Roadway Both Sides	Normal Travel Lanes Open	1000 (850-1050)	10	56	45 (R)
4	IH-10 in Houston[b]	Urban 6-Lane Freeway	Major Reconstruction	Within Normal Travel Lanes	Detour	1550 (1300-1750)	20	60	40 (R)
5	FM 2818 Near Bryan	Rural Two-Lane Highway	Widening to 4 Lanes	Off-Roadway Adjacent to Opposing Lane	Shoulder Use, Physical Separation from Work Activity	300 (150-450)	12	52	40 (A)
6	SH 105 Near Navasota	Rural Two-Lane Highway	Widening to 4 Lanes	Off-Roadway Adjacent to Travel Lane	Physical Separation from Work Activity	125 (100-150)	5-10	56	45 (R)

[a]Advisory Speed Limit - (A).
Regulatory Speed Limit - (R).

[b]Source Reference 3.

Speed Control Methods

As discussed in the previous chapter, 5 speed control methods were selected for field testing on the 2-lane, 2-way highways: flagging, law enforcement, CMSs, effective lane width reduction, and rumble strips. Conventional speed signing (regulatory or advisory) was also evaluated as a base condition at all sites. Rumble strips were not evaluated in the FHWA studies.

Study Design and Treatments

The study approach was an incomplete factorial design in which several different treatments within each speed control approach were tested, but all treatments were not tested at every site. Table 3 identifies and describes the treatments evaluated for each speed control approach.

Detailed descriptions of the treatments and how they were implemented are presented in Appendix C. It should be noted that the various treatments were installed in one direction of travel only. In addition, all of the treatments were supplemented by an advisory or regulatory speed sign displaying the desired work zone speed. The signing was included at the request of the highway agency for liability protection. In addition to its legal function, the signing served a critical role in supporting and enhancing the intended speed message of the various treatments. The highway agency established the posted (desired) work zone speed at the sites. Table 4 presents a summary of the treatment studied by site.

Study Procedure

To perform the studies, a treatment was installed, the necessary data were collected and then the treatment was removed. Once the treatment was completely removed and traffic returned to normal, another treatment was installed and the procedure was repeated. Treatments were installed in one travel direction only. Allowing time for data collection, each treatment was in place for 1-2 hours. Generally, 2 or 3 treatments, plus a base condition, were evaluated per day at a site. Thus, the studies took 3-4 days to complete at each site. Studies were conducted only during daylight, off-peak periods when traffic was free-flowing.

Data Collection

Treatment effects on speeds were determined by evaluating speeds at 3 points within the work zone study sites. The locations of the spot speed stations at each site are shown on the site layouts. (Figures 10 through 15 in Appendix B.) The first spot speed station at each site was located upstream and out of sight of any work zone signing or activity. The second station was immediately downstream of where the speed control treatments were implemented. This station measured initial response to the treatments. The

TABLE 3. SPEED CONTROL TREATMENTS EVALUATED

Speed Control Method	Treatment	Description
Flagging	MUTCD Procedure	Flagger equipped with red flag and orange vest, performed "Alert and Slow" signal detailed in Part VI, MUTCD.
	Innovative Procedure	MUTCD "Alert and Slow" signal enhanced by 2 additional movements: 1) Flagger motioned traffic to slow with free hand, then 2) pointed with with free hand to nearby speed sign.
Law Enforcement	Stationary Patrol Car--Lights and Radar Off	Marked patrol car parked on side of road parallel to traffic.
	Stationary Patrol Car--Lights On, Radar Off	Marked patrol car parked on side of road parallel to traffic with flashing red and blue lights on.
	Stationary Patrol Car--Lights Off, Radar On	Marked patrol car parked on side of road perpendicular to traffic with radar on and pointed toward traffic stream.
	Circulating Patrol Car[a]	Marked patrol car continuously driven back and forth through work zone without lights or radar on.
	Police Traffic Controller	Uniformed officer standing on side of road next to speed sign and manually motioning traffic to slow down.
CMS	Speed and Informational Message	1- or 3-line bulb matrix sign displaying work zone information tion message plus a speed advisory.
	Speed Message Only	1- or 3-line bulb matrix sign displaying speed advisory.
Effective Lane Width Reduction	Cones (12.5 feet)	1) On 2-lane highways, cones deployed to funnel traffic through a 12.5' wide travel path. 2) On multilane highways, cones positioned along the pavement edges leaving a 12.5 foot travel path between the cones and lane lines.
	Cones (11.5 feet)	Same as above except the travel path width decreased to 11.5 feet.
Conventional Signing	Regulatory Signing	Black-on-white regulatory speed sign with the desired work zone speed.
	Advisory Signing	Black-on-orange advisory speed sign with the desired work zone speed.
Rumble Strips[a]	8 Strips--Decreasing Spacing	Eight 1/2-inch high, polycarbonate strips installed across the travel lane in decreasing spacing, perpendicular to the travel direction.

[a]Tested only on 2-lane highways.

TABLE 4. SUMMARY OF TREATMENTS STUDIED BY SITE

Treatment	Urban Arterial	Rural Freeway		Urban Freeway	Rural 2-Lane, 2-Way Highway	
	Site 1 FM 1960	Site 2 IH-35 Kyle	Site 3 I-35 Selma	Site 4 I-10	Site 5 FM 2818	Site 6 SH 105
MUTCD Flagging	X	X (L)[a]	X	X	X	X
Innovative Flagging	X		X	X	X	X
Innovative Flagging Both Sides		X		X		
Stationary Patrol Car	X	X (L)	X[b]	X	X	X
Police Traffic Controller	X				X	X
Circulating Patrol Car					X	X
Stationary Patrol-Lights On				X		
Stationary Patrol-Radar On				X		
CMS-Speed-Only Message	X	X (L)		X		
CMS-Speed & Informational Message	X	X (L)		X		
CMS-Speed & Advisory-Alternate Location				X		
Effective Lane Width Reduction - 11.5'	X	X	X	X	X	X
Effective Lane Width Reduction - 12.5'	X	X	X	X	X	X
No Signing	X		X	X	X	X
Advisory Speed Signing		X				X
Regulatory Speed Signing	X		X	X	X	X
Rumble Strips					X	X[c]

[a]All treatments were implemented on the right unless noted by (L) indicating left implementation.

[b]Both left and right side treatments were studied.

[c]Rumble strips would not adhere to the pavement; thus no data were collected.

third and final station was positioned farther downstream of the treatment location to determine if the treatments suppressed speeds beyond the point of treatment.

For each treatment, 125-vehicle speed samples were collected simultaneously at the 3 spot speed stations. Only vehicles traveling in the treatment direction were included. Every effort was made to sample unbiasedly and randomly from the total directional flow. The number of trucks sampled was proportional to the total trucks in the directional traffic stream. Also, the number of vehicles sampled from each lane was proportional to the lane volume.

Speeds were determined by measuring vehicle travel times through a marked distance on the roadway (i.e., "trap" section). A 200-foot "trap" length was used at all sites except Site 5 where a 176-foot length was used (3). Travel times were manually measured and recorded using digital, electronic stopwatches. The data collectors were positioned off the road 50-100 feet from the travel lanes. Every effort was made to conceal the data collectors from view wherever possible. The data collection method allowed individual vehicle speeds to be collected to within ±2 mph.

In addition to the travel time/speed data, hourly traffic volumes, by vehicle type, were collected during the studies at each site. These volume data were used to estimate percent trucks and lane distribution, and also to account for any volume effects on speeds. The field crew observed traffic operations and flow, noting any instances of driver confusion, erratic maneuvers, or accidents. Agency and enforcement personnel were interviewed to obtain input on treatment practicality, preference and institutional limitations.

Data Reduction and Analysis

The travel time data, classified by treatment type, spot speed station and site, were stored in computer files. Individual travel times were then converted to speeds. Using the MEANS procedure of the Statistical Analysis System (SAS), mean speed and standard deviation statistics were calculated for each station, treatment and site combination. Speed profiles were developed from the mean speed results.

Treatments were evaluated based on their effectiveness in reducing speeds at Station 2. Relative comparisons among the speed control treatments were made by performing one-way analysis of variance (ANOVA) tests and Duncan's Multiple Range tests using the ANOVA procedure of SAS.

Cumulative Frequency distributions were also generated for selected treatments at each site. The best treatment within each general approach was plotted.

4. FIELD STUDY RESULTS

General Results

Figure 1 summarizes the performance of all the speed control treatments tested. The figure shows the reductions in mean speeds (in mph) and percentage speed reductions attained by each treatment on a site-by-site basis. The data in the figure are based on driver responses at Station 2 to the treatments and were generated by comparing mean speeds when a treatment was in place to mean speeds during the base condition. The posted speed at each site is also shown in the figure for reference.

Based on the data in Figure 1, analyses of the general influences of roadway type, site differences and posted speed were performed. The following sections present the findings.

Roadway Type

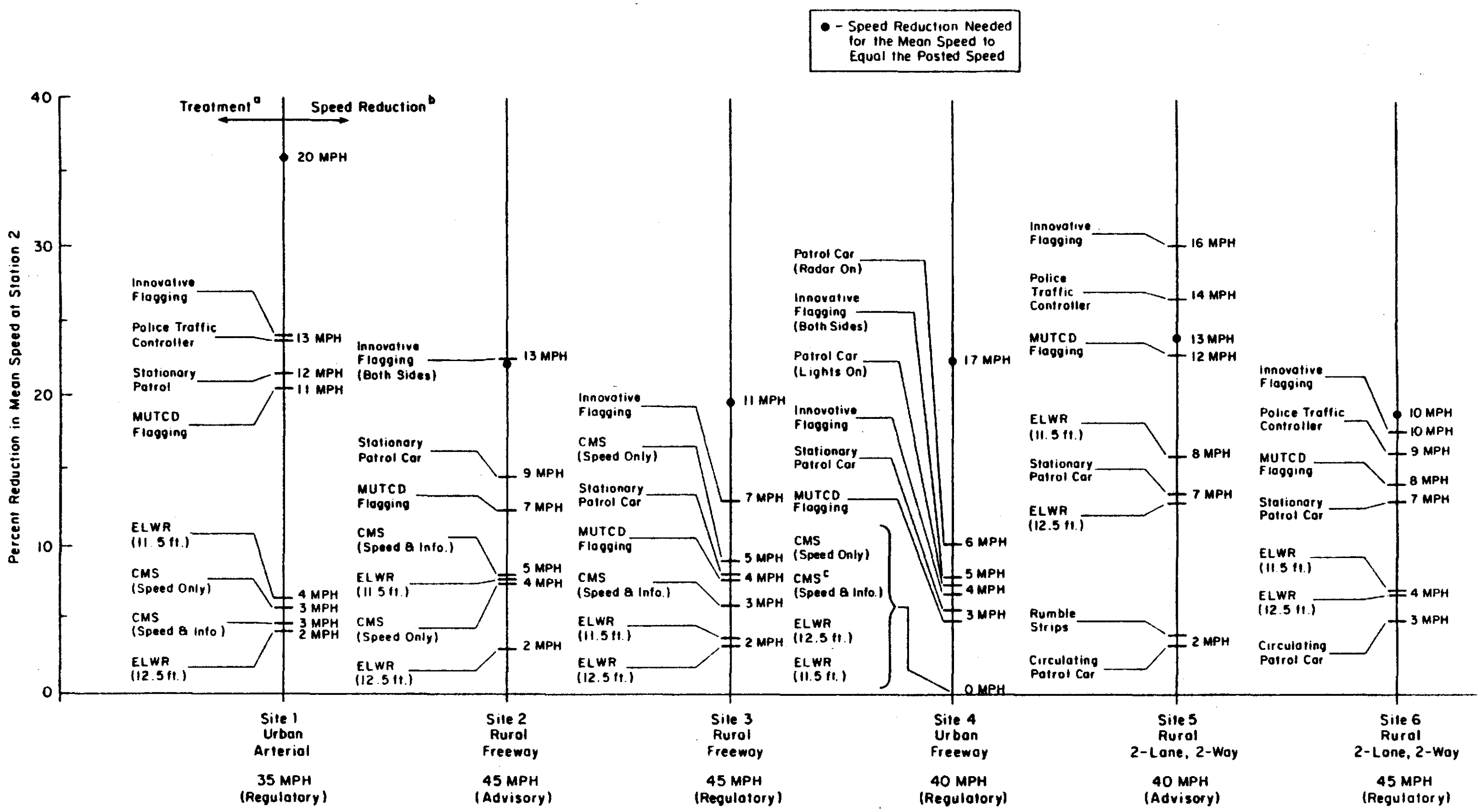
The small number of sites within each roadway category made it difficult to fully assess the influence of roadway type on speed control method and treatment performance. Figure 1, however, does support some basic trends related to roadway type observed during the studies. Generally, the speed control treatments were less effective in reducing speeds at the urban freeway site and more effective at the 2-lane, 2-way highway and urban arterial sites. From Figure 1, the best treatment at the urban freeway site (Site 4) only reduced the mean speed by 6 mph. However, at the 2-lane highway sites (Sites 5 and 6) and urban arterial site (Site 1), the best treatment reduced the mean speeds by 16 mph, 10 mph and 13 mph respectively.

The data, with respect to roadway type, were not consistent for the rural freeway sites (Sites 2 and 3). At Site 2, the best treatment reduced mean speed by 13 mph, but at Site 3, the best treatment reduced the mean speed by only 7 mph. One possible explanation for this result is that the work activity at Site 3 was less noticeable compared to Site 2.

Site Differences

It is very important to emphasize that some of the variation in method and treatment performance was due to individual site differences. However, since the work zones were generally complicated and diverse in character, it is difficult to evaluate what effects site differences had on the results. Nevertheless, Figure 1 provides some evidence of the apparent site effects.

Sites 5 and 6, for example, were both on 2-lane, 2-way rural highways. The type of work and traffic control strategy were the same at both sites. However, as shown in Figure 1, most of the speed control treatments performed significantly better at Site 5. It can only be speculated which site characteristics accounted for this better performance. Site 5 was nearer to an



[a] The base condition signing treatment and the "no speed signing" treatment are not shown. In addition, the various regulatory and advisory signing treatments tested at Site 5 are not included.

[b] Between the base condition mean speed and the treatment mean speed.

[c] When the CMS was relocated closer to the work area, the Speed and Information Message treatment reduced Station 2 speeds by 2 mph (3%).

Figure 1. Summary of Speed Control Treatments by Site

urban center, and it had more repeat drivers, more turning traffic, more trucks, and straighter alignment than Site 6.

Posted Speed

Figure 1 shows the regulatory or advisory speed limit at each study site. The speed limit was displayed and used as an "anchor" speed for all treatments tested at the site. As seen in the figure, the posted speed limit varied from site to site ranging from 35 to 45 mph. The highway agency selected the speed limit for each site based on its assessment of site conditions.

In Figure 1, it is seen that none of the treatments tested reduced mean speeds to the posted speed limit at Site 1 (urban arterial), Site 3 (rural freeway) or Site 4 (urban freeway). Apparently the posted speed limit at these sites was simply too low for drivers to accept under the prevailing site conditions. At the remaining sites, certain treatments did reduce mean speeds down to or below the posted speed limit.

Based on the limited data, it is difficult to determine if any of the posted speed limits affected treatment performance. At Site 6, however, the relatively high posted limit of 45 mph may have discouraged even better performance by some of the speed reduction treatments. Stated another way, the full potential of the speed control treatments may not have been achieved at Site 6 due to the relatively high posted speed of 45 mph.

Method Performance

Table 5 summarizes the relative effectiveness of the 4 speed control methods in reducing work zone speeds. For each speed control method, the table shows the range and average reduction in mean speeds observed across all sites due to the method. The data in the table are based on the drivers' immediate responses to the speed control methods (i.e., at Station 2), and on the best treatment within each method on a site-by-site basis.

As seen in the table, flagging was the most effective overall method. The best flagging treatment at each site, reduced speeds from 8 to 30% On the average, the best flagging treatments reduced speeds about 19%.

Law enforcement was generally very effective also. The best law enforcement treatments at each site reduced speeds from 8 to 26% and averaged 18% across all sites.

CMSs were not tested at the 2-lane, 2-way highway sites and thus caution should be exercised in comparing the overall performance of CMSs with the other methods. At the freeway and urban arterial sites, the best CMS treatments reduced speeds from 0 to 9%, and on the average, they reduced speeds 7%.

Effective lane width reduction using cones reduced speeds an average of 7%. The effectiveness of this method varied widely by site from no effect at one site up to a 16% speed reduction. It should be noted that more restrictive treatments than those tested would likely result in larger speed reductions. "More restrictive" refers to the use of narrower lanes and/or more formidable devices than cones (e.g., barrels or portable barriers).

The effects of the 4 speed control methods on speed sample variance were analyzed based on standard deviation statistics and cumulative distribution speed plots. The analyses revealed that none of the methods generally altered speed variance. However, certain individual speed control treatments did significantly effect speed sample variance at some sites. The effects of treatment and site on speed variance are discussed in detail in the following section.

TABLE 5. EFFECTIVENESS OF SPEED CONTROL METHODS[a]

Speed Control	Speed Reduction[b]			
	Amount		Percent	
	Range	Average	Range	Average
Flagging	3-16	11	(8-30)	(19)
Law Enforcement	3-14	9	(8-27)	(18)
Changeable Message Signs[c]	2- 5	3	(3- 9)	(7)
Effective Lane Width Reduction w/Cones	0- 8	3	(0-16)	(7)

[a]Based on best treatment within each speed control method on a site-by-site basis.

[b]Reduction in mean speed at Station 2 due to speed control method.

[c]No data were available for 2-lane, 2-way rural highways. The average speed reduction shown for CMSs may therefore be misleading (i.e., too low) because all the other speed control methods generally performed better at the 2-lane, 2-way highway sites.

Treatment Performance

Flagging Treatments

Table 6 summarizes the performance of the various flagging treatments in terms of the percent mean speed reduction. Performance of the flagging treatments in terms of mean speed and standard deviation is shown in Appendix D, Table 21. The data in the tables are based on drivers' responses to the treatments at Station 2. The percent reduction in mean speed was generated by comparing the mean speed when a treatment was in place to the mean speed during the base (i.e., signing only) condition.

Table 6 and Figure 1 show that the innovative flagging treatment resulted in larger speed reductions than MUTCD (33) flagging at 5 of the 6 study sites. (A direct comparison between the two flagging treatments could not be made at one of the rural freeway sites (Site 2) because field studies were conducted on different days.) For example, on one of the rural 2-lane, 2-way highways (Site 5) the innovative flagging treatment reduced the mean speed by 16 mph (30%) while MUTCD flagging reduced the mean speed by 12 mph (23%). It should be noted, however, that the difference between the innovative and MUTCD flagging treatments was small at some of the sites. On the urban freeway (Site 4), for example, innovative flagging reduced speeds by 4 mph (7%), and MUTCD flagging reduced speeds by 3 mph (5%).

Table 21 illustrates that there were statistically significant mean speed differences between innovative flagging and MUTCD flagging. The differences were only in the magnitude of about 2-4 mph, and thus they may or may not be significant from a traffic safety and operational standpoint. Nevertheless, the innovative flagging treatment did produce very favorable speed reduction results and allowed the flagger to direct a specific speed message to drivers. MUTCD flagging, on the other hand, displays a more general "alert and slow" message.

The data in the tables and Figure 1 reveal that the various flagging treatments produced the greatest speed reductions at the 2-lane, 2-way highway and urban arterial sites. They generally resulted in smaller speed reductions at the freeway sites, particularly the urban freeway site (Site 4). The results suggest that flagging may not be a solution for all situations where it is desirable to reduce speeds at work zones.

Tables 6 and Figure 1 do not clearly indicate if flagging effectiveness is improved on freeways by using flaggers on both sides of the travel lanes. At Site 2, innovative flagging on both sides reduced speeds by 13 mph (22%), while MUTCD flagging on one side reduced speeds by 7 mph (12%). These data suggest that using 2 flaggers may be beneficial, however, they do not allow a direct comparison between 1 flagger and 2 flaggers using the same flagging approach.

Law Enforcement Treatments

Figure 1, Table 7 and Table 22 in Appendix D summarize the performance of the various law enforcement treatments. As seen in the figure and tables, the police traffic controller treatment was very effective in slowing traffic at the 3 sites where it was tested. At the urban arterial site (Site 1), the treatment reduced mean speeds by 13 mph (26%) and at the 2-lane, 2-way highway sites (Sites 5 and 6), it reduced speeds by 14 and 9 mph (26 and 16%). A police traffic controller was not evaluated at any of the freeway sites because the participating police officers were reluctant to stand on the side

TABLE 6. PERFORMANCE OF FLAGGING TREATMENTS IN TERMS OF REDUCTION IN MEAN SPEED AT STATION 2

Flagging Treatment	Reduction in Mean Speed, Mph					
	Urban Arterial	Rural Freeway		Urban Freeway	Rural 2-Lane Highway	
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Innovative Flagging	13 (24)[a]	--[b]	7 (13)	4 (7)	16 (30)	10 (18)
Innovative Flagging-Both Sides	--	13 (22)	--	5 (8)	--	--
MUTCD Flagging	11 (20)	7 (12)	4 (8)	3 (5)	12 (23)	8 (14)

[a]Numbers in () indicate percent.

[b]Not available.

TABLE 7. PERFORMANCE OF LAW ENFORCEMENT TREATMENTS IN TERMS OF REDUCTION IN MEAN SPEED AT STATION 2

Law Enforcement Treatment	Reduction in Mean Speed, Mph					
	Urban Arterial	Rural Freeway		Urban Freeway	Rural 2-Lane Highway	
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Police Traffic Controller	13 (24)[a]	--[b]	--	--	14 (26)	9 (16)
Stationary Patrol Car	12 (22)	9 (15)[c]	5 (8)	3 (6)	7 (14)	7 (13)
Stationary Patrol Car with Lights on	--	--	--	4 (8)	--	--
Stationary Patrol Car with Radar on	--	--	--	6 (10)	--	--
Circulating Patrol Car	--	--	--	--	2 (3)	3 (5)

[a]Numbers in () indicate percent.

[b]Not available.

[c]Patrol car on left side of travel lanes.

of the road, away from their vehicles, in the freeway environment. The officers cited two reasons for their reluctance. Some were concerned about their personal safety, while others believed that the speed control effort would be unsuccessful and thus an unproductive use of their talent and expertise.

A stationary patrol car was tested at all 6 sites. This treatment effectively reduced speeds between 4 and 12 mph (6 and 22%). It was most successful at the urban arterial site (Site 1) and least effective at the urban freeway site (Site 4). At Site 4, a stationary patrol car was evaluated with its lights on and then with its radar in operation. Both of these treatments performed slightly better than a stationary patrol car without lights or radar. The stationary patrol car reduced mean speeds at Site 4 by 3 mph (6%). When the patrol car's overhead flashing lights were turned on, the mean speed reduction increased by 1 mph (8%) to 4 mph. When the officer turned on a hand-held radar gun and pointed it at passing motorists, the mean speed reduction increased to 6 mph (10%).

The circulating patrol car treatment was tested only on the 2-lane, 2-way highway sites (Sites 5 and 6). It proved to be the least effective of all the law enforcement treatments studied, reducing the mean speed by only 2 mph (3%) at Site 5 and 3 mph (5%) at Site 6. The circulating patrol car treatment was not evaluated at the other sites because of its relative poor performance on the 2-lane highway sites, and because it would likely be even less effective on divided, multilane roadways with limited access points.

The various law enforcement treatments did not have much effect on speed sample variance with one notable exception. The stationary patrol car without lights or radar generally reduced speed sample standard deviation by 1 to 2 mph.

CMS Treatments

The performance of the 2 CMS treatments are summarized in terms of percentage mean speed reductions, mean speed and standard deviation in Tables 8 and Table 23 in Appendix D. From the tables and Figure 1, it is apparent that, for a given site, both treatments had approximately the same effects on speeds. Depending on the site, the "Speed-Only Message" treatment reduced mean speeds ranging from 0 to 5 mph (0 to 9%), and the "Speed and Information Message" reduced speeds ranging from 0 to 5 mph (0 to 8%).

The CMS treatments were least effective in slowing drivers at the urban freeway site (Site 4). In fact, neither CMS treatment had any effect on speeds when the CMS was located in the usual treatment location (i.e., near the advance signing for the work zone). However, when the sign was relocated closer to the actual work area, the "Speed and Information Message" treatment reduced Station 2 speeds by 2 mph (3%).

Neither of the CMS treatments had a significant effect on speed sample variance (Table 23).

Effective Lane Width Reduction Treatments

Table 9 and Table 24 in Appendix D show the performance of the 2 effective lane width reduction treatments by site and roadway type. The data in the tables and Figure 1 indicate that the 2 treatments, for a given site, had approximately the same effect on speeds, with observed speed reductions ranging from 0 to 8 mph (0 to 16%) depending on the site. The 11.5-foot treatment resulted in slightly higher speed reductions at 3 of the 6 sites compared to the 12.5-foot treatment. However, the differences between treatments were not statistically or practically significant.

It is important to note that the highway agency would not allow cones to be placed on the lane lines at any of the multilane sites (i.e., Sites 1-4) in the interest of safety. Thus, effective lane narrowing at these sites was accomplished by placing cones on the edges of the travel lanes. This may explain why the treatments generally did not reduce speeds as much at the multilane sites compared to the 2-lane, 2-way highway sites. At the 2-lane highway sites, lane narrowing was accomplished by placing cones on the edge of the travel lane and on the centerline.

Another important finding of the study was that cones proved to be somewhat hazardous devices for effectively reducing lane widths below 12 feet. At the 11.5-foot width, cones were hit frequently, and on one occasion at a rural 2-lane, 2-way site (Site 5), were knocked into the travel lane causing erratic maneuvers and stoppage of traffic.

The effective lane width reduction treatments had some interesting effects on speed sample variance. At every site except Site 6, the 11.5-foot treatment resulted in a larger speed sample standard deviation than the 12.5-foot treatment (Table 24). At Site 6, the 2 treatments resulted in about the same standard deviation.

The studies also revealed that when a treatment was effective in slowing traffic at a site, it also produced a higher speed sample variance. For example, the 11.5-foot treatment produced an 8 mph (16%) reduction in mean speed at Site 5, but also increased the standard deviation of the speed sample by 2.4 mph. At Site 4, the 11.5-foot treatment had no effect on the mean speed, and the standard deviation actually decreased by 0.5 mph (i.e., the treatment had no significant effect on variance).

Work Area Speeds

Speed data were collected at the study sites downstream of the treatment location to measure the effects of the various speed control treatments on traffic entering the work area. The location of the downstream speed station (Station 3) at each site is shown on the site layout (see Appendix B). Station 3 was positioned 1/3 to 1/2 mile downstream of the treatment location, but always just in advance of the work activity.

TABLE 8. PERFORMANCE OF CMS TREATMENTS IN TERMS OF REDUCTION IN MEAN SPEED AT STATION 2

CMS Treatment	Reduction in Mean Speed, Mph					
	Urban Arterial	Rural Freeway		Urban Freeway	Rural 2-Lane Highway	
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Speed-Only Message	3 (5)[a]	4 (7)	5 (9)	0 (0)	--[b]	--
Speed & Information Message	3 (5)	5 (8)	3 (6)	2 (3)[c]	--	--

[a]Numbers in () indicate percent.

[b]Not available.

[c]CMS relocated nearer to the work zones.

TABLE 9. PERFORMANCE OF EFFECTIVE LANE WIDTH REDUCTION TREATMENTS IN TERMS OF REDUCTION IN MEAN SPEED AT STATION 2

Effective Lane Width Reduction Treatment	Reduction in Mean Speed, Mph					
	Urban Arterial[a]	Rural Freeway[a]		Urban Freeway[a]	Rural 2-Lane Highway[b]	
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
11.5-foot Width Using Cones	4 (5)[c]	5 (8)	2 (4)	0 (0)	8 (16)	4 (7)
12.5-foot Width Using Cones	2 (5)	2 (3)	2 (3)	0 (0)	7 (13)	4 (7)

[a]Cones placed on edges of pavement only.

[b]Cones placed on edge of pavement and centerline.

[c]Numbers in () indicate percent.

The data from Station 3 were combined with data from the upstream stations to generate speed profiles for each site. The profiles illustrate the effects of the speed control treatments upstream of and entering the work area. As an example, Figure 2 presents speed profiles for selected treatments at the urban arterial site (Site 1). Similar speed profiles for the other sites are shown in Appendix E (Figures 20-24).

Figure 2 and the other speed profiles shown in Appendix E illustrate two important findings of the studies. First, after being exposed to a particular speed control treatment, drivers continued slowing down or at least maintained a reduced speed as they approached and entered the work area. In other words, drivers did not return to their normal speed immediately after passing by the treatment.

Secondly, most of the treatments (and especially innovative flagging and a stationary patrol car in Figure 2) reduced work area entry speeds well below normal or base entry speeds. Thus, the treatments encouraged drivers to slow down much more than they would have simply in response to sighting the work activity. For example, the mean work area entry speed at Site 1 was 50 mph under base (i.e., signing-only) conditions. The innovative flagging treatment reduced the mean entry speed to 39 mph, while the stationary patrol car treatment reduced the mean entry speed to 41 mph. The 11.5-foot effective lane width reduction treatment and "Speed-Only Message" CMS treatment reduced the mean work area entry speeds to 46 and 47 mph, respectively.

Statistical Significance

Figures 25 through 30 in Appendix F present bar charts summarizing the mean speed data from Station 2 at each site. (Mean speeds and standard deviations at all three stations for all treatments by site are shown in Tables 25 through 30 in Appendix G.) In addition to showing the mean speed for each treatment tested, the figures indicate which treatments produced statistically different speeds based on the results of Duncan's Multiple Range Tests. As seen in the figures, many of the treatments were statistically different. Because of the large sample sizes and consistent variances, however, mean speed differences as low as 1 to 2 mph were statistically significant.

From a practical standpoint, a 1 to 2 mph mean speed difference may not be significant, since such a small speed difference would likely have no measurable effects on safety or traffic operations. Mean speeds would probably have to differ by 4 mph or more to support a contention that one treatment was truly <u>better</u> than another. However, this is merely speculation by the authors.

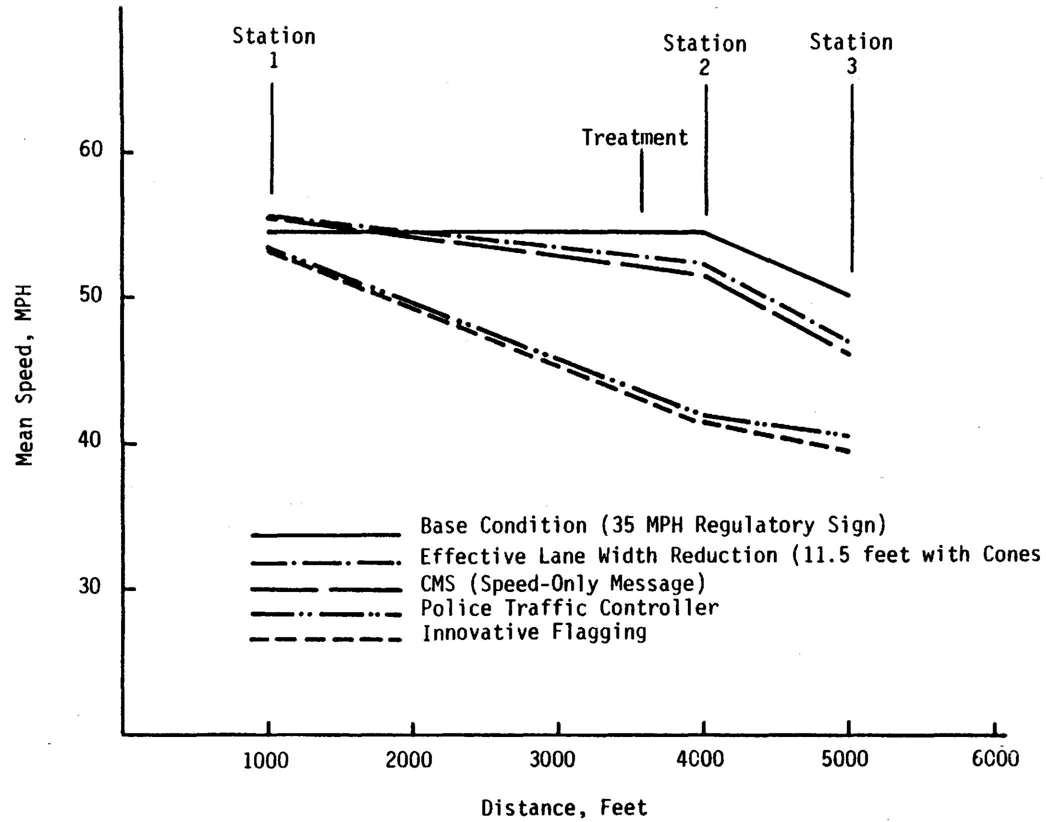


Figure 2. Speed Profiles of Selected Treatments at Site 1 (Urban Arterial)

Speed Distributions

Figure 3 presents cumulative distribution plots of Station 2 speed data for selected treatments tested at the urban arterial site (Site 1). Included in the figure is a cumulative distribution plot for the base (i.e., signing-only) condition. From the figure, it can be seen that certain of the speed control treatments significantly shifted the speed distribution to the left of the base curve. This indicates that these treatments lowered speeds in general (i.e., both fast and slow drivers reponded to the speed control treatment). Most notably in Figure 3, the innovative flagging and stationary patrol car treatments shifted the speed distribution at Site 1.

It is also important to observe in Figure 3 that all of the distribution curves shown in the figure have approximately the same shape. This is further evidence that the treatments did not greatly affect speed variance, except in the few cases discussed in the Treatment Performance section of this chapter.

Similar speed distribution plots for selected treatments at the other study sites are shown in Figures 31 through 35 in Appendix H.

Safety Performance

Along with the speed measurements, field personnel observed and recorded erratic maneuvers and other evidence of safety problems. None of the treatments resulted in any accidents or recurring safety problems at any site. In fact, only a few minor incidences were witnessed during the studies:

1. At one of the 2-lane, 2-way highway sites (Site 5), the flagger was at times too zealous and aggressive in using the innovative flagging procedure. As a result, a few drivers (i.e., 3 or 4 in a 1-hour period) over-reacted and slowed excessively. One driver even pulled onto the shoulder thinking that he was supposed to stop. These problems were avoided at the remaining sites simply by exercising proper flagging techniques.

2. At the 2-lane, 2-way highway sites (Sites 5 and 6), effective lane width reduction was accomplished by placing cones on the pavement edge and centerline. When the 11.5-foot treatment was implemented at these sites, cones were hit or blown out of place on several occasions. On one occasion, several cones were hit by a truck and knocked into the travel lane. Rather than running over the displaced cones, a motorist stopped in a lane and got out of his vehicle to move the cones. Several other vehicles in turn were forced to stop and wait for the motorist to move his car. In another incident, a wide mobile home passed through the narrow lane section and took out several cones.

3. At the freeway sites, large trucks tended to "straddle" the lane line within the narrow lane section (i.e., if other traffic was not present).

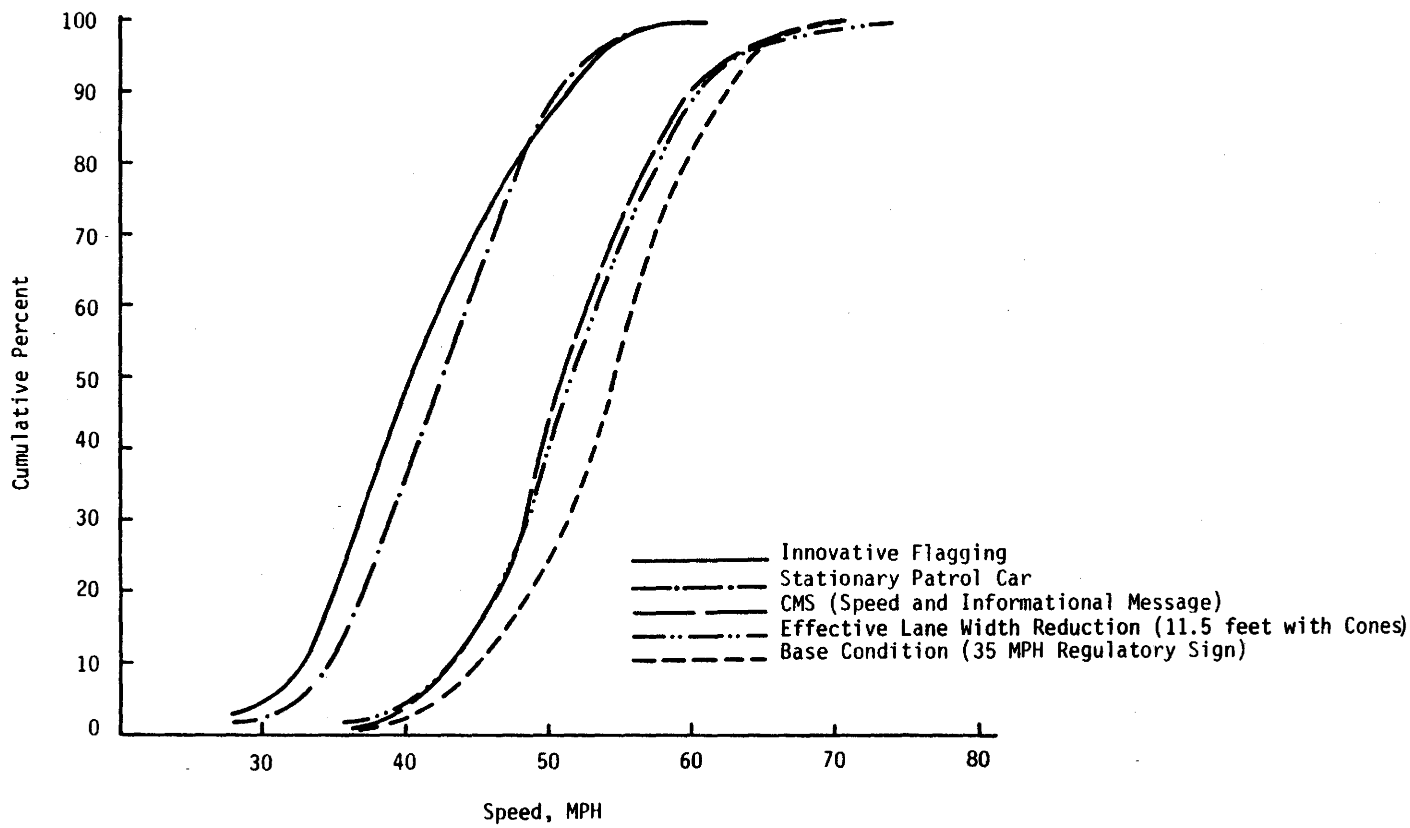


Figure 3. Cumulative Speed Distributions of Selected Speed Control Treatments at Site 1 (Urban Arterial)

5. IMPLEMENTATION OF WORK ZONE SPEED CONTROL MEASURES

The implementation of work zone speed control involves several steps. These steps include: determining the need for speed reduction, selecting a reasonable speed, selecting a treatment based on effectiveness, practicality and cost, and selecting a location for treatment implementation. Each of these will be discussed in this chapter. Also presented is a summary of treatment implementation considerations and limitations.

Determination of the Need for Speed Reduction

The research did not specifically address the issue of when an agency should encourage reduced speeds at a particular work zone. However, after visiting numerous work zones, several important considerations became apparent.

Credibility

Speed control abuse and misuse at a work zone can render a speed reduction attempt ineffective and can damage the credibility of work zone speed reduction efforts in general. Abusive practices include using unreasonably low speed limits and leaving reduced speed limits in place after the work activity is removed.

Specific Goal

As with all traffic control efforts, any effort to reduce work zone speeds should be founded on an identifiable need. Speed reduction should be aimed at decreasing the number and/or severity of work zone accidents, or the potential for accidents at sites where speed-related potential hazards exist.

In addition, it should be recognized that none of the speed reductions methods are "cure-alls" which will automatically safeguard motorists and workers. In fact, other traffic control approaches (e.g., the use of a buffer area or portable barriers) may provide a safer work zone environment and alleviate the need for speed reductions.

Speed-Related Potential Hazards

Speed-related potential hazards are those which exist, or are made worse, because traffic is traveling too fast for conditions. Typical examples of speed-related potential hazards are cited below:

1. Insufficient sight distance to the work zone, particularly to a lane closure.

2. Hidden or unobvious work zone features (e.g., subtle changes in alignment, edge drop-offs etc).

3. Reduced work zone design speed. (Design speed, as used here, refers to a real speed which is based on such factors as stopping sight distance, superelevation, degree of curvature, passing sight distance, etc.)

4. Unprotected work space where an errant vehicle could result in catastrophic damage.

Passive versus Active Control

Passive speed control refers to posting a reduced speed limit on a static sign (e.g., conventional regulatory and advisory signing). It is appropriate for all sites where reduced speeds are desired in the interest of safety. Passive control alone is generally sufficient at sites where the hazards are obvious, and drivers have plenty of time and information available to make reasonable and safe speed decisions without special encouragement.

Active control refers to techniques which restrict movement, display real-time dynamic information, or enforce compliance to a passive control. Such techniques include: flagging, law enforcement, CMSs, effective lane width reduction, rumble strips, Iowa Weave sections, etc. Active control would be needed in situations where drivers were unable or unwilling to select the appropriate safe speed without "active" encouragement.

Duration of Potential Hazard

Another practical consideration is time. If a particular work activity will be in progress for an extended period of time (e.g., 1 year) it would probably be impractical to use active speed control techniques for the life of the project. First of all, it would be too costly. Secondly, it would be unnecessary since the majority of drivers would eventually become familiar with work zone conditions and drive at their own comfortable speed. A better approach might be to use active control only during the opening days of the project and then again following major changes in conditions. Passive speed control would be used during other times.

Selection of a Reasonable Speed

After it has been determined that reduced speeds are desirable and practical, a safe and reasonable speed should be selected. A speed control strategy should be adopted which will reduce speeds to what is safe and reasonable for the conditions. The selected speed should not be unreasonably low. The fastest speed which is still considered safe should be sought.

Existing Speeds

Several factors influence what is a safe and reasonable speed for a given work zone. First of all, it should be recognized that drivers will only slow down to a certain level regardless of the presence of a speed control treatment. Based on the study results presented in the previous chapter, reductions in average speeds range from 5 to 20 mph, depending on the type of facility. Table 10 presents suggested maximum speed reductions for different types of roadways based on the study results and Reference 3.

TABLE 10. SUGGESTED MAXIMUM SPEED REDUCTIONS BY TYPE OF ROADWAY

Roadway Type	Speed Reduction, Mph
Rural 2-Lane, 2-Way Highway	10-15
Rural Freeway	5-15
Urban Freeway	5-10
Urban Arterial	10-20

Work Zone Design Speed

The design speed of the various work zone features (e.g., horizontal curvature, sight distance, superelevation, etc.) also may dictate what is a safe and reasonable speed. It is very important that the design speed is not significantly lower than drivers reasonably expect or will tolerate. If the work zone design speed is too low, even active speed control may not be enough. Suggested maximum speed reductions in work zones by type of highway are shown in Table 10.

Work Zone Conditions

Work zones often involve workers and equipment very near the traffic stream, supply trucks entering and leaving the traffic stream, uneven pavement, shoulder drop-offs, fixed object hazards, rough pavement surfaces, distractions and a number of other potential safety hazards. Selecting an appropriate speed for a particular set of conditions requires experience, objectivity and good judgment.

It is extremely important that a reasonable speed for conditions be selected. If an unreasonably low speed is encouraged by the highway agency, drivers will quickly lose respect for the speed control effort. The loss of credibility and respect will result in reduced effectiveness of the speed control technique at the site and possibly other sites.

Location of Speed Reduction

A speed control treatment should be first initiated 500 to 1000 feet upstream of the hazardous location within the work zone. This will insure that drivers have adequate time to react, and the speed message will still be fresh in their minds when they reach the potential hazard. This applies especially to the flagging, law enforcement and CMS speed control treatments which are applied at a point.

The effective lane width reduction treatment is unique in that it is applied over a section. The lane width reduction treatment should be initiated approximately 500-1000 feet upstream of the potentially hazardous location within the work zone, and continued to a point just past the end of the potential hazard. It is critical to initiate the narrow lane section before the potential hazard so that drivers have time to adjust their speeds and to focus their attention on the potentially hazardous condition rather than on the discomfort of driving in narrow lanes.

Location Relative to Other Work Zone Features

The relative location of speed control treatments to other work zone signing is also important. Ideally, speed control should be initiated after the first advanced sign and in a section which is relatively free of other work zone signs. This practice will lessen the possibility of overloading drivers with too much information. Also, it will maximize the amount of driver attention focused on the speed control effort.

Speed control treatments should not be placed in high driver work-load areas such as near ramps, intersections or lane closure tapers.

Downstream Effects

The studies reported in this report did not evaluate the effective length of each particular speed control treatment. However, it is reasonable to assume that all treatments will lose their impact eventually as drivers travel farther and farther through a long work zone. Therefore, it is likely that, if potentially severe hazards exist and drivers are not slowing down on their own, additional speed control applications (e.g., another flagger station, CMS or law enforcement officer) may be needed downstream.

Selection of Speed Control Treatment

Regulatory or advisory signing will not slow drivers down at work zones under normal circumstances. However, at the majority of long duration work zones where drivers become conditioned to the work zone environment and select their own safe and reasonable speed, passive control can reinforce the existing speeds and provide a sound basis of speed enforcement. Also, if used prudently, advisory speeds will warn and advise unfamiliar drivers of common potential hazards experienced routinely in work zones.

With regard to active measures, research reported herein focused on 4 speed control methods: flagging (including a police traffic controller), law enforcement (a stationary patrol car), CMSs and effective lane width reduction. The selection of one or a combination of these methods for use at a particular work zone should consider a number of interrelated factors including:

1. Duration of potential hazard requiring speed control

2. Type of facility

3. Desired speed reduction

4. Overall cost of treatment

5. Institutional constraints (e.g., availability of CMSs, police officer, patrol cars, trained flaggers).

As a guide to speed control selection, Tables 11 through 14 summarize the general advantages and disadvantages of the various speed control methods with respect to the above factors. Specific cost and implementation considerations of the various methods are discussed in the following sections.

Implementation Costs

As part of the studies, implementation costs for the various speed control approaches were assessed. The purpose of the assessment was not to attempt a detailed cost evaluation of specific treatments at individual sites, but rather to identify the major cost considerations of each approach.

Flagging

The cost of flagging includes the cost of labor, fringe benefits, equipment (e.g., flag, vest and hard-hat) and transportation to and from the site. It is important to budget for dead time (i.e., the time spent waiting for work to get started each day). Even more important is the requirement that flaggers be relieved every 1 1/2 to 2 hours. This is based on personal experience of the authors who served as flaggers during the speed control studies.

TABLE 11. GENERAL ADVANTAGES AND DISADVANTAGES OF FLAGGING AND POLICE TRAFFIC CONTROL

Advantages	Disadvantages
1. Large speed reductions possible	1. Requires specially trained and conscientious personnel
2. Agency/Contractor has direct control over performance[a]	2. Fatigue and boredom necessitate frequent relief
3. Relatively inexpensive for short duration applications	3. High labor costs for long duration applications
4. Little or no disruption to traffic flow	4. Effectiveness may decrease with continuous use
5. Quick and easy to implement and remove	5. Two flaggers (one each side) may be needed on multilane roadways
6. Suitable for all types of highways and work zones	6. Additional flaggers may be needed for long sections
	7. Drivers may have a problem seeing flaggers or police traffic controllers at night

[a]The agency/contractor may not have as much control over a paid police traffic controller as it would over its own personnel. Also, availability of officers may be restricted by the police agency or officer interest. Some officers in urban areas are reluctant to attempt to manually control freeway traffic.

TABLE 12. GENERAL ADVANTAGES AND DISADVANTAGES OF LAW ENFORCEMENT[a]

Advantages	Disadvantages
1. Large speed reductions possible	1. Constrained by availability of police officers and patrol cars
2. Relatively inexpensive for short duration applications	2. Agency/contractor does not have direct control over performance
3. Quick and easy to implement and remove	3. High cost for long duration applications
4. Can be effective at night, especially with lights flashing	4. Competes with other police functions
5. Sporadic use may encourage reduced speeds during "non-use" periods	5. Long work zones may require additional patrol car units
6. Suitable for all types of highways and work zones	6. Success depends on good cooperation form enforcement agencies

[a]Stationary patrol car treatments only.

TABLE 13. GENERAL ADVANTAGES AND DISADVANTAGES OF CMSs

Advantages	Disadvantages
1. Relatively inexpensive for both short and long duration applications	1. Only modest speed reductions possible
2. Agency/contractor has direct control over performance	2. Constrained by availability of signs
3. Little or no disruption to traffic flow	3. Effectiveness may decrease with continuous use
4. Quick and easy to implement and remove	4. Sign maintenance and repair may require technical expertise
5. Suitable for all types of highways and work zones	
6. Effective at night and in inclement weather	
7. May be used in combination with other techniques (e.g., flagger, law enforcement) for best results	

[a]If sign cost is extended over sign life (sign lease cost for a single, short-duration use may be high).

TABLE 14. GENERAL ADVANTAGES AND DISADVANTAGES OF EFFECTIVE LANE WIDTH REDUCTION

Advantages	Disadvantages
1. Moderate speed reductions possible	1. Expensive to implement and maintain, for short duration applications, depending on devices used
2. Agency/Contractor has direct control over performance	2. May disrupt traffic flow (i.e., reduce capacity)
3. Relatively inexpensive for long duration applications, depending on devices used	3. May increase certain types of accidents
4. Retains effectiveness with continuous use and-long duration use	4. Device maintenance may be expensive
5. Speed reduction achieved throughout narrow lane section	5. May not be as effective on multilane highways
	6. Not easy to implement or remove

Considering all costs, a highway official in Texas estimated that it costs his agency approximately $20 per flagger-hour (in 1983 dollars) (35).

Law Enforcement

Table 15 presents the results of a survey of city, county and state police agencies in Texas regarding the cost of hiring off-duty officers for work zone traffic control. From the table, the hourly rates ranged from $10.00 to $22.50, with the average charge being about $15.00 per hour.

Most of the police agencies surveyed do not normally allow officers the use of a patrol car for off-duty work. The agencies said that cars were too scarce. The Texas Department of Public Safety, by state statute, will not allow off-duty officers to use state vehicles or equipment, or even to wear their uniforms.

During the survey, the police agencies were asked about furnishing on-duty officers and patrol cars for work zone speed control. Most of the agencies said they would provide assistance for no charge at selected sites. However, they do not have the resources to provide men and vehicles on a regular basis.

CMSs

In Texas where the studies were conducted, portable CMSs are not readily available for lease from traffic control suppliers. One supplier, however, offered to lease a 3-line, bulb matrix sign for $3,000 per month. This does not include operating costs such as fuel, oil and routine servicing.

The Texas SDHPT has acquired most of its CMSs by requiring contractors on major projects to buy signs for their projects. Once the projects are completed, the signs are turned over to the State for use on future maintenance and construction projects. The latest bid price received by the State for a 3-line sign was just under $50,000.

CMSs require routine maintenance and repair, and the cost of skilled labor and parts can be high. Also, it is common that inoperative signs must be shipped to the manufacturer for repair.

Effective Lane Width Reduction

As noted earlier, the cost of implementing reduced lane widths can vary greatly. The total cost includes the cost of the devices as well as installation, maintenance, replacement, and removal of the devices. The salvage or reuse value of the devices can be subtracted from total costs, however, to yield the net cost to the agency.

TABLE 15. COST OF HIRING OFF-DUTY LAW OFFICERS FOR TRAFFIC CONTROL IN 1983 DOLLARS

Agency	Off-Duty Wage Rate
City of Austin	$22.50/hr.[a]
City of Arlington	$20.00/hr.
Brazos County Sheriff's Department	$10-12/hr.
City of Dallas	$15.00/hr.
City of Ft. Worth	$15.00/hr.
Harris County Sheriff's Department	$15-18/hr.
City of Houston	$15.00/hr.
City of San Antonio	$15.00/hr.[b]
Texas Department of Public Safety	$12-15/hr.[c]

[a]Rate includes use of patrol car if approved by city.

[b]Rate drops to $12/hr. after 3 hours of continuous service.

[c]State statute prohibits off-duty DPS officers from wearing their uniform or using any State equipment.

Treatment Anchoring

The studies indicated that a speed reduction technique, to accomplish its desired effects, should be anchored to an appropriate, reasonable speed. "Anchoring" refers to displaying a specific speed along with the speed control technique so that drivers know at what speed they should travel through the work zone. The speed control technique may be anchored to a regulatory speed sign, an advisory speed plate, or a speed message displayed on a CMS. Advisory speed plates are intended for use to supplement warning signs. By "anchoring" a speed reduction treatment, drivers can better relate to the treatment as a speed reduction device, and the specific meaning or intent of the device is reinforced.

Treatment Implementation Considerations

During the course of the research, several observations were made concerning how best to implement the various speed control treatments. Some of the practical limitations of the treatments were also identified. These implementation considerations and limitations are listed and discussed below.

Flagging

1. Flaggers should be conscientious and dependable workers with good vision, hearing and physical condition.

2. Flaggers are required to be properly attired in a fluorescent orange vest with reflective material. They may also wear a hard-hat. The vest will enhance the conspicuity of the flagger and connote to drivers that he/she is an official member of the work force with authority to control traffic.

3. The flagger is required to be equipped with a standard red flag or sign paddle. The flag serves as an attention-getting device and increases the target value of the flagging operation. (The research did not study the use of paddles.)

4. Flaggers should be well trained in the proper flagging procedures and signals. The studies revealed that both the MUTCD and innovative signals produce relatively large speed reductions. The innovative signal has the advantage of indicating the desired speed to motorists.

5. In the interest of personal safety, the flagger should not be in the travel lanes but rather on the shoulder, if it is wide (8-10 feet), or just off the pavement.

6. The flagging operation should be "anchored" to a speed sign. The research did not address whether a regulatory sign, advisory sign or

CMS was a better anchor, but did suggest that any of them would be adequate.

7. Flagging is a physically tiring and boring activity. To be effective, a flagger should be relieved at least every 1 1/2 to 2 hours.

8. Flagging appeared to be most effective on two-lane, two-way rural highways and urban arterials, where a flagger has the least competition for drivers' attention. On freeways, two flaggers may at times be needed, one on each side of the road, in order to achieve maximum effectiveness.

9. The studies did not evaluate the effective distance of flagging operations (i.e., how far speeds remained reduced downstream of a flagger station). However, it is reasonable to assume that in a long work zone (e.g., 1 mile or more) speeds would eventually rise again. Thus, it may be necessary to establish additional flagging stations at work zones where speed hazards exist over long distances.

10. For nighttime operation, flagger stations should be illuminated and flaggers should use an approved red latern, flashlight with red wand, reflectorized paddle or redlectorized sign.

11. It may be difficult or impossible to flag during inclement weather.

12. Flagging is well suited for short duration applications (i.e., less than 1 day), and for intermittent use at long duration work zones. It is likely that flagging would diminish in ineffectiveness if it was used continuously over several days or weeks.

Law Enforcement

1. Where it was tested, manual police traffic control was the most effective law enforcement strategy. (However, a uniformed police officer was no more effective in slowing drivers than a well-trained, properly attired flagger using proper flagging signals.)

2. A stationary patrol car, anchored to a speed sign, was very effective in slowing drivers. By turning on the patrol car lights or radar unit, a stationary patrol car may improve its effectiveness marginally.

3. A circulating patrol car was the least effective law enforcement strategy evaluated in reducing overall speed.

4. Many officers apparently are reluctant to attempt to reduce speeds at freeway work zones by manual traffic control hand signals. During the studies, some officers refused to participate in the manual control treatment saying that their services were better utilized performing other traffic control functions. Some officers believed

that they would not be effective, and some cited a concern over their personal safety. Officers were particularly hesitant to attempt manual traffic control at the urban freeway site.

5. To increase effectiveness during nighttime operation, a stationary patrol car probably would need to have its overhead emergency flashing lights on. This would assure that the patrol car is seen by most drivers. The safety effects of a stationary patrol car with emergency lights-on was not studied, although no problems were observed during the daylight tests. It is reasonable to assume, however, that there would be situations where the flashing lights would be too distracting and result in a safety hazard.

6. For maximum effectiveness, the patrol car should be highly visible to approaching traffic. The patrol car is only effective when in place, so attempts to pursue and ticket violators should be minimized. A second patrol unit could be used occasionally for this function if desired to possibly further enhance the effectiveness of the stationary patrol car approach.

7. The various law enforcement treatments may increase in effectiveness over a period of time as more and more drivers anticipate police presence and the threat of speed enforcement. However, if drivers eventually perceive that they will not be ticketed for violations, the effectiveness may subside. Therefore, for long-term applications, it may be necessary to occasionally issue citations to violators.

8. It is likely that occasional use of the various law enforcement strategies will reduce speeds even when the law enforcement is not present. This was not addressed in the studies.

9. Additional stationary units may be needed to encourage reduced speeds through a very long work zone.

CMSs

1. CMSs resulted in only modest speed reductions at the sites where they were tested (i.e., urban arterial and freeway sites). It is unlikely that CMSs alone could produce very large speed reductions (e.g., greater than 10 mph). These findings are consistent with CMS studies conducted by Hanscomb (7).

2. The 2 types of messages tested (Speed versus Speed and Informational) performed approximately the same.

3. CMSs are appropriate for day and night use.

4. CMSs retain most of their usefulness during inclement weather.

5. CMSs are versatile. The speed message may be changed as conditions change, and they may be used to display other types of information and warnings as needed. They are easy to install or relocate.

6. The appropriate type and size of CMSs should be used for the conditions. Reference 34 presents CMS selection and operation considerations.

7. CMSs must be properly serviced and repaired. Acquiring necessary parts and expert labor may require shipping the sign to a distant manufacturer or waiting for the manufacturer or his representative to service the sign locally.

8. CMSs, operated continuously for long periods with the same messages, may lose their effectiveness.

9. A survey of traffic control subcontractors conducted as part of this study, revealed that CMSs are currently not readily available for lease on a short-term basis. In Texas where all the field studies were conducted , the highway agency is requiring that its contractors purchase CMSs for use on some major projects. When a project is completed, the sign is turned over to the agency for use at future construction and maintenance sites.

Effective Lane Width Reduction

1. Slight effective lane width reductions (e.g., 11.5 and 12.5-foot widths) will reduce speeds modestly. Although not tested, it is assumed that even narrower lanes (e.g., 9-10 feet) may greatly lower speeds. However, the studies suggested that lane reduction, if effective, also increases speed variance and erratic maneuvers.

2. In order to implement a lane width reduction technique, it is usually necessary to interrupt traffic flow and expose workers to traffic (i.e., workers must get out into traffic and install the devices).

3. There are many devices and strategies available for implementing effective reduced lane widths (e.g., cones, drums, striping, barriers, barricades, etc.). The cost, maintainability, effectiveness and safety of the various approaches probably varies widely. Only cones were evaluated in the studies.

4. Cones proved to be quick and easy to install and remove. However, they were frequently hit by large trucks and mobile homes when the 11.5-foot treatment was used.

5. Effective lane width reduction appears to be more practical for long duration applications (i.e., several days or more). The time and initial cost to implement are relatively great, but once installed, there is little labor or expense.

6. On roadways with 3 or more lanes per direction, it may not be possible to accomplish the desired effective lane width reduction in the middle lanes without restriping the roadway.

7. Effective lane width reduction techniques may not suppress speeds long after the end of the narrow sections. Thus, the narrow lanes must be continued throughout the area where reduced speeds are desired.

REFERENCES

1. J.L. Graham, R.J. Paulsen, and J.C. Glennon. Accident and Speed Studies in Construction Zones. Midwest Research Institute. Report No. FHWA-RD-77-80. June 1977.

2. J.R. Humphries, H.D. Mauldin, and T.D. Sullivan. Identification of Traffic Management Problems in Work Zones. University of Tennessee. Report No. FHWA-RD-79-4. December 1979.

3. Improvements and New Concepts for Traffic Control in Work Zones. Contract DTFH61-81-C-00102. Texas Transportation Institute. Sponsored by U. S. Department of Transportation, Federal Highway Administration.

4. Z.A. Nemeth and D.J. Migletz. Accident Characteristics Before, During, and After Safety Upgrading Projects on Ohio's Rural Interstate System. Transportation Research Record 672, 1978.

5. S.H. Richards and M.J. Faulkner. An Evaluation of Work Zone Traffic Accidents Occurring on Texas Highways in 1977. Texas Transportation Institute, Report No. 266-3, July 1981.

6. S.H. Richards, M.J.S. Faulkner, and C.L. Dudek. Traffic Management During Freeway Reconstruction and in Rural Work Zones. Texas Transportation Institute, Report No. 263-9F, October 1982.

7. F.R. Hanscom. Effectiveness of Changeable Message Displays in Advance of High-Speed Freeway Lane Closures. National Cooperative Highway Research Program Report 235, September 1981.

8. R.J. Webb. The Effect of an Advisory Speed Signal on Motorway Traffic Speeds. Transport and Road Research Laboratory. Report No. SR 615, 1980.

9. J.A. Wattleworth, K.G. Courage, and J.D. Carvell. An Evaluation of Two Types of Freeway Control Systems. Texas Transportation Institute Research Report No. 388-6, April 1968.

10. Reduced Visibility (Fog) Study. A Report of the State of California Transportation Agency. Department of Public Works, Division of Highways, March 1967.

11. O.K. Dart, Jr., and W.W. Hunter. An Evaluation of the Halo Effect in Speed Detection and Enforcement. Transportation Research Record 609, 1976.

12. R.B. Goldblatt. Guidelines for Flashing Traffic Control Devices. Report No. FHWA-RD-76-190, July 1976.

13. W. Marconi. Speed Control Measures in Residential Areas. Traffic Engineering, Vol. 47, No. 3, March 1977.

14. K.A. Brewer. Safety Evaluation of Forced Weaving as a Traffic Control Measure in Freeway Maintenance Operations. Transportation Research Record 388, 1972.

15. W.C. Taylor. Colored Pavement Materials: An Evaluation of the Use of Colored Pavement as a Traffic Control and Guidance Device. Ohio Department of Highways, 1967.

16. L.B. Walsh. Speed Bump Study. San Jose Department of Public Works, San Jose, California, April 1975.

17. G.R. Watts. Road Humps for the Control of Vehicle Speeds. Transport and Road Research Laboratory Report No. LR 597, 1973.

18. R. Sumner and C. Baguley. Speed Control Humps on Residential Roads. Transport and road Research Laboratory Report No. LR 878, 1979.

19. R.C. Sumner and J. Shippey. The Use of Rumble Strips to Alert Drivers. Transport and Road Research Laboratory, Report No. LR 800, 1977.

20. R.L. Sumner and J. Shippey. The Effects of Rumble Strips at the Dartford Tunnel. Transport and Road Research Laboratory, Report No. LR 169, 1975.

21. H.E. Pattersson. Rumble Strips - Geometric Design and Behavioral Effects. Swedish Institute for Building Research, Report No. NR-80, 1976.

22. N. Emustun. Three Experiments with Transverse Pavement Strips and Rumble Bars. Michigan Department of State Highways, Report No. TSD-RD-216-72, 1972.

23. J.S. Koziol and P.H. Mengert. An Evaluation of Speed Control Signs for Small Rural Towns. Public Roads, Vol. 41, No. 1, June 1977.

24. T.H. Rockwell and J.C. Hungerford. Use of Delineation Systems to Modify Driver Performance on Rural Curves. Ohio State University, August 1979.

25. K.R. Agent. Transverse Pavement Markings for Speed Control and Accident Reduction. Transportation Research Record 773, 1980.

26. G.M. Burney. Behavior of Drivers on Yellow Bar Patterns - Experiment on Alton By-Pass, Hampshire. Transport and Road Research Laboratory, Report No. SR 262, 1977.

27. G.G. Denton. The Influence of Visual Pattern on Perceived Speed at Newbridge M8 Midlothian. Transport and Road Research Laboratory, Report No. LR 531, 1973.

28. G. Oeberg. Protective Devices and Preliminary Information on Permanent Road Works on Motorways: Effects on Vehicle Speeds and Lane Changing. National Swedish Road and Traffic Research Institute, Report No. VTI-179, 1979.

29. K.B. Joscelyn, T.H. Bryan, and D.M. Goldenbaum. A Study of the Effects of Law Enforcement on Traffic Flow Behavior. National Highway Traffic Safety Administration, Report No. DOT-HS-800-505, January 1971.

30. R.D. Smith. The Effect of Enforcement on Driving Behavior. International Association of Chiefs of Police, Washington, D.C., 1962.

31. R.Q. Brackett and M.L. Edwards. Comparative Evaluation of Speed Control Strategies. Texas Transportation Institute, TOTS Report No. 787-6300-30A, September 1977.

32. S.H. Richards, N.D. Huddleston, and J.D. Bowman. Driver Understanding of Work Zone Flagger Signals and Signaling Devices. Texas Transportation Institute, Report FHWA/TX-81/18+228-3, January 1981.

33. Manual on Uniform Traffic Control Devices for Streets and Highways. U.S. Department of Transportation, Federal Highway Administration, 1978.

34. C.L. Dudek, R.D. Huchingson, et al. Human Factors Requirements for Real-Time Motorist Information Displays, Vol. 1 - Design Guide. Texas Transportation Institute, Report No. FHWA-RD-78-5, September 1978.

35. Conversation with Mr. Steven Z. Levine. Traffic Management Supervisor, District 12, Texas State Department of Highways and Public Transportation.

APPENDIX A - PROVING GROUND STUDIES

Study Description

The proving ground studies tested a total of 9 speed control treatments (e.g., 3 treatments for each of 3 approaches). The various treatments are illustrated in Figures 4 through 6.

The studies were conducted on a 2-lane track at the Texas A&M University Research and Extension Center. The 2-mile long test track consisted of three simulated work zones spaced some distance apart. Each simulated zone was identified by a ROAD WORK AHEAD sign and contained one of the speed control treatments under investigation.

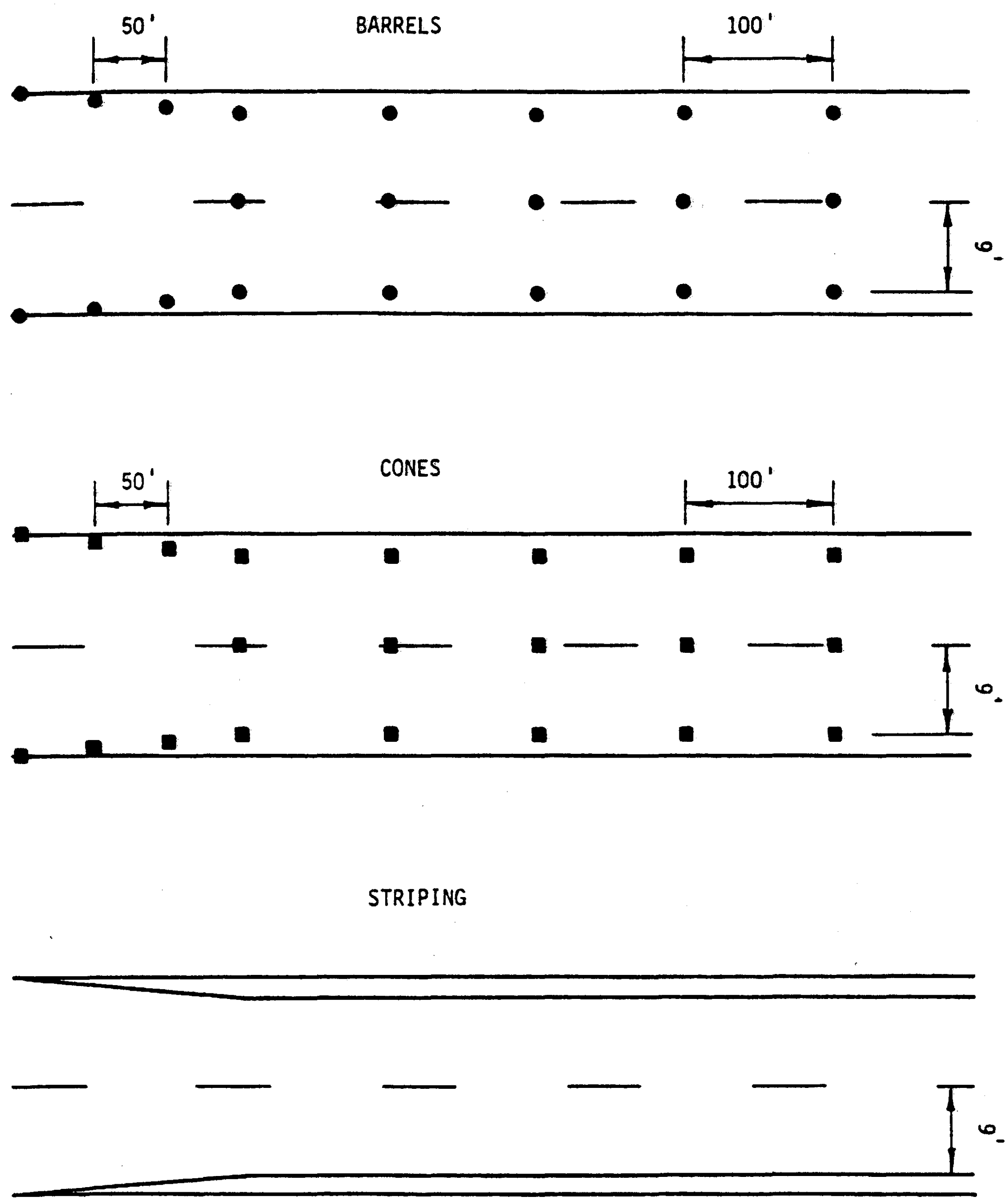
The studies were conducted in three phases. In each phase, the three treatments of a particular speed control strategy were evaluated. During the first phase, for example, effective lane width reduction using striping, cones and then barrels was studied. To minimize the effects of the driver learning process and site variations, the various treatments were rotated from work zone to work zone.

The studies were administered to drivers on an individual basis. Faculty and staff from Texas A&M University were used as volunteer subjects. The study sample was better educated, on the average, than the driver population in the country. Seventeen drivers were sampled in evaluating the transverse striping strategy, 18 drivers were sampled for the lane width reduction strategy, and 18 drivers were sampled for the rumble strip strategy.

Subjects were read the following instructions before entering the test track:

> **You are being asked to drive through three simulated work zones. You will approach these zones at 50 mph. As you drive through each of the zones, please remember the way it was set up, particularly any part of the course that might have required that you change speed or directions. You will take a short break between zones so try to remember what you can. You'll be asked to fill out a short question form after you've driven through all three simulated zones.**
>
> **Any questions?**

NARROW LANES



Note: All 3 treatments were approximately 800 feet in length.

Figure 4. Effective Lane Width Reduction Treatments

TRANSVERSE STRIPING

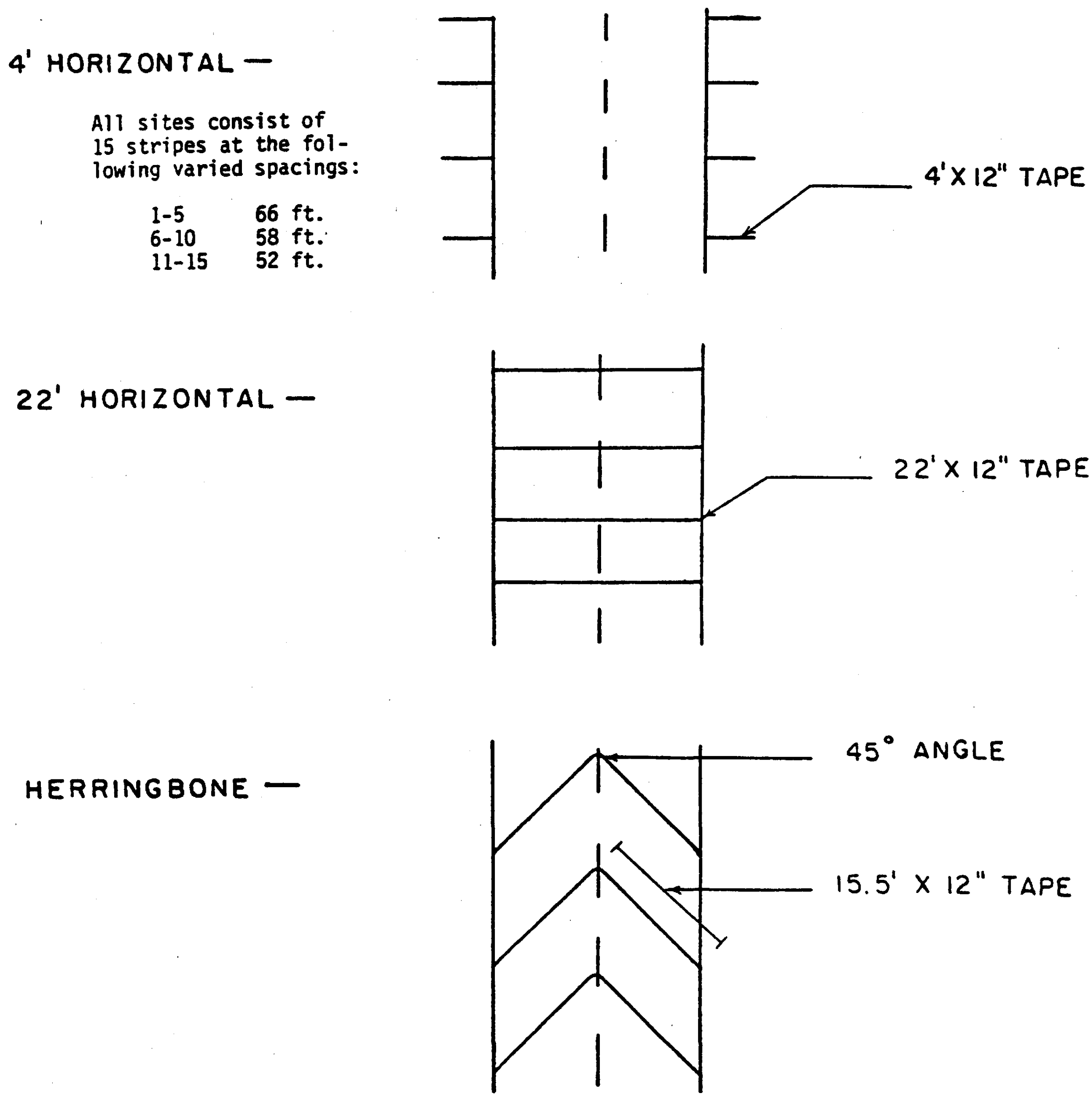


Figure 5. Transverse Striping Treatments

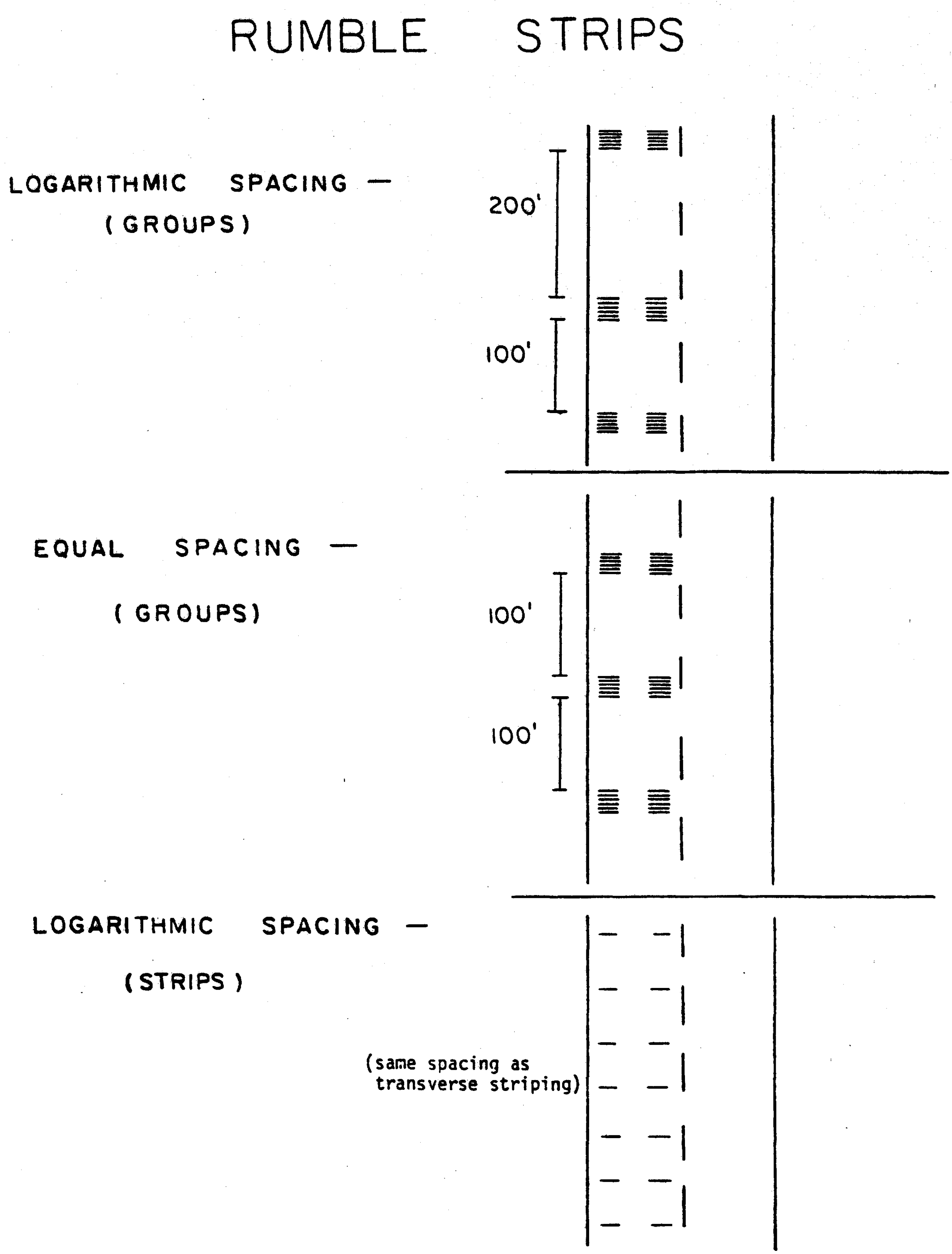


Figure 6. Rumble Strip Treatments

Spot speed data collected by radar were used as the primary data source. Test vehicle speeds were measured at 5 check points:

1. 500 feet in advance of the speed control treatment (at ROAD WORK AHEAD sign).
2. At the beginning of the speed control treatment.
3. 400 feet into the speed control treatment.
4. At the end of the speed control treatment.
5. 500 feet beyond the speed control treatment.

Study Results

The results of the studies are shown in Figures 7 through 9. As seen in the figures, none of the 9 treatments had much effect on mean driver speeds. In fact, Repeated Measures ANOVA tests performed on the data indicated that no treatment had a statistically significant effect on mean speed. The subject drivers, on the average, maintained the instructed speed of 50 mph. For the lane width reduction strategy using barrels, average driver speed dropped to 45.5 mph at the final speed check point 500 feet beyond the barrels (see Figure 7). Whether or not this speed drop was caused by the speed control treatment is questionable since drivers maintained a mean speed of 50 mph while traveling through the barrel section.

Table 16 shows the standard deviations in the speeds for each treatment. It is apparent that the transverse striping treatments resulted in relatively low speed variations among individual drivers compared to the effective lane width reduction and rumble strip strategies. Standard deviations in speeds for the various transverse striping treatments ranged from 4.41 to 6.02 mph. The lane width reduction strategy using barrels yielded the largest speed deviations of all of the treatments. At the midpoint of the barrel section (Station 3), the standard deviation of the subjects' speeds was 12.70 mph.

Preference Survey

Following the proving ground studies, the participating drivers were administered a questionnaire survey to determine their preferences for the various treatments within the speed control method to which they had been exposed. Driver responses to the preference survey are summarized in Tables 17 through 19. These tables show the percentages of drivers who indicated that a particular treatment: 1) produced the greatest speed reduction, 2) produced the least speed reduction and 3) resulted in the greatest hazard.

Table 17 shows driver response to the 3 effective lane width reduction treatments (striping, cones and barrels). From the table, 88% of the drivers thought that the barrel treatment produced the greatest speed reduction, and 94% thought that the striping treatment produced the least speed reduction. Even though most drivers believed that the barrel treatment was effective in slowing drivers, they did not necessarily support the use of the barrel

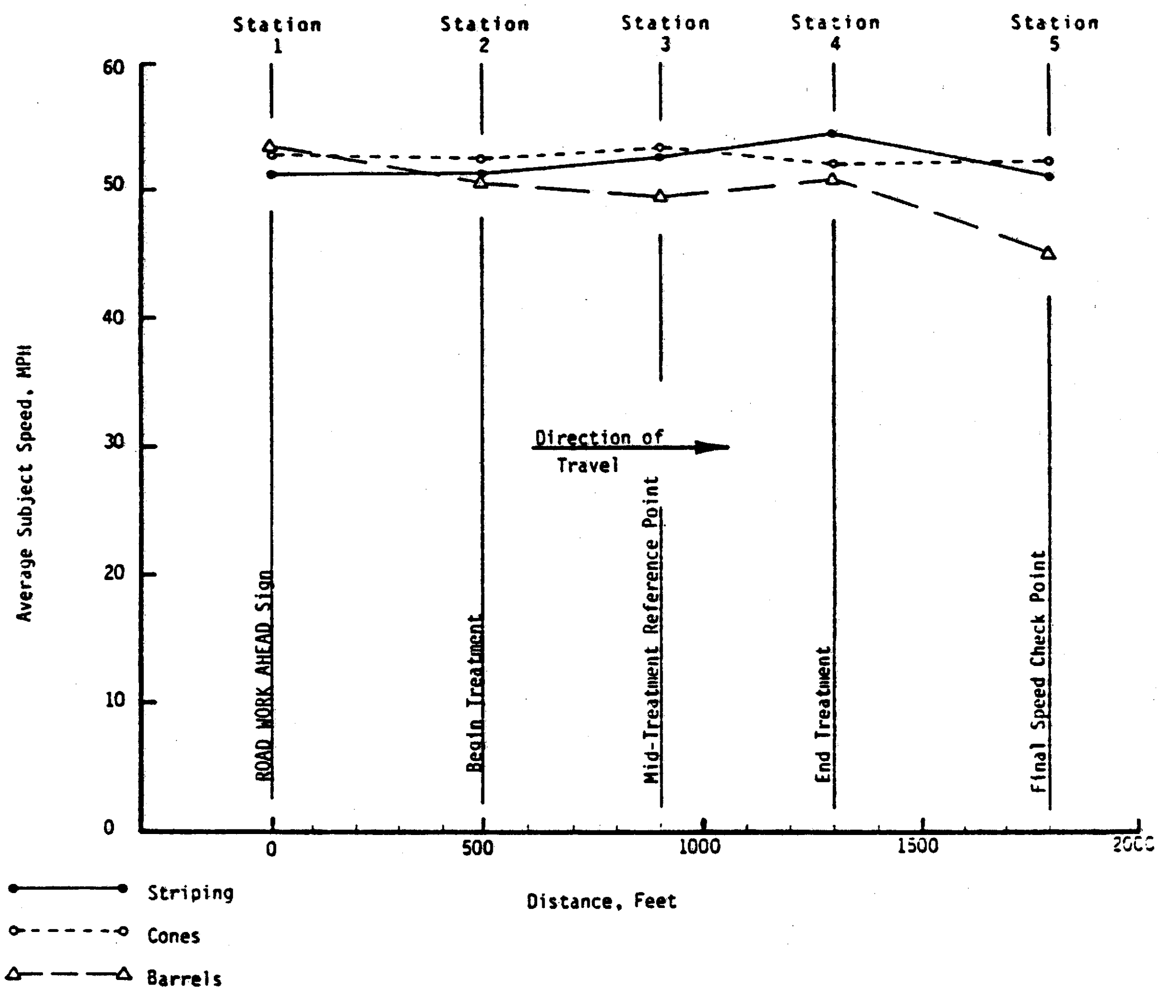


Figure 7. Effect of Lane Width Reduction Treatments on Mean Speeds

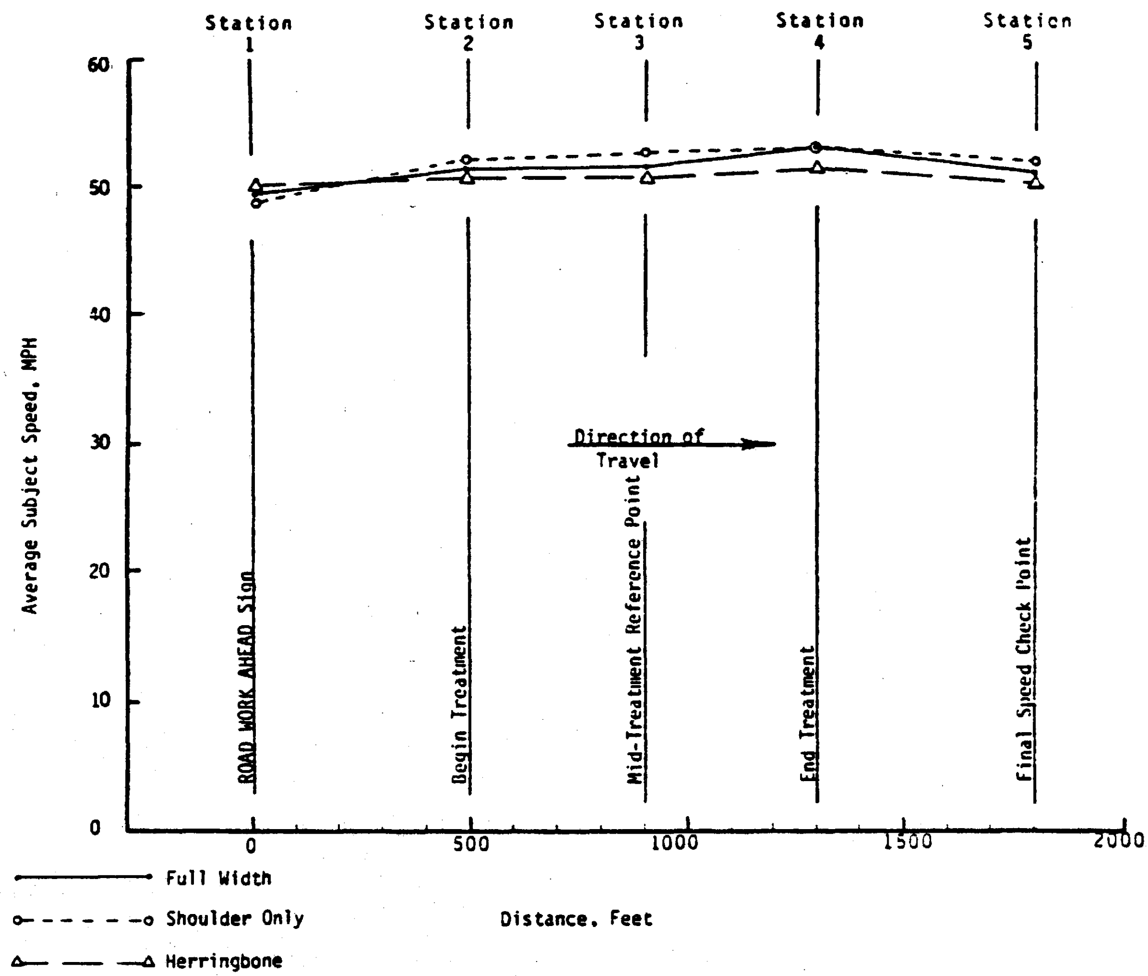


Figure 8. Effect of Transverse Striping Treatments on Mean Speeds

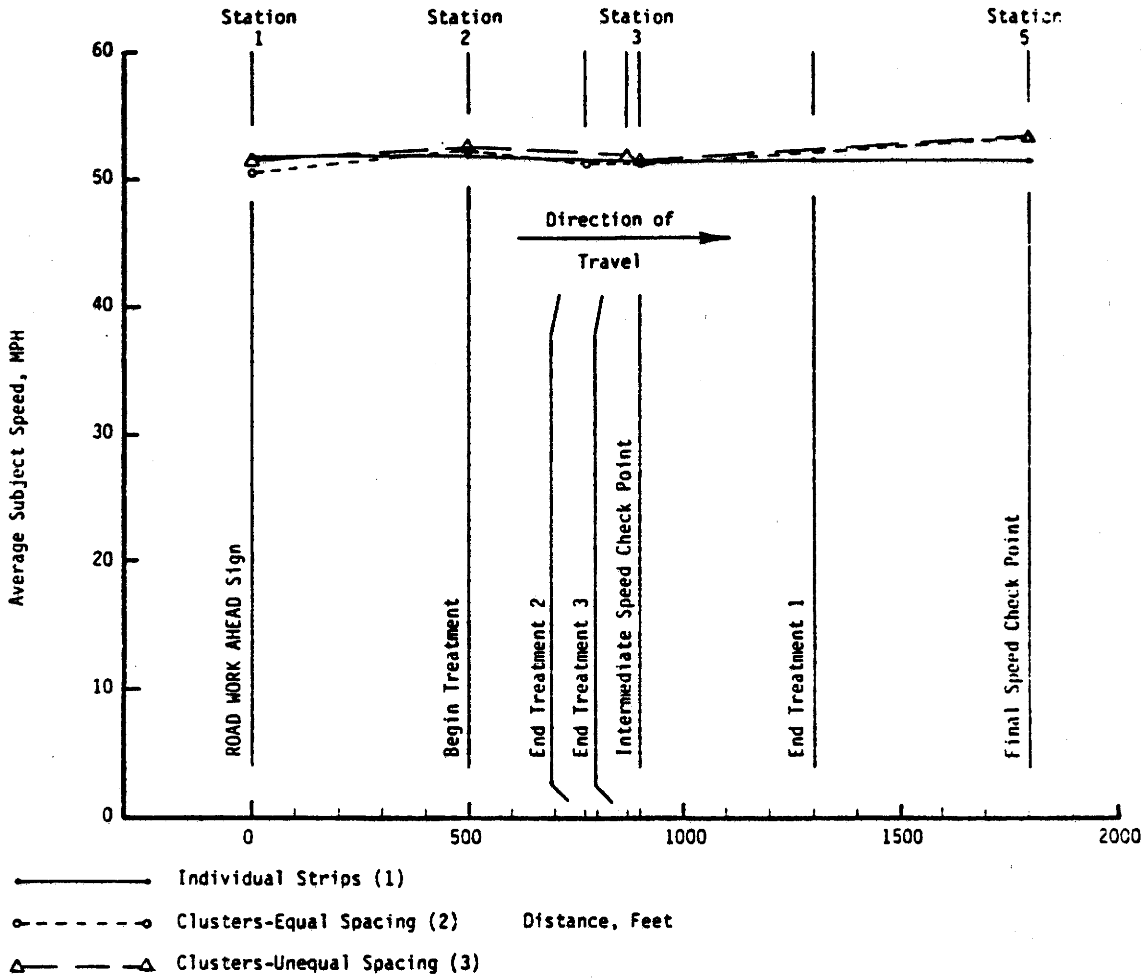


Figure 9. Effect of Rumble Strip Treatments on Mean Speeds

TABLE 16. EFFECT OF WORK ZONE SPEED CONTROL TREATMENTS ON STANDARD DEVIATION

Treatment		Standard Deviation, MPH				
		Station 1	Station 2	Station 3	Station 4	Station5
Effective Lane Width Reduction *	Striping	7.78	10.08	9.50	7.25	4.85
	Cones	5.95	7.69	8.08	6.02	5.48
	Barrels	8.22	11.52	12.70	11.45	10.15
Transverse Striping **	Full Width	5.26	4.58	4.41	4.87	5.96
	Shoulder Only	5.14	4.64	4.48	4.81	5.66
	Herringbone	3.49	4.71	6.02	5.96	5.68
Rumble Strips *	Individual Strips	7.22	8.14	9.09	10.2	9.19
	Cluster-Equal Spacing	4.17	6.77	7.67	8.11	6.77
	Clusters-Unequal Spacing	9.24	9.07	8.88	9.18	8.10

* N=18
** N=17

TABLE 17. DRIVER RESPONSE TO EFFECTIVE LANE WIDTH REDUCTION TREATMENTS

Treatment	Percent of Subjects (N=18)		
	Produced Greatest Speed Reduction	Produced Least Speed Reduction	Resulted in Greatest Hazard
Striping	6	94	6
Cones	6	6	0
Barrels	88	0	94
Totals	100	100	100

TABLE 18. DRIVER RESPONSE TO TRANSVERSE STRIPING TREATMENT

Treatment	Percent of Subjects (N=17)		
	Produced Greatest Speed Reduction	Produced Least Speed Reduction	Resulted in Greatest Hazard
Full Width	35	6	18
Shoulder Only	0	88	41
Herringbone	65	6	41
Totals	100	100	100

TABLE 19. DRIVER RESPONSE TO RUMBLE STRIP TREATMENTS

Treatment	Percent of Subjects (N=17)		
	Produced Greatest Speed Reduction	Produced Least Speed Reduction	Resulted in Greatest Hazard
Individual Strips	24	76	29
Clusters-Equal Spacing	47	0	41
Clusters-Unequal Spacing	29	24	29
Totals	100	100	100

treatment. In fact, 94% of the drivers said the barrel treatment resulted in the greatest hazard.

Driver responses to the transverse striping treatments are shown in Table 18. From the table, 65% of the drivers thought that the "herringbone" pattern was most effective in reducing speeds, while the remaining 35% thought that the "full width" pattern was most effective. Most drivers (88%) believed that the "shoulder only" treatment was least effective in reducing speeds. Equal percentages of drivers (41% in each case) said that the "shoulder only" and "herringbone" patterns resulted in the greatest hazard.

Table 19 summarizes driver responses to the rumble strip treatments. From the table, about one-half (47%) of the drivers said that the "clusters-equal spacing" treatment produced the greatest speed reduction. Approximately three-fourths (76%), on the other hand, said that the "individual strips" treatment produced the least speed reduction. Drivers were split in their hazard ratings of the three treatments.

Summary

The proving ground studies and follow-up preference surveys did not clearly indicate that any of the speed control treatments would be effective. The results did reveal that certain of the treatments were subjectively considered more effective by the subject drivers; however, the most effective treatments were also the most hazardous in the opinion of the drivers.

The proving ground study results also suggested the following considerations:

1. Rumble strips should span the entire width of the travel lanes (and possibly even the shoulder) to be effective.

2. The barrel configuration tested was very confining at the recommended study speed of 50 mph. Less confining configurations should be used.

3. The effective lane width reduction using striping was totally ineffective. The markings were not visible from an adequate distance and they did not create a feeling of confinement. (With narrow lanes, it is adjacent traffic which causes the feeling of confinement.)

APPENDIX B - SITE LAYOUTS

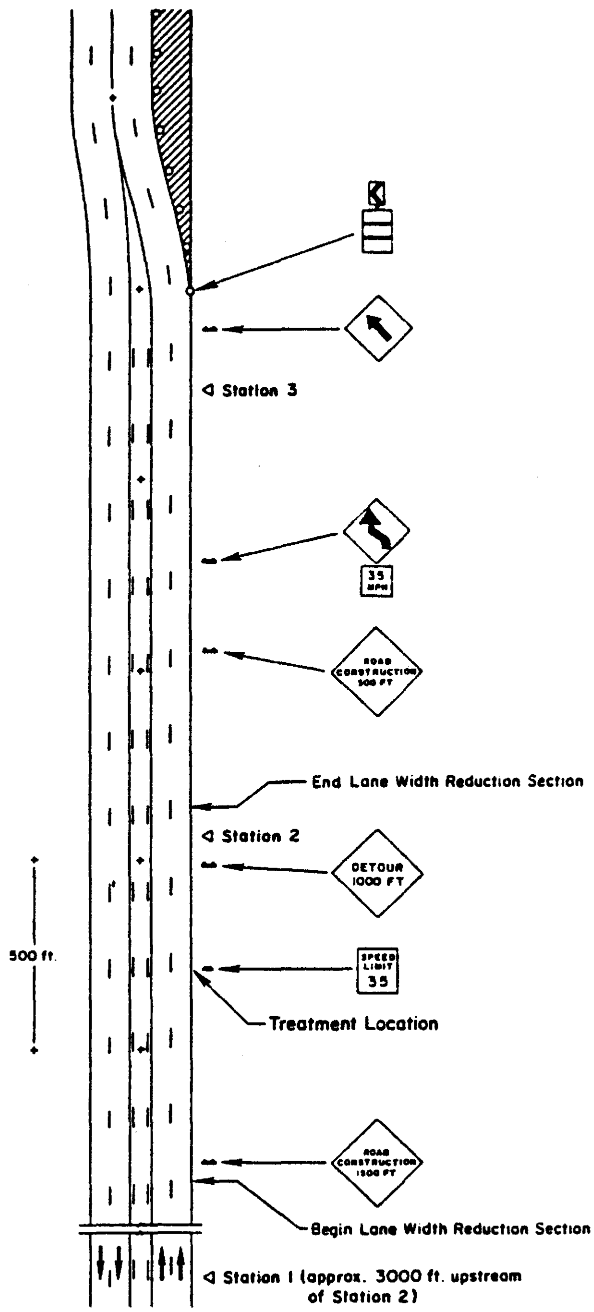


Figure 10. Layout, Site 1 (Urban Arterial)

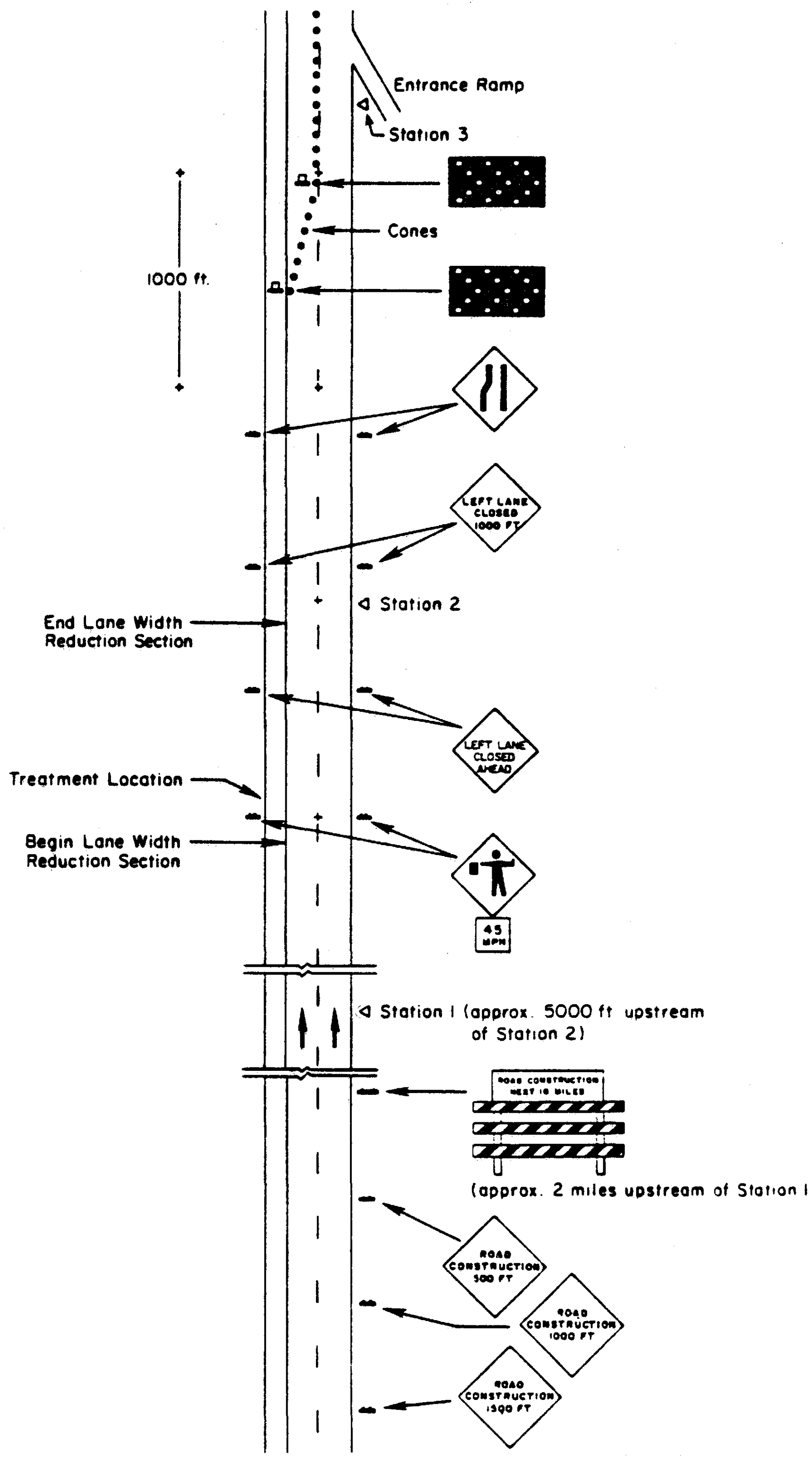


Figure 11. Layout, Site 2 (Rural Freeway)

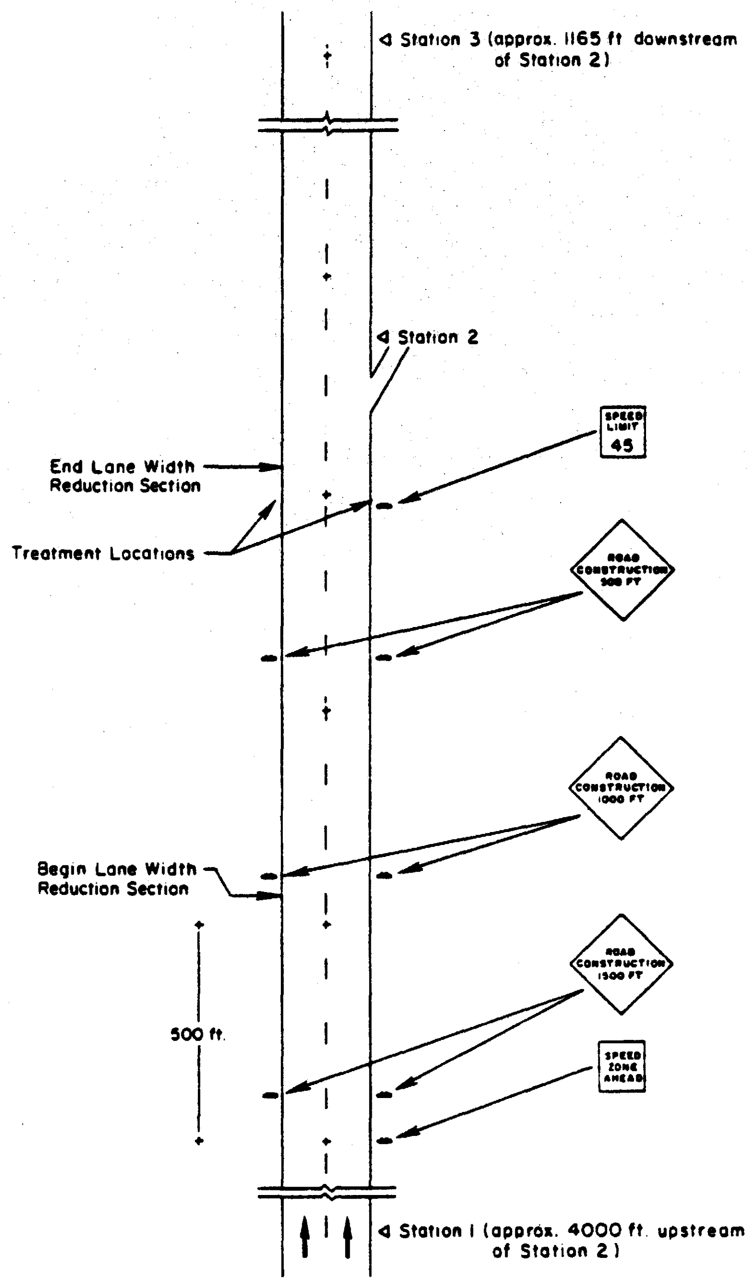


Figure 12. Layout, Site 3 (Rural Freeway)

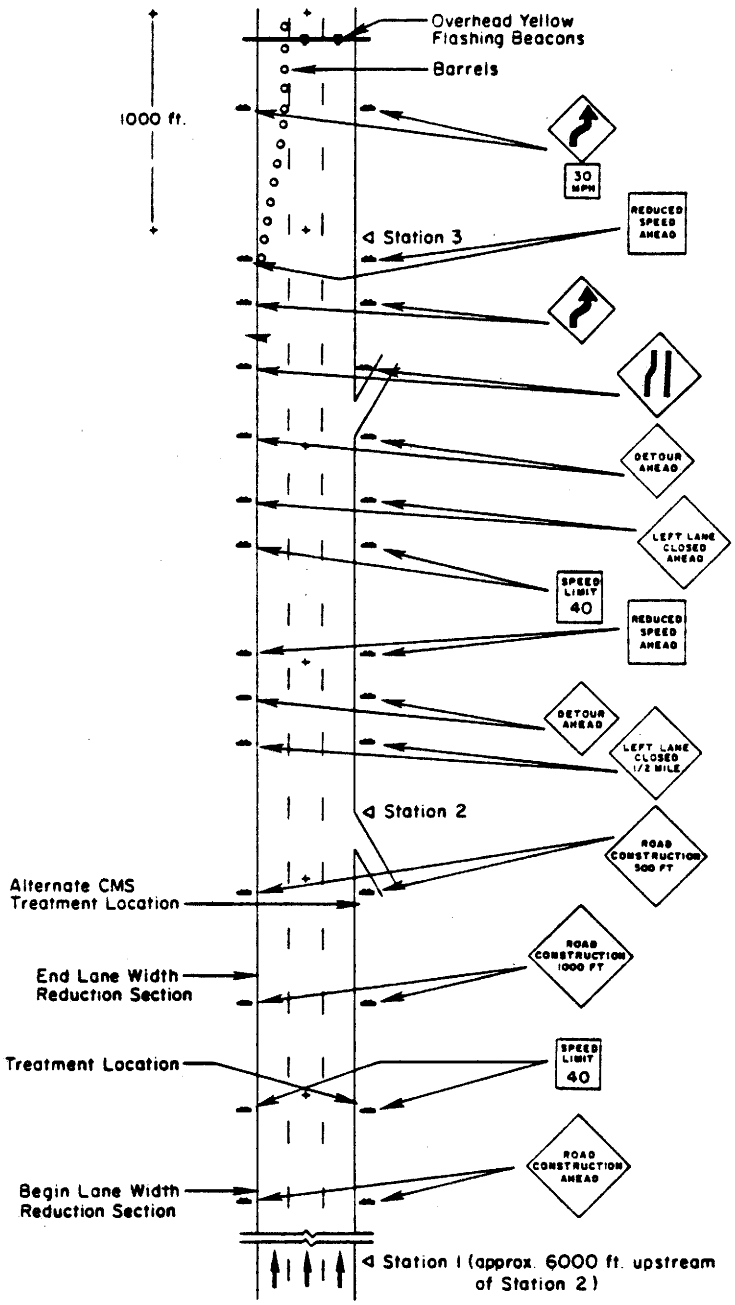


Figure 13. Layout, Site 4 (Urban Freeway)

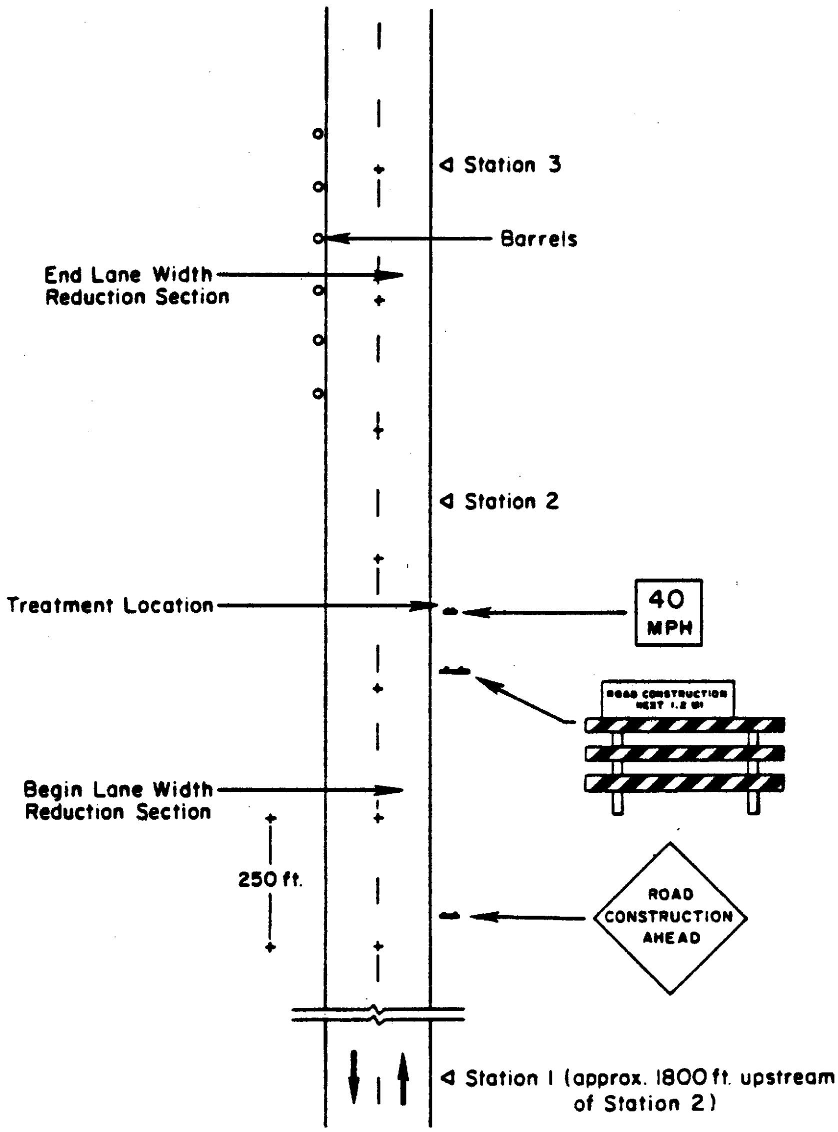


Figure 14. Layout, Site 5 (Rural 2-Lane, 2-Way Highway)

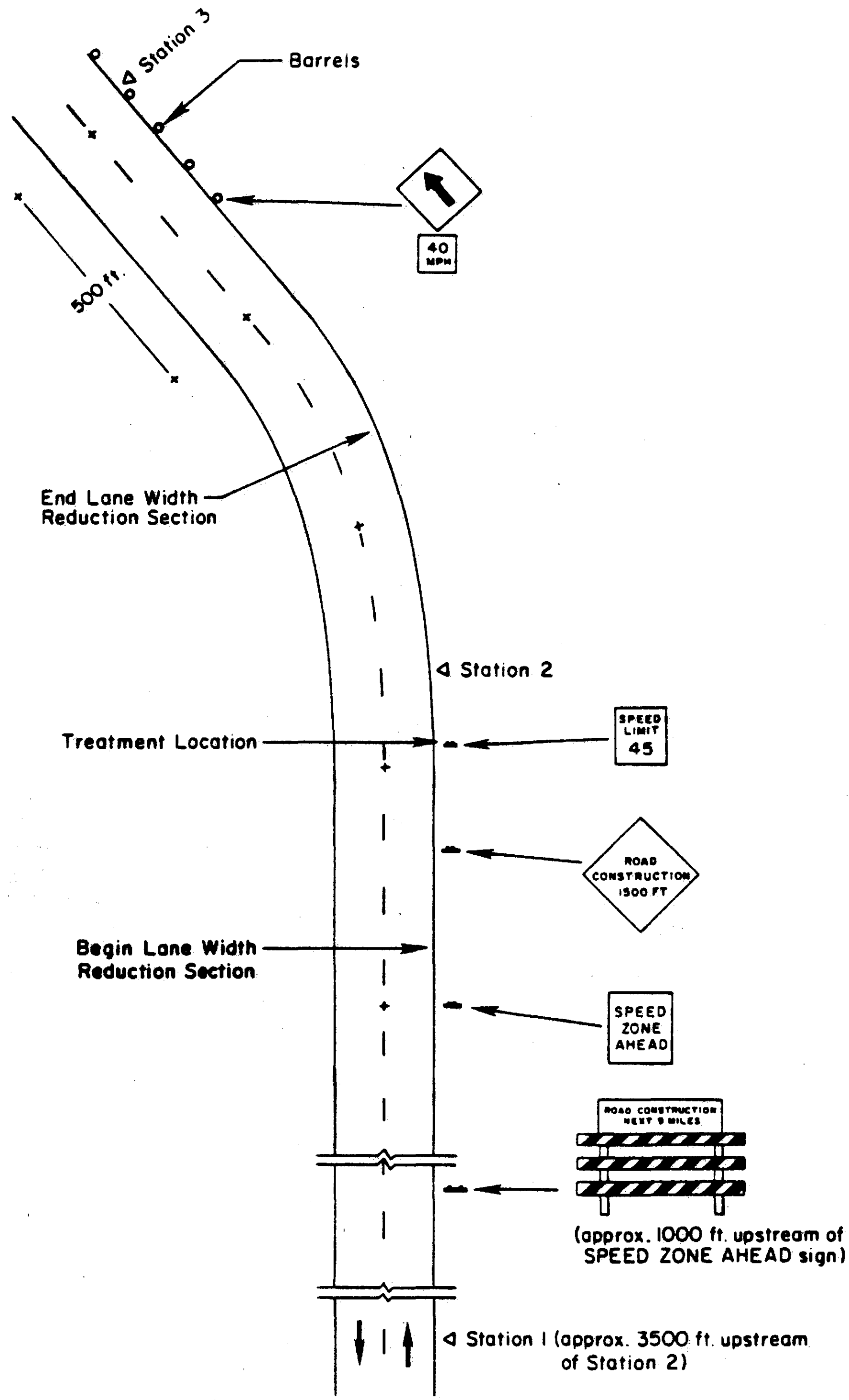


Figure 15. Layout, Site 6 (Rural 2-Lane, 2-Way Highway)

APPENDIX C - DESCRIPTION OF SPEED CONTROL TREATMENTS

Flagging Treatments

Three flagging treatments were evaluated during the studies. For all treatments, the flagger wore an orange vest and used a red flag. The flagger was positioned beside a regulatory or advisory speed sign facing traffic.

MUTCD Flagging

The flagger performed the "alert and slow" signal detailed in Section 6F-4, Part VI, of the MUTCD. The flagger slowly waved the flag in a sweeping motion with an extended arm from shoulder level to straight down without raising the flag above a horizontal position. The flagging maneuver was performed continually whenever traffic was present.

Innovative Flagging

The innovative flagging treatment was a modified version of the MUTCD treatment. First, the MUTCD flagging motion was performed to get the attention of approaching motorists. Then the flagger established eye contact with the motorist.

Having established eye contact, the flagger motioned for drivers to slow by raising and lowering his/her free hand, palm down, several times. The flagger then pointed to the adjacent speed sign to indicate the appropriate speed.

Thus, the innovative procedure consisted of 4 steps, repeated continuously whenever traffic was present:

1. Wave flag to gain driver's attention.
2. Develop eye contact with approaching motorist.
3. Motion with free hand for traffic to slow down.
4. Point with free hand to speed sign.

Under light traffic volumes, the flagger could direct the innovative flagging signal to each motorist. When traffic volumes were heavy, the signal was presented to lead drivers in a platoon and to as many additional drivers as was physically possible.

Innovative Flagging on Both Sides

At some of the freeway sites, the innovative flagging procedure was tested using flaggers on both sides of the travel lanes. The 2 flaggers simultaneously performed the innovative flagging technique described previously.

Law Enforcement Treatments

Five law enforcement treatments were tested. No citations were issued while any of the treatments were in effect.

Stationary Patrol Car - Lights and Radar Off

A uniformed officer sat in a marked patrol car parked on the roadside parallel to traffic. The patrol car was equipped with roof-mounted emergency lights and radar equipment, but these were not operated.

Stationary Patrol Car - Lights On

This treatment was identical to the previous treatment, with the exception that the patrol car's red and blue, roof-mounted, flashing lights were operated continuously.

Stationary Patrol Car -Radar On

A uniformed officer in a marked patrol car pointed an operative radar gun at vehicles as they approached. The patrol car was parked on the shoulder perpendicular to traffic such that the officer and radar gun were visible to approaching drivers.

Circulating Patrol Car

A uniformed officer drove a marked patrol car back and forth through the work zone area continuously. The patrol car's emergency lights and radar were not operated.

Police Traffic Controller

A uniformed officer, positioned on the shoulder beside a speed sign, motioned approaching drivers to slow down by raising and lowering his hand with the palm down. After attracting a driver's attention, the officer pointed to the speed sign to indicate the appropriate speed. This procedure was performed continuously whenever traffic was present.

A patrol car was parked beside the officer at Sites 3 and 6. At Site 5, the patrol car was not visible to oncoming traffic.

CMS Treatments

Two CMS treatments were evaluated at Sites 1-4. The treatments differed in the type of message presented (i.e., speed and information message or speed only message). The CMS speed advisory matched the posted speed limit. The specific messages displayed at each site are detailed in Table 20. The table also shows the type of CMS used at each site.

TABLE 20. CMS MESSAGES

Treatment	Site	Sign Type	Message[a]
Information Message and Speed Advisory	1	Truck-mounted, 1-line, bulb-matrix	DETOUR / AHEAD / 35 MPH
	2	Trailer-mounted, 3-line, bulb matrix	LEFT LANE CLOSED AHEAD / SLOW 45 MPH
	3	Trailer-mounted, 3-line, bulb-matrix	ROAD WORK AHEAD / 45 MPH
	4	Truck-mounted, 1-line bulb-matrix	DETOUR / AHEAD / 40 MPH
Speed Advisory Only	1	Truck-mounted, 1-line, bulb-matrix	35 MPH[b]
	2	Trailer-mounted, 3-line, bulb matrix	SLOW[b] 45 MPH
	3	Trailer-mounted, 3-line, bulb-matrix	45[b] MPH
	4	Truck-mounted, 1-line bulb-matrix	40 MPH[b]

[a]Slash (/) indicates phase change.

[b]Flashing off and on.

Effective Lane Width Reduction Treatments

Two effective lane width reduction treatments were tested. The difference between the two treatments was the resulting travel lane width (i.e., 12.5 feet or 11.5 feet).

Cones were used as the lane narrowing device for both treatments due to their availability and ease of transport, implementation and removal. Cones also presented a low level of hazard relative to other more formidable channelizing devices.

At the freeway and urban arterial sites (Sites 1-4), the cones were placed on both edgelines but not on the lane lines. Figure 16 illustrates the general treatment layout at these sites.

At the 2-lane, 2-way highway sites (Sites 5 and 6), cones were placed on the edge of the travel lane and on the centerline. Figure 17 displays the treatment layout for 2-lane, 2-way highways.

12.5-foot Lane Width

At the multilane sites (Sites 1-4), the cones were positioned as illustrated in Figure 18a. They were positioned just outside the edgelines so that the distance between the base of the cone and the nearest lane line was 12.5 feet.

At the 2-lane, 2-way highway sites (Sites 5 and 6), the cones were positioned so as to provide a 12.5 foot width between the bases of the cones (Figure 18b).

11.5-foot Lane Width

Figure 19 illustrates the application of the 11.5-foot effective lane width reduction treatment at the freeway and urban arterial sites (Sites 1-4) and 2-lane, 2-way highway sites (Sites 5 and 6).

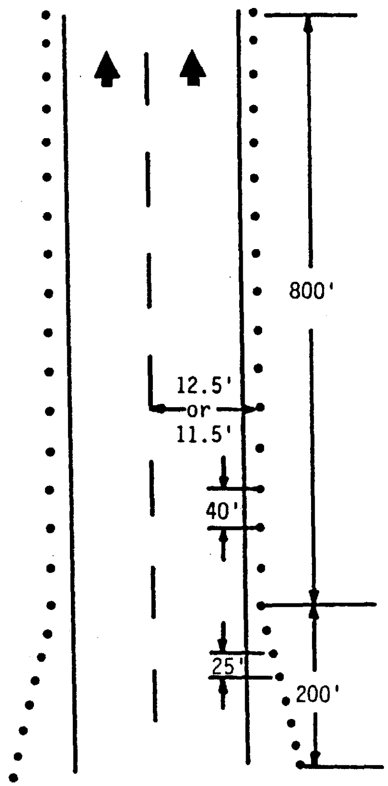


Figure 16. Effective Lane Width Reduction Layout at Freeway and Arterial Sites

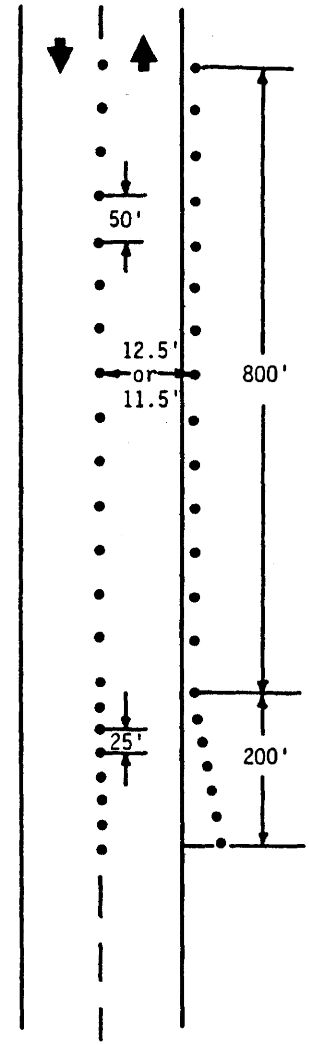
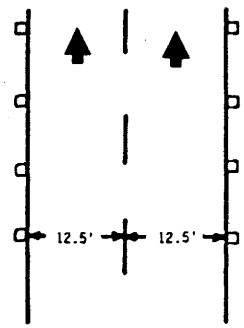
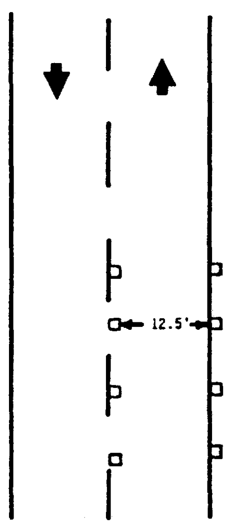


Figure 17. Effective Lane Width Reduction Layout at 2-Lane Highway Sites

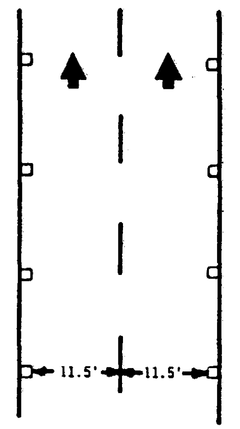


a. Cone Layout at Freeway and Arterial Sites

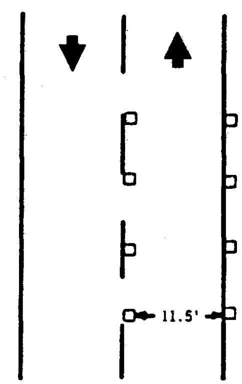


b. Cone Layout at 2-Lane, 2-Way Highway Sites

Figure 18. 12.5-Foot Effective Lane Width Reduction Configuration



a. Cone Layout at Freeway and Arterial Sites



b. Cone Layout at 2-Lane, 2-Way Highway Sites

Figure 19. 11.5-Foot Effective Lane Width Reduction Configuration

TABLE 21. PERFORMANCE OF FLAGGING TREATMENTS IN TERMS OF MEAN SPEED AND STANDARD DEVIATION AT STATION 2

Treatment	Urban Arterial	Rural Freeway		Urban Freeway	Rural 2-Lane Highway	
	Site 1	Site 2[b]	Site 3	Site 4	Site 5	Site 6
			MEAN SPEED (mph)			
Base Condition	54.8	58.4	56.1	57.4	51.9	55.4
Innovative Flagging	41.6[c]	--[a]	49.0	53.3	36.6	45.7
Innovative Flagging - Both Sides	--	45.3	--	52.8	--	--
MUTCD Flagging	43.6	49.8	51.7	54.5	40.6	47.7
			STANDARD DEVIATION (mph)			
Base Condition	6.4	5.0	5.5	5.6	6.8	5.7
Innovative Flagging	7.1	--	5.5	6.0	7.0	8.9
Innovative Flagging - Both Sides	--	5.4	--	6.1	--	--
MUTCD Flagging	7.3	6.1	5.8	5.3	6.6	7.7

[a]Not available.

[b]Two separate studies.

[c]___ = Significantly smaller mean compared with other flagging treatments at Site (.05 level).

TABLE 22. PERFORMANCE OF LAW ENFORCEMENT TREATMENTS IN TERMS OF MEAN SPEED AND STANDARD DEVIATION AT STATION 2

Treatment	Urban Arterial	Rural Freeway		Urban Freeway	Rural 2-Lane Highway	
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
			MEAN SPEED (mph)			
Base Condition	54.8	58.4	56.1	57.4	51.9	55.4
Police Traffic Controller	41.7	--	--	--	38.6[b]	46.5
Stationary Patrol Car	43.0	(49.9)[a]	51.6(51.7)	54.0	45.4	48.2
Stationary Patrol Car with Lights on	--	--	--	53.0	--	--
Stationary Patrol Car with Radar on	--	--	--	51.5	--	--
Circulating Patrol Car	--	--	--	--	50.7	52.6
			STANDARD DEVIATION (mph)			
Base Condition	6.4	5.0	5.5	5.6	6.8	5.7
Police Traffic Controller	7.3	--	--	--	5.7	6.4
Stationary Patrol Car	6.2	5.2	4.6(4.2)[a]	4.5	5.2	5.5
Stationary Patrol Car with Lights on	--	--	--	5.4	--	--
Stationary Patrol Car with Radar on	--	--	--	5.5	--	--
Circulating Patrol Car	--	--	--	--	6.2	6.7

[a]Parenthesis indicates patrol car on left side of travel lanes.

[b]___ = Significantly smaller mean compared with other law enforcement treatments at Site (.05 level).

TABLE 23. PERFORMANCE OF CMS TREATMENTS IN TERMS OF MEAN SPEED AND STANDARD DEVIATION AT STATION 2

Treatment	Urban Arterial	Rural Freeway		Urban Freeway	Rural 2-Lane Highway[a]	
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
MEAN SPEED (mph)						
Base Condition	54.8	58.4	56.1	57.4	51.9	55.4
Speed-Only Message	51.5	54.1	51.1[c]	59.4	--	--
Speed & Information Message	52.2	53.8	52.8	59.3(57.7)[b]	--	--
STANDARD DEVIATION (mph)						
Base Condition	6.4	5.0	5.5	5.6	6.8	5.7
Speed-Only Message	7.2	5.8	6.3	6.1	--	--
Speed & Information Message	6.6	4.7	6.1	5.9(6.0)	--	--

[a]No CMS available.

[b]Parenthesis indicates CMS relocated nearer to the work zones.

[c]___ = Significantly smaller mean compared with other CMS treatment at Site (.05 level).

TABLE 24. PERFORMANCE OF EFFECTIVE LANE WIDTH REDUCTION TREATMENTS IN TERMS OF MEAN SPEED AND STANDARD DEVIATION AT STATION 2

Treatment	Urban Arterial[a]	Rural Freeway[a]		Urban Freeway[a]	Rural 2-Lane Highway[b]	
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
MEAN SPEED (mph)						
Base Condition	54.8	58.4	56.1	57.4	51.9	55.4
11.5-foot Width Using Cones	52.3	52.5[c]	54.0	58.1	44.1	51.5
12.5-foot Width Using Cones	51.2	55.2	54.2	57.5	45.6	51.6
STANDARD DEVIATION (mph)						
Base Condition	6.4	5.0	5.5	5.6	6.8	5.7
11.5-foot Width Using Cones	6.7	5.9	6.1	4.9	8.8	6.8
12.5-foot Width Using Cones	6.1	5.6	4.5	4.7	6.4	6.9

[a]Cones placed on edges of pavement only.

[b]Cones placed on edge of pavement and centerline.

[c] ___ = Significantly smaller mean compared with other effective width reduction treatment at Site (.05 level).

APPENDIX E - SPEED PROFILES

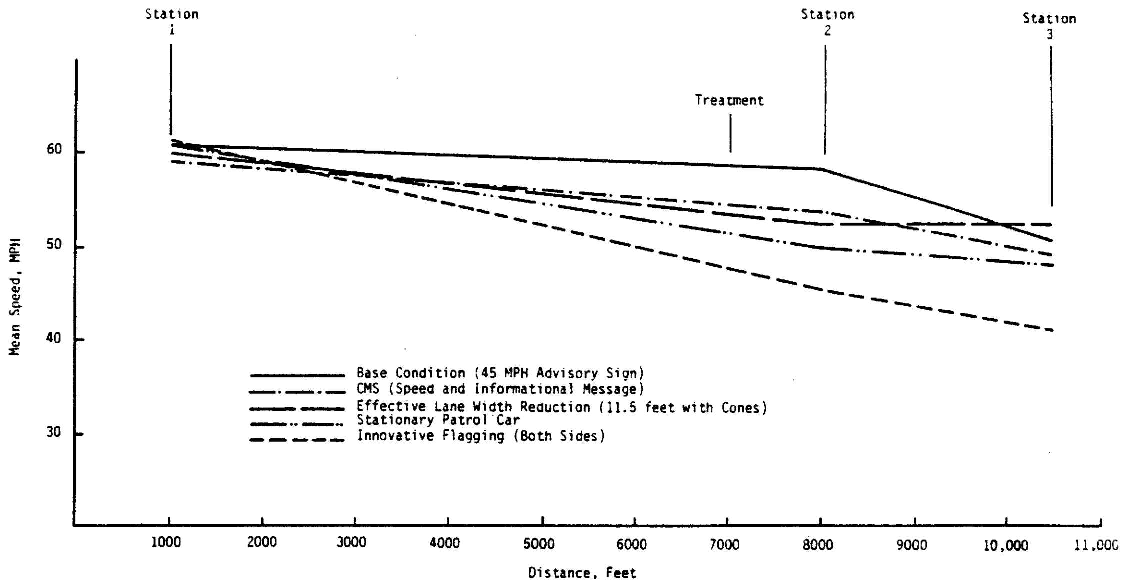


Figure 20. Speed Profiles of Selected Speed Control Treatments at Site 2 (Rural Freeway)

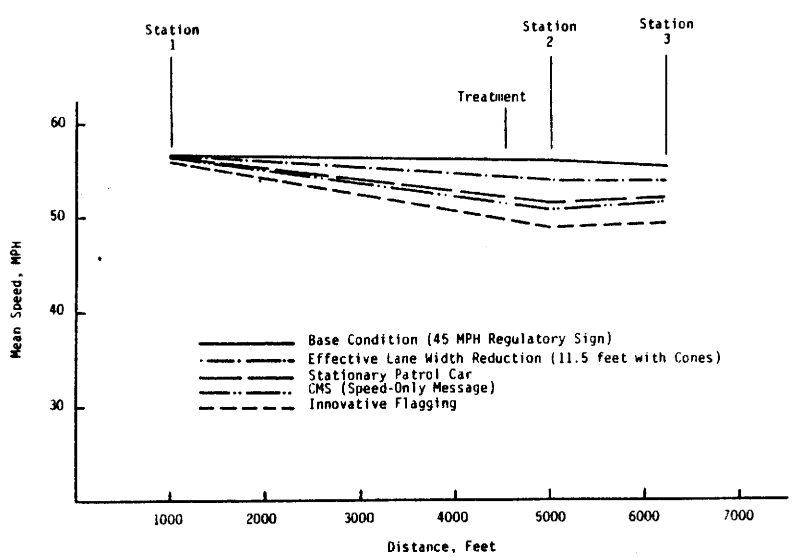


Figure 21. Speed Profiles of Selected Speed Control Treatments at Site 3 (Rural Freeway)

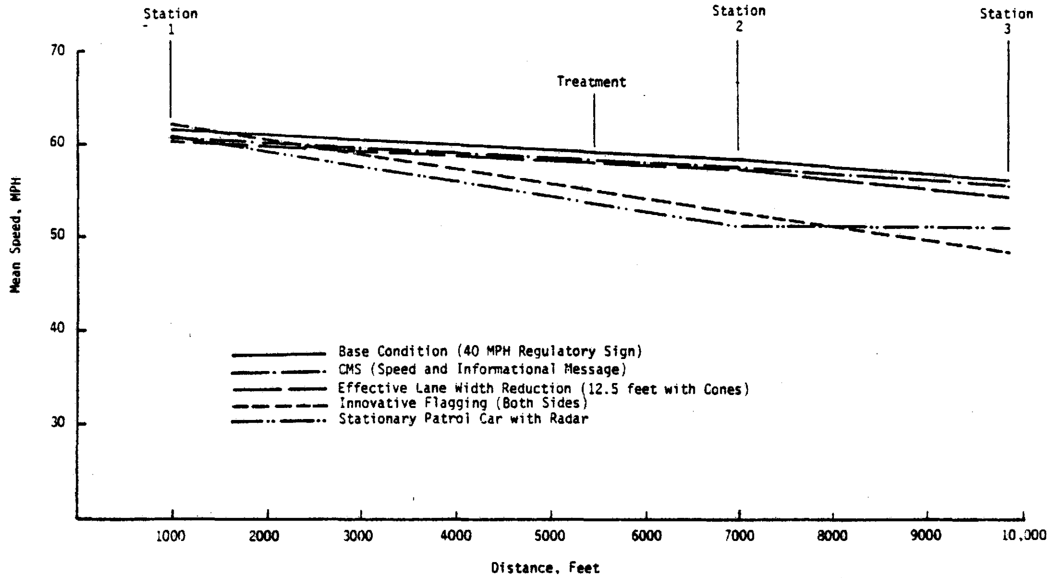


Figure 22. Speed Profiles of Selected Traffic Control Treatments at Site 4 (Urban Freeway)

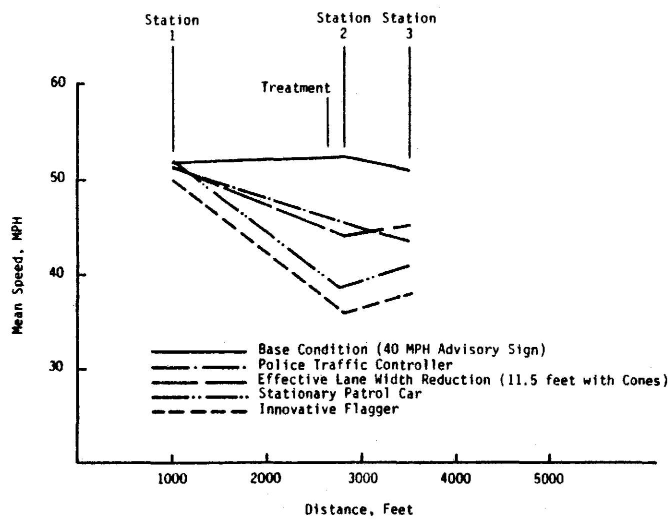


Figure 23. Speed Profiles of Selected Speed Control Treatments at Site 5 (Rural 2-Lane, 2-Way Highway)

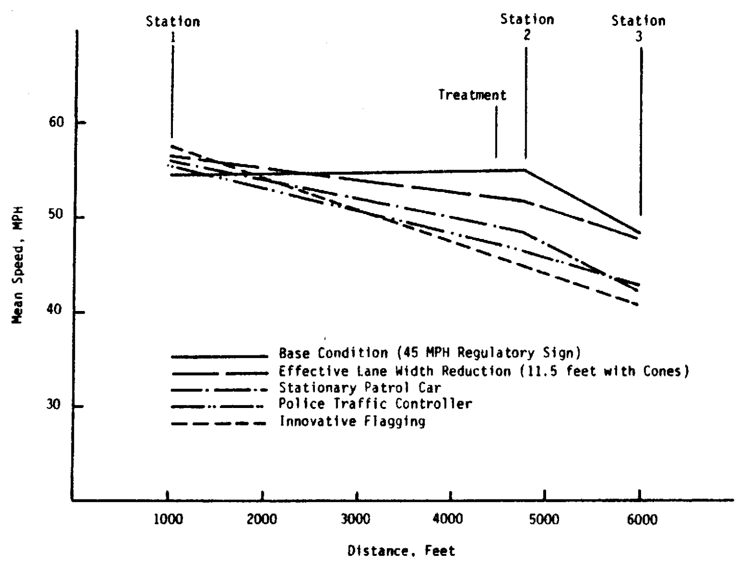
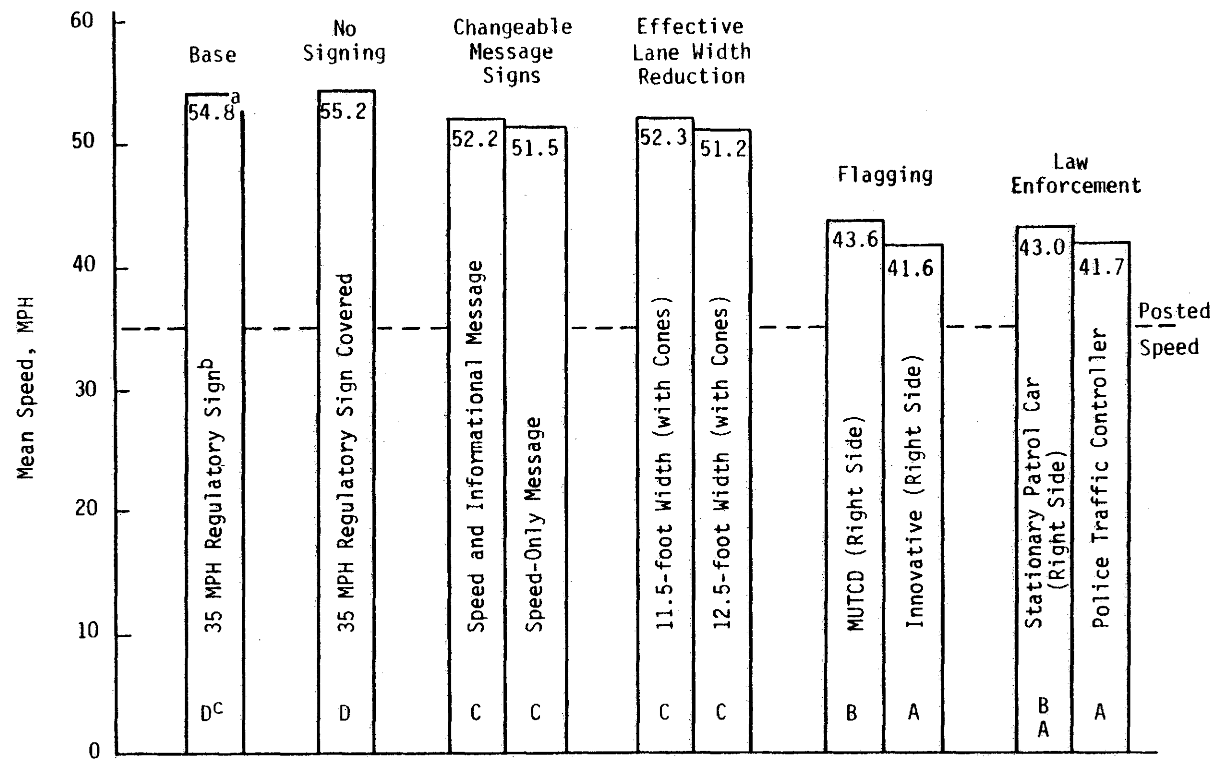


Figure 24. Speed Profiles of Selected Traffic Control Treatments at Site 6 (Rural 2-Lane, 2-Way Highway)

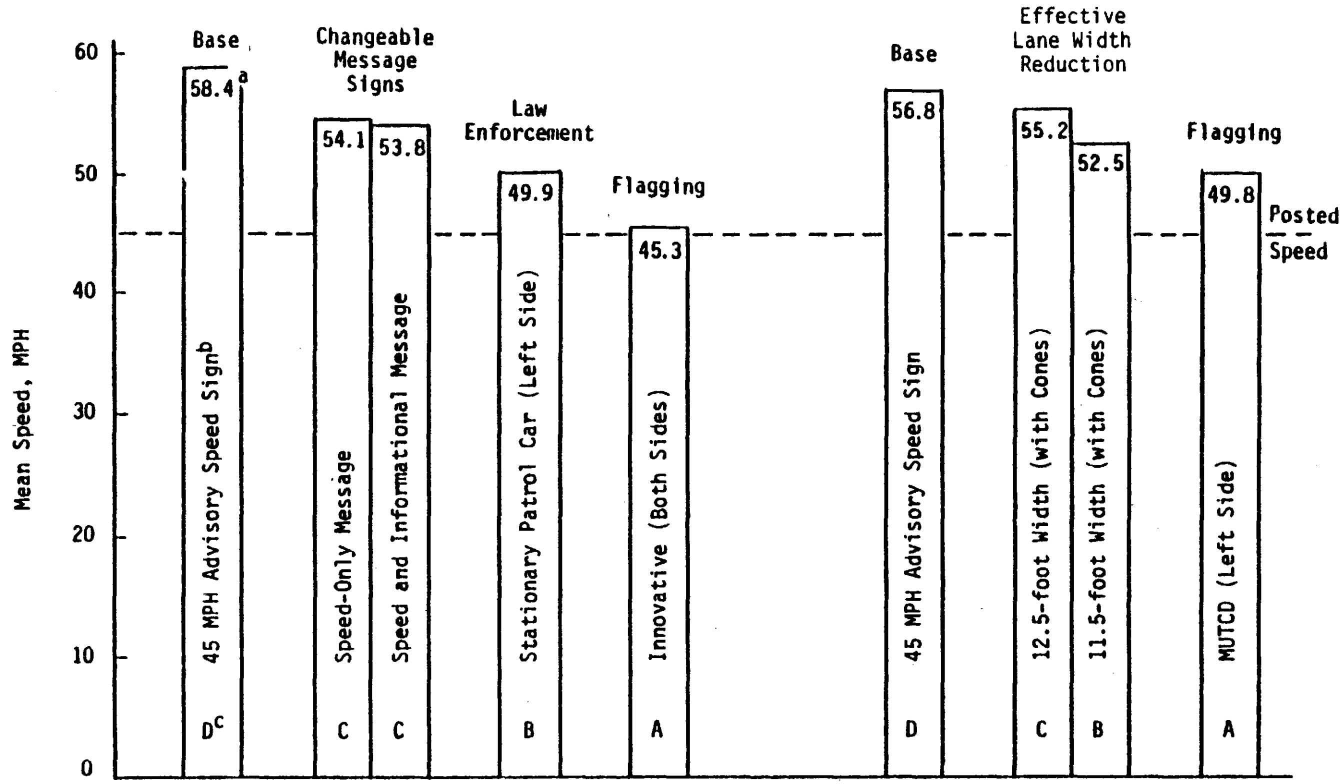


[a] Mean speed at Station 2 in miles per hour.

[b] Speed control treatment.

[c] There is no statistically significant mean speed difference between treatments with the same letter, based on Duncan's Multiple Range Tests.

Figure 25. Comparison of Speed Control Treatment Means at Site 1 (Urban Arterial)

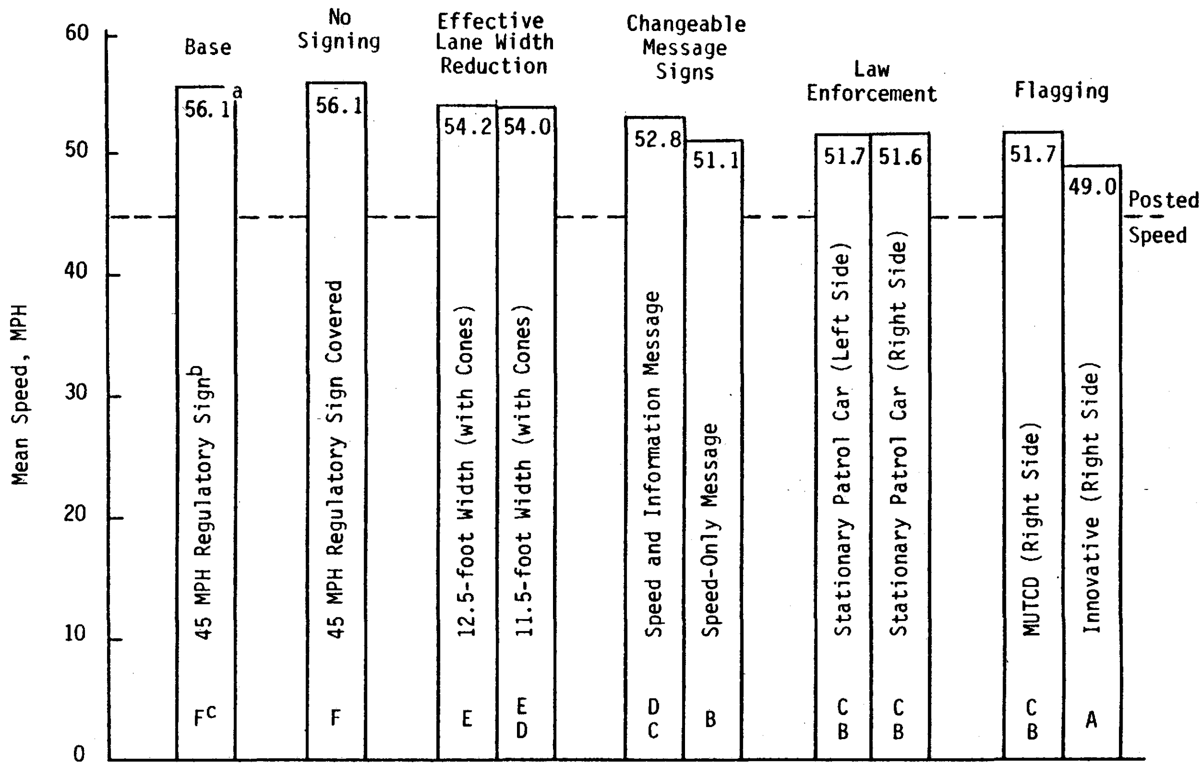


[a] Mean speed at Station 2 in miles per hour.

[b] Speed control treatment.

[c] There is no statistically significant mean speed difference between treatments with the same letter, based on Duncan's Multiple Range Tests.

Figure 26. Comparison of Speed Control Treatment Means at Site 2 (Rural Freeway)

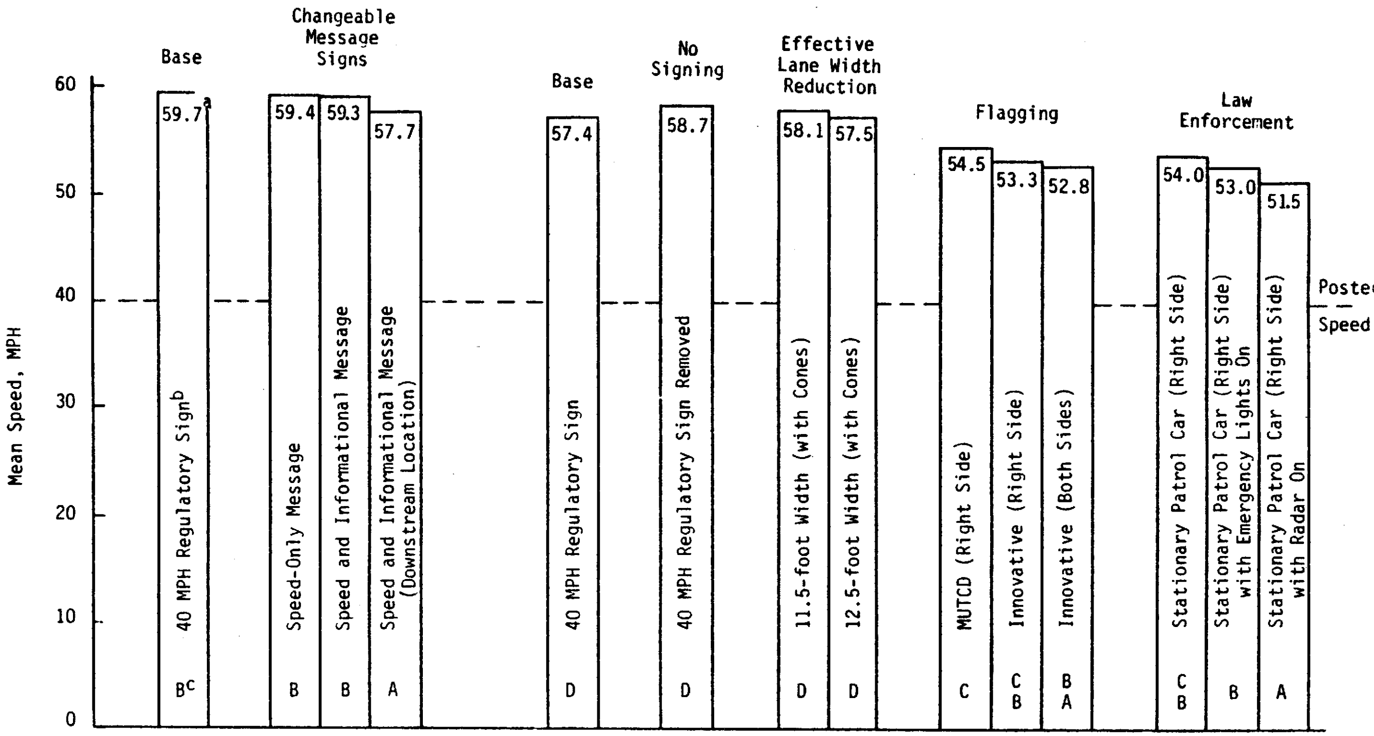


[a] Mean speed at Station 2 in miles per hour.

[b] Speed control treatment.

[c] There is no statistically significant mean speed difference between treatments with the same letter, based on Duncan's Multiple Range Tests.

Figure 27. Comparison of Speed Control Treatment Means at Site 3 (Rural Freeway)

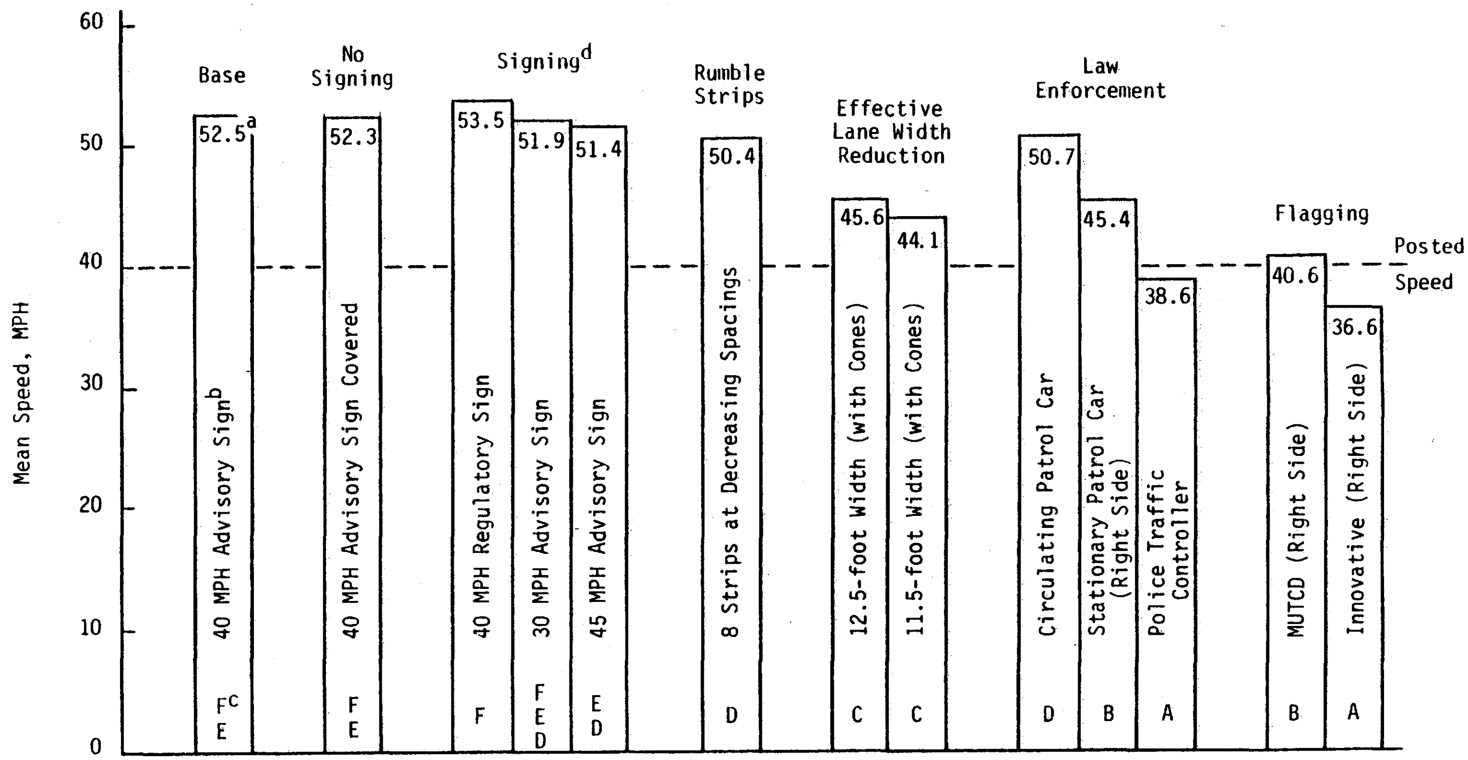


[a] Mean speed at Station 2 in miles per hour.

[b] Speed control Treatment.

[c] There is no statistically significant mean speed difference between treatments with the same letter, based on Duncan's Multiple Range Tests.

Figure 28. Comparison of Speed Control Treatment Means at Site 4 (Urban Freeway)



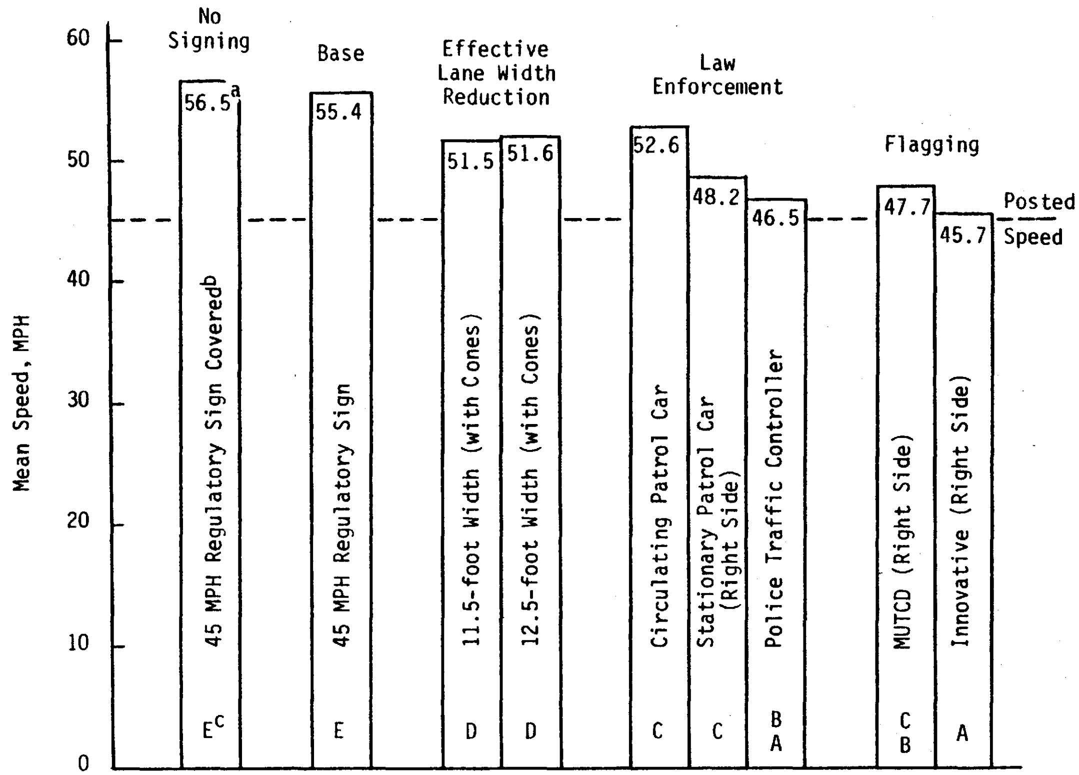
[a] Mean speed at 2 in miles per hour.

[b] Speed control treatment.

[c] There is no statistically significant mean speed difference between treatments with the same letter, based on Duncan's Multiple Range Tests.

[d] 40 MPH Advisory Sign (Base Condition Sign) was removed.

Figure 29. Comparison of Speed Control Treatment Means at Site 5 (Rural 2-lane, 2-way Highway)



[a] Mean speed at Station 2 in miles per hour.

[b] Speed control treatment.

[c] There is no statistically significant mean speed difference between treatments with the same letter, based on Duncan's Multiple Range Tests.

Figure 30. Comparison of Speed Control Treatment Means at Site 6 (Rural 2-lane, 2-way Highway)

APPENDIX G - MEAN SPEEDS AND STANDARD DEVIATIONS BY SITE

TABLE 25. SUMMARY OF MEAN SPEEDS AND STANDARD DEVIATIONS -- SITE 1 (URBAN ARTERIAL)

Speed Control Treatment	Mean Speed, MPH (Standard Deviation, MPH)		
	Station 1	Station 2	Station 3
Base-35 MPH Regulatory Signing	54.7 (6.7)	54.8 (6.4)	50.2 (6.1)
No Speed Signing	54.7 (6.3)	55.2 (6.1)	49.4 (5.6)
Effective Lane Width Reduction 11.5'	55.6 (6.7)	52.3 (6.7)	47.2 (5.7)
Effective Lane Width Reduction 12.5'	55.5 (5.8)	51.2 (6.1)	47.4 (5.8)
CMS-35 MPH Speed Message	55.5 (7.1)	51.5 (7.2)	46.3 (6.2)
CMS-Advisory and 35 MPH Speed Message	52.9 (5.2)	52.2 (6.6)	46.3 (6.2)
Police Traffic Controller	55.2 (6.1)	41.7 (7.3)	40.6 (5.0)
Stationary Patrol Car	53.5 (5.9)	43.0 (6.2)	41.0 (4.9)
Innovative Flagging-Right Side	53.5 (5.8)	41.6 (7.1)	39.8 (5.4)
MUTCD Flagging-Right Side	52.8 (6.0)	43.6 (7.3)	42.1 (5.9)

TABLE 26. SUMMARY OF MEAN SPEEDS AND STANDARD DEVIATIONS -- SITE 2 (RURAL FREEWAY)

Speed Control Treatment	Mean Speed, MPH (Standard Deviation, MPH)		
	Station 1	Station 2	Station 3
Base-45 MPH Advisory Signing*	60.7 (5.3)	58.4 (5.0)	50.5 (6.5)
Stationary Patrol Car-Left Side*	60.5 (5.9)	49.9 (5.2)	48.2 (6.0)
Innovative Flagging-Both Sides*	61.5 (4.9)	45.3 (5.4)	41.2 (5.9)
CMS-45 MPH Speed Message*	62.2 (5.3)	54.1 (5.8)	46.2 (7.9)
CMS-Advisory and 45 MPH Speed Messages*	58.8 (4.7)	53.8 (4.7)	48.6 (6.1)
Base 45 MPH Advisory Signing	59.0 (4.1)	56.8 (6.5)	52.8 (6.3)
Effective Lane Width Reduction 11.5'	59.9 (4.7)	52.5 (5.9)	52.8 (4.8)
Effective Lane Width Reduction 12.5'	59.2 (4.5)	55.2 (5.6)	52.9 (6.3)
MUTCD Flagging-Left Side	60.5 (4.8)	49.8 (6.1)	50.2 (5.2)

*Treatments conducted on (4-28-83).

TABLE 27. SUMMARY OF MEAN SPEEDS AND STANDARD DEVIATIONS -- SITE 3 (RURAL FREEWAY)

Speed Control Treatment	Mean Speed, MPH (Standard Deviation, MPH)		
	Station 1	Station 2	Station 3
Base-45 MPH Regulatory Signing	56.5 (4.0)	56.1 (5.5)	55.7 (4.8)
No Speed Signing	55.2 (3.8)	56.1 (5.1)	55.1 (4.0)
Effective Lane Width Reduction 11.5'	55.3 (3.8)	54.0 (6.1)	53.9 (4.9)
Effective Lane Width Reduction 12.5'	56.2 (4.7)	54.2 (4.5)	54.2 (4.8)
CMS-45 MPH Speed Message	56.1 (4.3)	51.1 (6.3)	52.1 (5.3)
CMS-Advisory and 45 MPH Speed Messages	56.3 (4.5)	52.8 (6.1)	52.7 (5.6)
Stationary Patrol Car-Left Side	55.7 (4.0)	51.7 (4.2)	52.5 (4.8)
Stationary Patrol Car-Right Side	56.5 (4.4)	51.6 (4.6)	53.0 (5.2)
Innovative Flagging-Right Side	55.9 (4.0)	49.0 (5.5)	49.3 (4.9)
MUTCD Flagging-Right Side	55.8 (4.4)	51.7 (5.8)	51.7 (4.5)

TABLE 28. SUMMARY OF MEAN SPEEDS AND STANDARD DEVIATIONS -- SITE 4 (URBAN FREEWAY)

Speed Control Treatment	Mean Speed, MPH (Standard Deviation, MPH)		
	Station 1	Station 2	Station 3
First Base-40 MPH Regulatory Signing	59.3 (6.1)	57.4 (5.6)	56.0 (5.5)
No Speed Signing	59.0 (6.4)	58.7 (5.6)	57.3 (6.9)
Effective Lane Width Reduction 11.5'	58.5 (6.1)	58.1 (4.9)	56.0 (5.9)
Effective Lane Width Reduction 12.5'	60.1 (7.5)	57.5 (4.7)	54.8 (5.5)
Stationary Patrol Car With Lights On	62.9 (7.5)	53.0 (5.4)	53.3 (5.7)
Stationary Patrol Car With Radar On	60.2 (6.7)	51.5 (5.5)	51.5 (5.4)
Stationary Patrol Car	60.5 (6.9)	54.0 (4.5)	53.6 (5.8)
Innovative Flagging-Right Side	58.8 (6.4)	53.3 (6.0)	53.2 (5.9)
Innovative Flagging-Both Sides	61.3 (8.0)	52.8 (6.3)	49.0 (6.0)
MUTCD Flagging	58.8 (6.7)	54.5 (5.3)	54.2 (5.5)

TABLE 28. (Continued)

Speed Control Treatment	Mean Speed, MPH (Standard Deviation, MPH)		
	Station 1	Station 2	Station 3
Second Base-40 MPH Regulatory Signing	62.1 (6.6)	59.7 (5.5)	57.2 (6.0)
CMS-40 MPH Speed Message	62.4 (6.1)	59.4 (6.1)	56.8 (6.4)
CMS-Advisory and 40 MPH Speed Messages	60.9 (6.4)	59.3 (5.9)	56.7 (5.9)
CMS-Advisory and 40 MPH Speed Messages (Downstream Location)	61.2 (6.6)	57.7 (6.0)	56.4 (6.0)

TABLE 29. SUMMARY OF MEAN SPEEDS AND STANDARD DEVIATIONS -- SITE 5 (RURAL 2-LANE, 2-WAY)

Speed Control Treatment	Mean Speed, MPH (Standard Deviation, MPH)		
	Station[a] 1	Station 2	Station 3
Base-40 MPH Advisory Sign	51.9 (5.6)	52.5 (6.4)	50.8 (6.9)
30 MPH Advisory Sign	51.8 (5.8)	51.9 (6.8)	50.4 (7.3)
45 MPH Advisory Sign	52.4 (6.1)	51.4 (5.9)	50.0 (5.9)
40 MPH Regulatory Sign	51.4 (5.3)	53.5 (6.2)	50.3 (6.3)
No Speed Signing	51.4 (5.1)	52.3 (5.8)	50.9 (6.7)
Effective Lane Width Reduction 11.5'	51.4 (5.5)	44.1 (8.8)	45.2 (8.4)
Effective Lane Width Reduction	51.5 (6.6)	45.6 (6.6)	45.7 (7.8)
Police Traffic Controller	51.9 (5.6)	38.6 (5.7)	41.2 (4.5)
Circulating Patrol Car	50.8 (5.5)	50.7 (6.2)	48.9 (6.7)
Stationary Patrol Car	51.6 (5.1)	45.4 (5.2)	44.3 (5.0)
Innovative Flagging	50.1 (6.4)	36.6 (7.0)	37.9 (5.6)
MUTCD Flagging	52.7 (5.8)	40.6 (6.6)	43.7 (6.0)
Rumble Strips	51.4 (5.1)	50.4 (6.2)	49.3 (6.6)

[a] Station Locations.

TABLE 30. SUMMARY OF MEAN SPEEDS AND STANDARD DEVIATIONS -- SITE 6 (RURAL 2-LANE, 2-WAY)

Speed Control Treatment	Mean Speed, MPH (Standard Deviation, MPH)		
	Station 1	Station 2	Station 3
45 MPH Regulatory Sign	54.6 (5.0)	55.4 (5.6)	48.7 (6.9)
No Speed Signing	55.6 (6.3)	56.5 (6.4)	51.4 (6.5)
Effective Lane Width Reduction 11.5'	56.5 (6.1)	51.5 (6.8)	48.2 (7.0)
Effective Lane Width Reduction 12.5'	54.7 (6.3)	51.6 (6.9)	47.9 (7.3)
Police Traffic Controller	55.1 (6.0)	46.5 (5.6)	42.2 (6.4)
Circulating Patrol Car	55.7 (5.6)	52.6 (5.6)	45.5 (6.7)
Stationary Patrol Car	55.9 (5.5)	48.2 (4.6)	42.6 (5.5)
Innovative Flagging	57.2 (6.0)	45.7 (8.9)	41.0 (6.2)
MUTCD Flagging	56.6 (6.5)	47.7 (7.7)	42.3 (7.0)

APPENDIX H - SPEED DISTRIBUTIONS

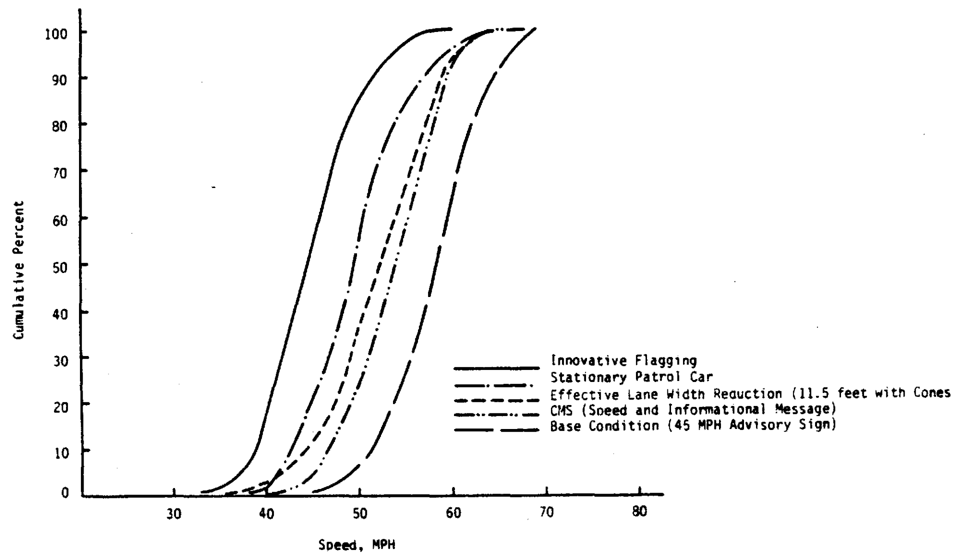


Figure 31. Cumulative Speed Distributions of Selected Speed Control Treatments at Site 2 (Rural Freeway)

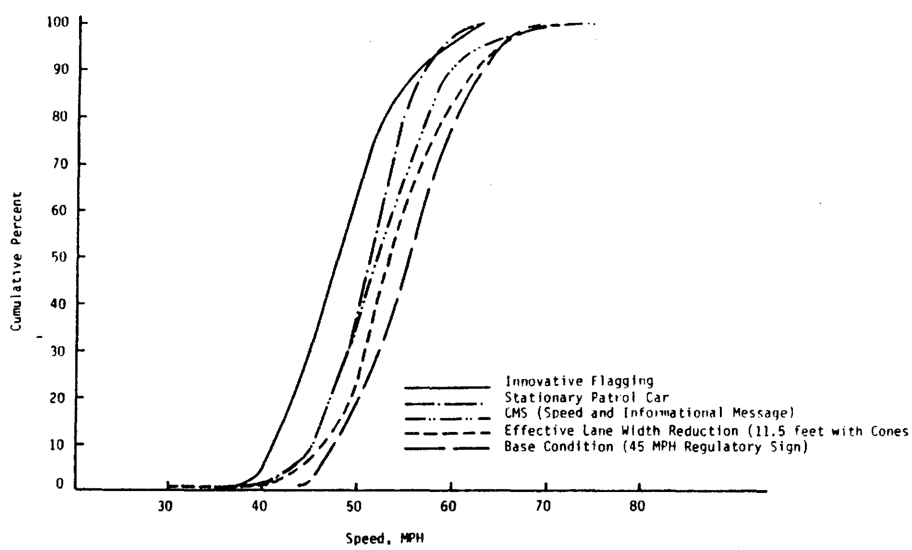


Figure 32. Cumulative Speed Distributions of Selected Speed Control Treatments at Site 3 (Rural Freeway)

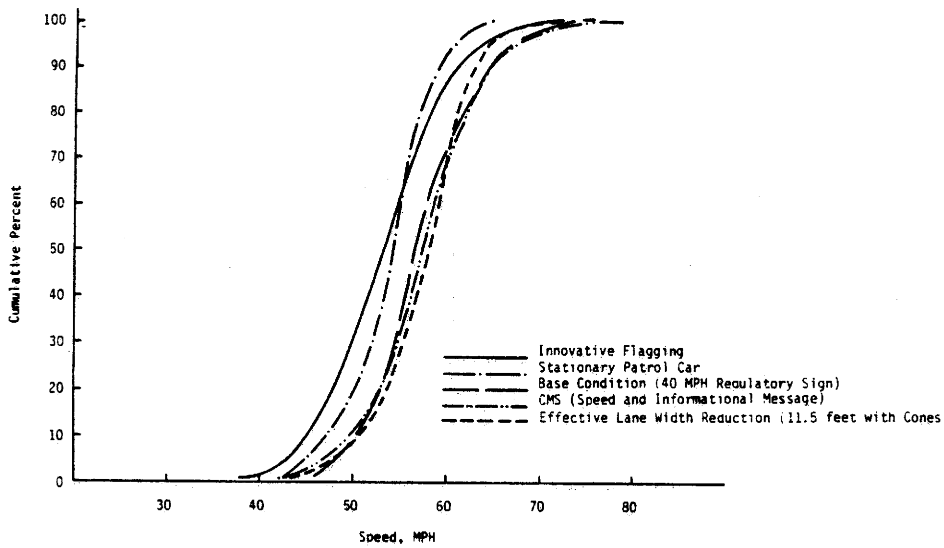


Figure 33. Cumulative Speed Distributions of Selected Speed Control Treatments at Site 4 (Urban Freeway)

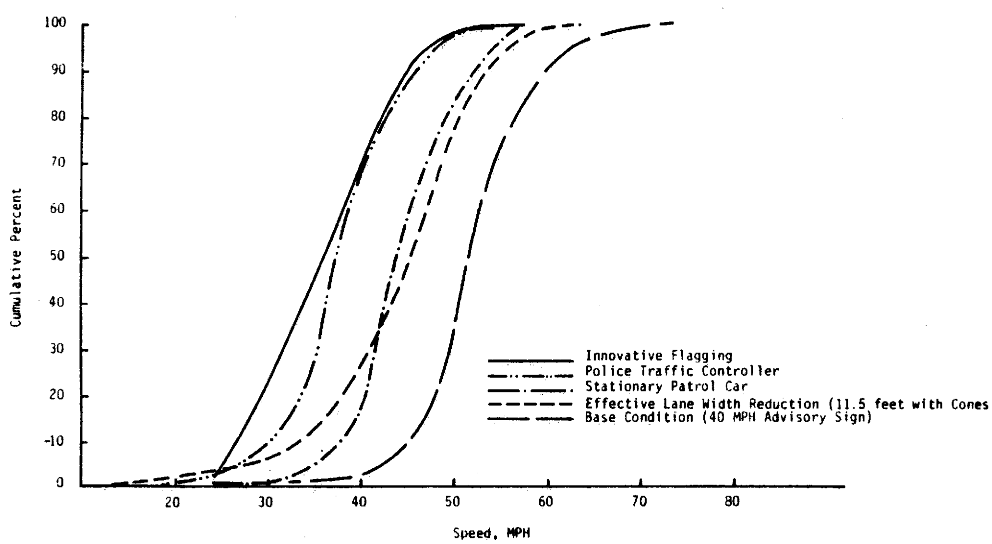


Figure 34. Cumulative Speed Distributions of Selected Speed Control Treatments at Site 5 (Rural 2-Lane, 2-Way Highway)

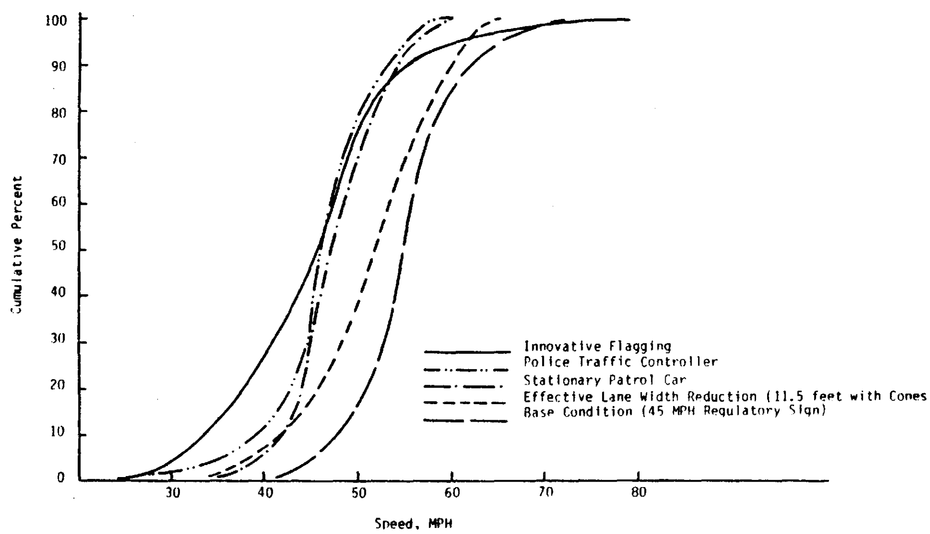


Figure 35. Cumulative Speed Distributions of Selected Speed Control Treatments at Site 6 (Rural 2-Lane, 2-Way Highway)

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F