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FOREWORD

The papers in this RECORD provide information on two important maintenance responsibilities: improving maintenance worker productivity and protecting workmen against intrusion of oncoming traffic into the work space.

Increased axle load limits, higher traffic volumes, and an aging highway system coupled with a serious loss of public support for highway funding indicate that maintenance managers will, in years to come, be sorely tried in their efforts to provide an adequate level of service. Managers hope mechanization will improve productivity and, in fact, new types of equipment are now being marketed: mobile concrete and asphalt plants, giant carbide-tipped cutting wheels, heated patching trucks, and litter machines. In this RECORD, Creech describes a machine for retexturing the surface of hardened concrete, and Long traces development of a quiet pavement breaker. These new tools will be valuable additions to maintenance equipment fleets.

Clearly, also, more work must be accomplished on even more congested highways, and this is likely to subject workmen to ever-increasing hazards unless better protective measures are forthcoming. An Organization for Economic Cooperation and Development report states: "Studies recently undertaken in the United States (California and Virginia) suggest that there can be an appreciable accident problem at construction sites." The study by Seymour, Deen, and Havens on sign effectiveness offers guidance in improving worker protection. The authors indicate that orange signs are slightly more effective than yellow signs but, significantly, they emphasize the importance of new or well-maintained signs in attracting the attention of motorists. A trip by automobile across the United States clearly indicates that the importance of this finding is not universally appreciated, and more attention should be given to improving the appearance of signs in daily use.

The papers in this RECORD will be of greatest interest to maintenance personnel, traffic engineers, and equipment engineers, but some of the results have application to construction forces, location crews, and others as well.

QUIET PAVEMENT BREAKING RESEARCH AND DEVELOPMENT AT THE INSTITUTE OF GAS TECHNOLOGY SINCE 1962

George M. Long, Institute of Gas Technology, Chicago

This paper reports research and development work by the Institute of Gas Technology on three nonconventional and quieter ways of breaking concrete pavement: plasma torch cutting, microwave cracking, and microwave cracking aided by a high-pressure water jet. The work, done under the sponsorship of gas distribution utilities, covers a 10-year span from 1962 to 1972. The most recent method, microwave cracking aided by a high-pressure water jet, has the potential of being quieter than conventional methods, of creating no shock to underlying or adjacent facilities, and of raising no dust. Its water use is minimal, and its power consumption and production rates are estimated as equal to or better than conventional large boom-mounted breakers.

•THE PROBLEM this specific research was trying to alleviate is the noise of pavement breaking with conventional pneumatic, mechanical, and hydraulic pavement breakers. Construction and maintenance crews, as well as the general public, have long suffered this seemingly unavoidable side effect of breaking up pavement to effect gas main construction, repairs, and replacements.

In spite of our tight gas supply situation and its effect on new construction, increased attention to maintenance, relocations, and replacements will most likely keep pavement breaking at past levels, if not above them. In addition, there is increased public and labor union awareness of the undesirable effects of noise. Recent federal, state, and municipal regulations limiting noise levels and exposures suggest that the problem will receive increased attention in the years ahead.

FEDERAL LEGISLATION AND ADMINISTRATION

Of nationwide interest is the recently passed federal Occupational Safety and Health Act of 1970 (OSHA) (1), which led to the creation of an administrative section within the Department of Labor made up of some 2,000 persons and headed by an Assistant Secretary. There were also staffs in seven regional offices throughout the United States (New York City, Philadelphia, Atlanta, Chicago, Kansas City, Dallas, and San Francisco). For noise provisions, the new act adopted the regulations of the older Walsh-Healey Public Contracts Act. These regulations place limits on the amount of time a worker may be exposed to various noise levels during his 8-hour workday. These levels are given in Table 1.

If we compare these sound levels to those that an operator of a hand-held or boom-mounted jackhammer hears, we find that the permissible duration time (working time) per workday is quite short, and, in many work situations, unacceptably short. The only legal solutions are to use several workers per tool, quiet the tool, or break pavement another, quieter way. The use of ear plugs or muffs is not considered by OSHA to be more than a temporary solution (presuming you could get workers to consistently wear them), and, of course, this does nothing to diminish the public nuisance.

Publication of this paper sponsored by Committee on Maintenance Equipment.

Using several workers is generally uneconomical. It neither reduces the public nuisance nor satisfies the community noise-level ordinances as fostered by the Office of Noise Abatement of the Environmental Protection Agency. Such community noise level ordinances specify acceptable instantaneous noise limits at property lines or at 50 ft from the source, and these may be harder to meet than the higher levels and durations permitted by OSHA at the operator's ear. Quieting the tool has been attempted over the years and has succeeded to various degrees, although market response to the attachments developed has been minimal. One reason for this minimal response is that most attachments are exhaust mufflers, which reduce the power output of the pneumatic tool. Another, less rational, reason is that many construction men associate noise with productivity; that is, if you are not making noise, you are not working.

INITIAL WORK, 1962

The Institute of Gas Technology (IGT) began to develop low-noise methods of pavement removal in 1962 under the sponsorship of the Consolidated Edison Company of New York, a combined gas and electric utility serving New York City. That the utility serving our nation's largest city should take the lead in seeking quieter ways of doing its work should be no surprise. With most of its facilities—mains and cables—under the "wall-to-wall" paving of New York, ConEd was further obliged to do much of its work at night to minimize interference with traffic. Day or night, New York's "canyons of steel" cause any noises to reverberate and seem magnified. Consider, too, the utility employee working over a noisy jackhammer all night and trying to sleep during a typical day in New York City.

To begin developing a method for quieter pavement breaking, IGT selected and investigated 10 potential nonconventional methods then viable. Speed, costs, availability of equipment, and noise characteristics of the methods were compared in literature and in preliminary laboratory work. All methods were capable of destroying the structural integrity of concrete paving, which was considered to be the hardest kind to remove. After investigation the field was narrowed to one method, plasma flame, for which equipment was then readily available. Plasma flame also appeared to offer the best means of cutting a variety of paving materials in addition to concrete, such as asphalt, asphalt-concrete composites, and reinforcing bars or wires.

PLASMA FLAME DEVICE, 1963-1965

Plasma is defined as a highly ionized, electrically conducting, compressible fluid. Both hot and cool plasmas exist. Neon signs and fluorescent lights are examples of cool-plasma applications. I am concerned here, however, with hot plasmas such as those formed in direct-current arc discharges. Such hot plasmas can be either stationary or flowing. Arc-welding and electric-arc furnaces for melting are examples of stationary hot-plasma devices. IGT selected a flowing hot-plasma torch capable of directing an extremely hot gas through an orifice in one of the electrodes. (The hot-plasma torch, developed by Gage of Union Carbide Corporation in the early 1950's, is capable of temperatures from 10 000 to 20 000 K.) A simplified cutaway drawing of the Plasmadyne Corporation torch used initially is shown in Figure 1. A dc arc for heating the gas is maintained between a solid tungsten electrode and a hollow, water-cooled copper electrode with the gas, initially argon, forced through under high pressure. Other, less expensive gases were gradually interchanged with argon; later work completely eliminated the need for argon.

A 150-kW dc generator with variable voltage was used to establish and maintain the arc; a control console monitored voltage, current, and gas flow; and a resistor bank controlled operating currents during start-up. This generator, control console, resistor bank, and the torch (Fig. 1) made up the total equipment package. All elements except the generator are shown in Figure 2.

The system cuts concrete by melting it and blowing much of the lava out of the cut (Fig. 3). The cut considerably weakened the concrete below and adjacent to it, which made breakage possible without full-depth cutting. The most significant variable affecting the depth of the cut was the rate of travel along the concrete, with a low penetration

Table 1. Permissible noise exposures.

Duration per Day (hours)	Sound Level (dBA, slow response)
8	90
6	92
4	95
3	97
2	100
1½	102
1	105
½	110
<¼	115

Notes: When daily noise exposure is composed of two or more periods of noise exposure of different levels, their combined effect should be considered, rather than the individual effect of each. If the sum of the following fractions: C1/T1 + C2/T2 . . . Cn/Tn exceeds unity, then the mixed exposure should be considered to exceed the limit value. Cn indicates the total time of exposure at a specified noise level, and Tn indicates the total time of exposure permitted at that level. (Exposure to impulsive or impact noise should not exceed 140 dBA peak sound pressure level.)

Figure 1. Plasma torch.

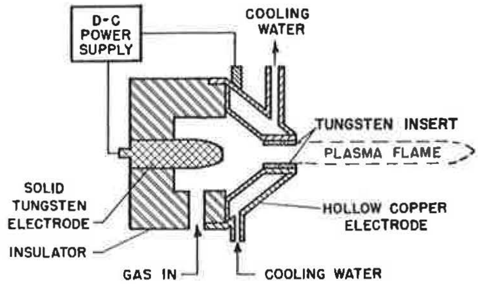


Figure 2. Plasma torch cart with sound-attenuation housing.

Figure 3. Concrete with cuts made by plasma torch.

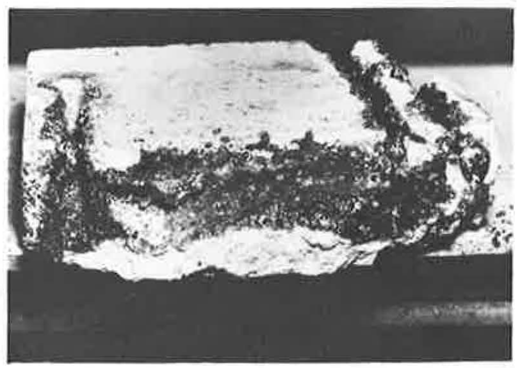
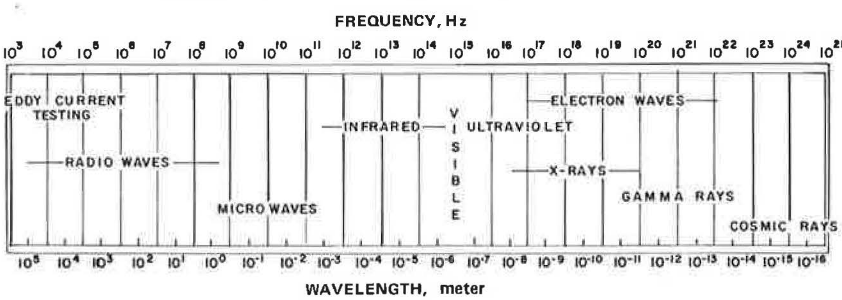


Figure 4. Electromagnetic spectrum showing relative position of microwaves.



at 10 to 12 in./min. and a 4-in. penetration at ½ in./min. However, the original torch had to be rebuilt several times because of melting from the radiant heat that resulted from the lower travel speed. New torch designs were developed to overcome this short life. These new torches also gave (a) 100 percent use of less expensive gases such as hydrogen and nitrogen, but not methane (natural gas); (b) quick production of slag sumps to drain off flowing lava; (c) lower noise levels; and (d) higher power levels.

Further development was halted, however, by a need for higher power levels for faster cutting. The 150-kW source already was considered almost "too big" for gas company field purposes. It also had a borderline high noise level (even when muffled) that would increase with the otherwise desirable higher power levels.

The search then turned to another of the original 10 nonconventional methods—microwave radiation, which promised quieter operation, lower power requirements, and available hardware.

MICROWAVE DEVICE, 1966-1969

Microwaves are electromagnetic waves of short wavelength and consequently high frequency. They have higher frequencies than most radio waves and lower frequencies than infrared or visible light (Fig. 4). Like radio waves they can penetrate most electrical nonconductors and, to some extent, poor conductors. Like light, microwaves can be reflected or focused by using metallic mirrors or lenses. They can also be directed through metal piping, metal ductwork, or flexible metal-containing wall conduits.

Principal industrial uses of microwaves are for cooking or other processing of foods and for drying of lumber and its products. Microwaves also have medical and communications applications. What I am concerned with here is another possible industrial use of the internal heating ability of microwaves: the expansion of local areas of concrete (hot spots) to induce tensile failure between them.

One of the initial applications of microwave heat cracking was demonstrated in 1962 by the Mullard Company of Great Britain, which used it to fracture rock (3). The Mullard applicator consisted of a probe inserted into a predrilled hole some 2 in. in diameter in an 18-in. basalt cube, which was then cracked. The British Building Research Station also cracked 9-in.-thick concrete by microwaves in 1962 or earlier. (The Russians had reportedly used microwaves to crack rock in 1952.)

IGT microwave development began with an extensive literature search into the reaction of concrete to microwave energy and a survey of available equipment. As a result IGT purchased the Mullard equipment and conducted many laboratory studies of the behavior of concrete under microwave radiation.

From this work several microwave applicators were designed, constructed, and tested. All of them were to alleviate the necessity of predrilling a hole as required for the probe type of applicator. One, a multihorn applicator design, was selected for further development because its linear alignment allowed crack location and direction to be reasonably well controlled.

The cracks produced were quite fine but ran the full depth of the concrete. The faces of a crack were rough, however, with a surface texture not unlike that produced by mechanical breakage methods. This created an interlock that prevented the concrete from being lifted out vertically unless some horizontal separation took place first.

After additional laboratory testing and refinement of this design, equipment elements were assembled for a field unit. A design was developed and built (Fig. 5) featuring a pair of applicator horns and one 5-kW output microwave-generating magnetron mounted in each of two caster-equipped modules. These modules were connected with flexible cables and hoses (for cooling water) to a van (Fig. 6) containing the power supply, which consisted of an ac generator driven by an engine-power take-off, transformers, ac to dc converters, and a magnetron cooling system. We also developed a microwave cavity (oven) for asphalt removal.

After laboratory testing and modification, field testing of the mobile equipment was done at IGT and in the New York City area (Fig. 7) under the sponsorship of ConEd. The results of these tests follow.

1. Concrete was cracked with low noise (the van's engine made most of the noise)

Figure 5. Microwave applicator modules.

Figure 6. Microwave van.

Figure 7. Microwave van and equipment in New York City.

Figure 8. Backhoe removal of microwave-cracked concrete from a free edge.

Figure 9. Use of an air hammer to break away microwave-fractured concrete.

and could be readily removed with a backhoe when working from a free edge as a starting point (Fig. 8).

2. If no free edge was available, as would be true for a midstreet repair hole, conventional tools (e.g., air hammers) were needed to provide room for the cracked, but interlocked, concrete to separate. Conventional tool use, however, was reduced to one-fifth to one-third the time required without microwave cracking (Fig. 9).

3. Cracks were easily controllable by the multihorn linear arrangement, and it could outline a hole or divide the concrete into manageable-sized pieces (Fig. 10).

4. With the 10-kW power level (two 5-kW adjacent modules), pavement cracking rates of 0.3 to 1 ft/min occurred with concrete from 9 to 5 in. thick. An 11-in.-thick concrete machinery foundation was readily cracked.

5. Extraneous microwave radiation was less than the maximum established health levels and is therefore safe (Fig. 11).

6. Sensitive, broad-band equipment could detect no radio and television interference.

7. Gas utility street crews performed the general operation of the microwave equipment.

8. Successful cracking was done after heavy rainfalls, although in one instance free water had to be baked out of a porous type of concrete by the microwaves before the usual heating and cracking took place.

9. Top layers of concrete less than 2 in. thick tended to spall and crater off down to the interface between layers rather than crack along the horn line.

10. No shock was transmitted to underlying gas or water mains, cable duct, sewers, etc., or to adjacent structures as is often the case with conventional pavement breaking methods, especially the larger boom-mounted and drop-hammer types.

At the conclusion of this work in 1969, the interlocking nature of the cracks was considered the major deterrent to field acceptance.

PAVEMENT BREAKING WORK SINCE 1970

High-pressure water jets are being investigated, tested, and constructed as a companion to the microwave concrete-breaker. When concrete samples were preweakened with microwave-induced cracks, water-jet shots effectively exploited those cracks (Fig. 12) and overcame the interlock problem caused by the uneven surface of the crack plane.

Both the microwaves and water jet caused the concrete to fail in tension. Because the tensile strength of concrete is only one-tenth its compressive strength (i.e., tensile strength of 300 to 600 psi versus compressive strength of 3,000 to 6,000 psi), less energy is required for breaking than with conventional methods that generally begin by exceeding compressive strength.

Further, the microwave preweakening considerably lessens the pressures and energy levels reported for water-jet devices used on nonpreweakened concrete. The overall system including microwaves and water jets also appears to provide faster breakage of concrete than unassisted water jets.

The basic component in producing the high-velocity water jet is a pressure intensifier (Fig. 13) consisting of two cylinders. The larger cylinder can be cocked by air, gas, or hydraulic fluid against a closed pressure vessel, which contains a compressed gas that acts like a spring when the cocking fluid is removed. When this happens, the gas spring forces the large piston, rod, and small piston (end of rod) into the water cylinder, which forces water at high pressure out of a small-diameter nozzle. The velocity of this small jet of water is quite high and imparts its energy to a small area of the concrete. The amount of water used is minimal. In addition to producing low noise levels, the water jet has the advantage of causing no shock to underlying facilities or adjacent structures and of raising no dust.

Current work at IGT involves building and field testing two portable water-jet devices under the sponsorship of six gas distribution utilities: Consumers' Gas Company (Toronto), Long Island Lighting Company (Hicksville), Consolidated Natural Gas Service Company (Cleveland), Southern California Gas Company (Los Angeles), Brooklyn Union Gas Company (Brooklyn), and Consolidated Edison Company of New York (New York City).

Figure 10. Example of microwave fracture pattern on 5-in.-thick concrete.

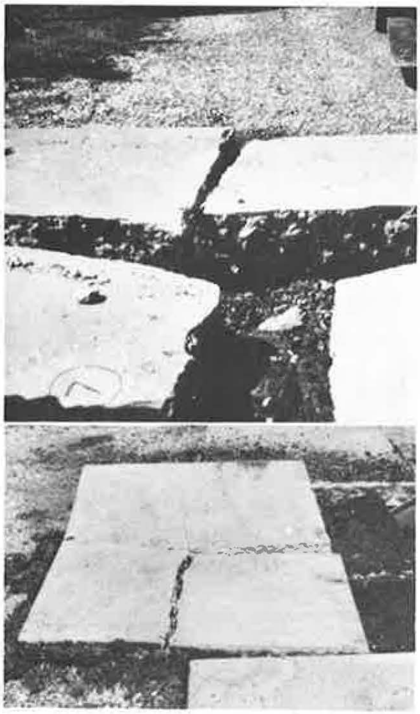
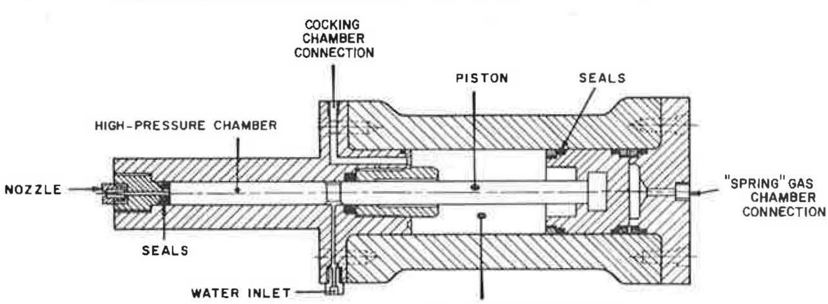


Figure 11. Checking for stray microwave radiation.

Figure 12. Results of three water-jet shots on microwave-cracked concrete.

Figure 13. Single-stage intensifier for producing high-pressure water jets.



The jets will first be compared in the laboratory with results previously achieved with a nonportable, laboratory water-jet device. Next, they will be compared with their microwave companion and then together both will be compared with conventional pavement breaking methods in relation to production rate, noise, shock, and dust. This will be done on uniform pavement slabs, including reinforced and asphalt-topped pavement. The systems will also be tried on frozen earth and, later, field-demonstrated in "sponsor territory."

Commercialization will require design and testing of preproduction prototypes based on the results of our current work. Both water jets and microwave equipment probably could be considerably reduced in size and weight and be more conveniently packaged as a system once operating parameters are established. I hope that an American manufacturer can be interested in providing the world's gas utilities and other pavement breakers with a desirable product that might help to quiet things down a bit and make pavement breaking a bit more tolerable and law-abiding.

REFERENCES

1. Occupational Safety and Health Act of 1970, Public Law 91-596, S. 2193.
2. New Scientist, May 31, 1962.

MECHANICAL ALTERATION OF THE TEXTURE OF OLD CONCRETE PAVEMENT WITH THE KLARCRETE MACHINE

Marion F. Creech, Virginia Highway Research Council, Charlottesville

Experiments were performed with the British Klarcrete machine to determine its capability for removing the top layer of roadway to a depth of ⅛ to ¼ in. (3.175 to 6.35 mm) and, in so doing, to expose a fresh surface of highly fractured coarse aggregate to give a better skid resistance. In addition, experimentation was performed to determine whether the machine could be used as an efficient means of completely cleaning bridge decks of coal-tar epoxy prior to resealing. The machine employs 11 percussive hammers, mounted side by side at 2¼-in. (57.15-mm) intervals, that each strike the pavement approximately 1,500 blows/min and cut a maximum swath of approximately 4 ft. Each impact removes only a small amount of material but does not injure the surrounding pavement. The sole power requirement is a 600 ft^3 (17 m^3) per minute compressor producing 100 $lb/in.^2$ (689 kPa) pressure. The machine is self-propelled and its forward speed determines the depth of surface removed. In the experiments, the machine removed the surface layer of pavement and exposed a new surface of coarse aggregate with fractured jagged edges slightly raised above the surrounding mortar. It left no irregularities for water to pond and did not impair the riding quality of the road. Extensive skid testing proved that the skid resistance was raised significantly under specified conditions. The bridge cleaning experiment was successful, with the bridge being cleaned more efficiently, faster, and with less expense than by sandblasting.

•THE EXPERIMENTS reported here were conducted as part of an evaluation of available methods for increasing the harshness of texture of old concrete pavements. Included among the methods to be evaluated in the overall study are those that are presently used, such as grooving and sandblasting, but the real emphasis is to discover new and better methods of roughening the pavement. It probably is not necessary to recount the reasons for effort being spent in search of better ways of increasing the texture of concrete pavements. It will suffice to note that concrete pavements have been proved to approach a slippery condition when wet after 20 to 25 million vehicle passes (1) and that many concrete pavements recently put into service are approaching that accumulated volume. Long before this type of pavement becomes slippery as measured by conventional methods, the surface becomes smooth, and this, when coupled with the inability of portland cement concrete to allow water to penetrate the surface even under pressure, provides an ideal condition for hydroplaning under specified water, tire tread depth, and velocity conditions.

One avenue of investigation emphasized in the study was the mechanical alteration of pavements (2). It was contemplated that the exploration of this avenue would include a search for new machines that would physically remove part of the pavement surface through abrasion or other methods so as to leave a slightly uneven and unpolished new surface.

Publication of this paper sponsored by Committee on Pavement Maintenance.

In pursuing this avenue of investigation, it was learned that a British company, Klarcrete, Ltd., had developed a machine for treating concrete pavements, and it was obtained on a rental basis for a pilot study.

THE KLARCRETE MACHINE

The Klarcrete general-purpose concrete repair machine removes the pavement surface by employing 11 percussive hammers that operate independently, each striking the pavement approximately 1,500 blows/min. The machine operates on compressed air and requires at least a 600-ft^3 (17-m^3) per min compressor capable of producing 100 lb/in.^{2} (689 kPa) of compressed air. The hammers are 2¼ in. (57.2 mm) in diameter and 2¼ in. apart. They are mounted on a carriage that allows vertical movement and that in turn is attached to a transverse carriage that allows lateral movement. The lateral movement is necessary to get uniform removal of concrete over the width of operation. The width of cut can be varied from 4½ in. (114.3 mm) (diameter of cutting head plus space between cutting heads) to 49½ in. (1.3 m) in 4½-in. (114.3-mm) increments by adding or deleting individual cutting heads. Figure 1 shows the configuration of the cutting heads. The cutting heads, which require no lubrication and are free to rotate, break the concrete into small particles of a gradation not much larger than dust and cause no damage to the surrounding concrete. A person standing on the pavement beside the machine while it is in operation can notice the vibrations, but they are not great. The machine removes the surface by the number of impacts rather than the force of individual impacts. When the object is to remove the top surface of the concrete in a continuous sweep, the machine travels slowly forward under its own power. The depth of removal of concrete depends on the forward speed of the machine. A small pneumatic motor attached to the left rear wheel allows automatic operation and permits the towing of a compressor power source.

Figure 2 shows the Klarcrete machine being positioned for operation with the cutting heads in the raised position. Figure 3 shows the machine with the 11 percussive hammers in operation, and Figure 4 shows the machine with the compressor attached.

The control mechanisms for adjusting the speed of the machine, reversing its direction, and steering it are located on the tiller, which is attached to the front of the machine. Figure 5 shows a technician backing the machine by the controls and steering mechanism on the tiller. A second set of controls located on the right side of the machine regulates the speed (both transverse and vertical) and the pressure to the cutting head. A side view of the control box is shown in Figure 5.

The technical and physical aspects of the machine are given in Table 1.

PURPOSE

This project was initiated to determine the ability of the Klarcrete machine to remove the surface layer of concrete to an approximate depth of ¼ in. (6.35 mm) and, in so doing, to chip and fracture the aggregate (granite) to give fresh, sharp edges that protruded slightly above the surrounding mortar. This would provide improved skid resistance and help prevent hydroplaning. A second purpose, to determine whether the Klarcrete machine could be used to effectively clean bridges of hard-to-remove substances such as coal-tar epoxy, was added after the project was initiated. Cost data were developed to afford comparisons with other methods of texturing and bridge cleaning. Also of importance was the speed at which the machine accomplished its task, because the less time spent on high-volume highways, the better.

TEST SITES

After establishing the availability of the machine, a search was begun for suitable sites for the experiments.

Some important site characteristics needed for the experiments to remove the pavement surface were that (a) the portland cement concrete should be constructed with nonpolishing aggregate, (b) the road should carry high traffic volumes, and (c) the road must be old enough to have high accumulated volumes. In addition, it was desirable to have a site that had been tested and judged slippery, i.e., one with a skid number less

Figure 1. Configuration of cutting heads of the Klarcrete machine. (Two-headed arrow indicates that the heads move to right and left on a transverse carriage to cut area in between.)

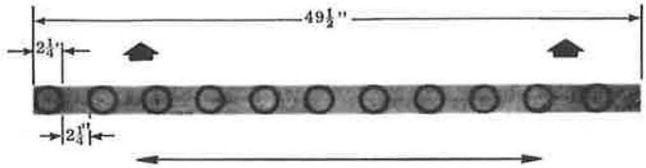


Figure 2. Klarcrete machine being positioned for operation.

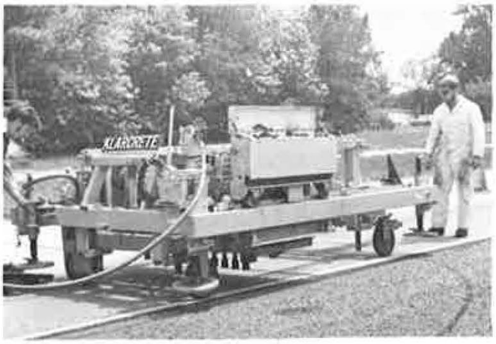


Figure 3. Klarcrete machine in operation.

Figure 4. Full view of Klarcrete machine and compressor.

Figure 5. Klarcrete machine being turned and positioned.

Table 1. Technical details of Klarcrete machine.

Item	Value
Overall length	14 ft (4.27 m)
Length without tiller	10 ft 4.5 in. (3.16 m)
Width	7 ft 6 in. (2.29 m)
Overall height	4 ft 6 in (1.37 m)
Weight	4,000 lb (1800 kg)
Power required, compressed air[a]	600 cfm at 100 psi (0.28 m^3/s at 689 kPa)
Cutting heads[b]	
Diameter	2¼ in. (57.15 mm)
Distance between heads	2¼ in. (57.15 mm)
Air consumption per head	30-35 cfm at 100 psi (0.014-0.017 m^3/s at 689 kPa)
Life	100 hours ± 25
Strokes per minute	≈ 1,500
Maximum cutting depth	4 in. (102 mm)
Accuracy	±⅛ in. (±3.18 mm)
Width of cut	4.5 to 49.5 in. (0.114 to 1.26 m)

[a]The Klarcrete machine is pneumatically and hydraulically operated and pneumatically controlled on a sequential system.

[b]There are 11 tungsten carbide cutting heads, composed of a motor and a head; each head can be controlled individually (except the first one). The cutting face is made up of 6 tips intersecting in the center of the head at 60 deg. Depth of the cut depends on forward speed of the machine.

Figure 6. Coal-tar epoxy on deck of northbound Meherrin River bridge.

than 40. The site selected was not the first choice, because the skid number was approximately 50 and the traffic volume was not extremely high (13,240 average daily traffic), but more desirable locations were not available for a variety of reasons.

The site is in the southbound direction of I-95 on the Emporia bypass in Greensville County, Virginia. The portland cement concrete pavement, constructed in 1959 of nonpolishing aggregate (granite), is 9 in. (0.23 m) thick and consists of 25-ft (7.6-m) and 50-ft (15-m) slabs. Although the site was not the best suited one for the experiment, it was entirely adequate for determining whether the machine would uniformly remove the surface and at the same time fracture the large aggregate so as to raise the skid values.

The bridges selected to test the machine's ability to clean coal-tar epoxy from the decks are over the Meherrin River in both the northbound and southbound directions of I-95, 0.4 mile (0.64 km) north of the pavement surface removal experiment.

EXPERIMENTS PERFORMED WITH THE KLARCRETE MACHINE

Removal of Road Surface

The first experiment performed with the Klarcrete machine was an operation called "mass area bush-hammering," a process by which the entire surface of the roadway is removed to a desired depth leaving exposed fresh, highly fractured aggregate slightly raised above the surrounding portland cement mortar. A ¼-mile (0.4-km) section of 24-ft (7.32-m) pavement was bush-hammered at the site, and ⅛ to ¼ in. (3.175 to 6.35 mm) of surface was removed. The operation was begun on May 14, 1973, and was completed May 24, 1973. The time of machine operation was 46 hours, 42 min. Each machine pass covered approximately 4 ft (1.22 m); six passes were required to treat the entire width of pavement. The total area treated was 30,934 ft^2 (2874 m^2), and the average area treated per hour was 680 ft^2 (63 m^2). The forward motion of the machine per hour was 170 ft (52 m).

Removal of Coal-Tar Epoxy From Bridge Decks

As previously noted, two bridges were selected for testing to determine the capabilities of the machine for bridge-deck cleaning. The bridges were covered with old, cracked, partially deteriorated coal-tar epoxy requiring removal before they were resealed with new epoxy. Considerable time, effort, and funds were spent the previous winter sandblasting the bridges in an effort to remove the epoxy, but with little success. Figure 6 is a view of one of the bridges showing the coal-tar epoxy after sandblasting. The right center cleared path was made by the Klarcrete machine.

Virginia highway department officials, after observing the machine in operation, wished to rent it in an attempt to remove the old epoxy from the bridges. The bridge cleaning operation, which was the same type of operation as bush-hammering (except for a different purpose and removal of different materials), began May 30 and was completed June 21. The time required to clean the southbound bridge was 36 hours, 50 min, for an average of 348 ft^2 (32 m^2) per hour. For the northbound bridge, the cleaning time was 49 hours, 54 min, for an average of 240 ft^2 (22 m^2) per hour. Progress on the northbound bridge was slower because the previous sandblasting on the southbound bridge had already removed some epoxy.

As may be seen, progress on both bridges was considerably slower than the 680 ft^2 per hour on the concrete road surface. This is explainable by comparing the different types of material that the machine was removing. The harder and more brittle a surface, the easier it is to fracture, and the more effective the operation of the Klarcrete machine becomes, because it functions by hammering the pavement surface into small particles. The road surface was hard and brittle and the machine operated efficiently on it, but the resilience of the coal-tar epoxy slowed operations on the bridges. In fact, it has been reported that attempts at removing bituminous overlays have not been very successful. In Virginia, however, the problem is not removing bituminous overlays from bridges, which can be done rather easily with a heater planer, but cleaning the bridges after the overlays have been removed.

PROBLEMS ENCOUNTERED DURING EXPERIMENT

Klarcrete Machine

With regard to maintenance, the Klarcrete machine performed creditably; minor problems did arise, however, in the form of broken air hoses. The average time for replacing a hose was 15 min. With sufficient hoses on hand, replacement was not a great problem, and downtime could be reduced by inspecting and replacing the hose where cracking occurs before operation. The cutting heads were replaced once during the experiments, but the time required was not prohibitive.

Compressor

The major equipment malfunction occurring during the entire experiment involved the compressor necessary to operate the machine. Four different compressors were used during the job, and each needed extensive repairs that necessitated long periods of downtime. The bush-hammering of the road surface required 9 working days, but the machine was in operation only 46 hours, 42 min. Over 90 percent of the downtime was attributable to compressor malfunction. For cleaning the southbound bridge, 36 hours, 50 min of machine time was necessary; however, the machine was inoperable 20 hours, 20 min because of compressor failure. In summary, malfunctioning of the compressors approximately doubled the time necessary for doing the job. A large compressor might do a better job, inasmuch as the air requirements of the Klarcrete machine are so great that the 600 cfm (0.28 m^3/s) compressors may have had difficulty sustaining production of the necessary air.

Regardless of the cause of compressor failure, the contractor should be required to guarantee a workable compressor because additional unwarranted time spent on a high-volume road increases the chances of accident to all involved, increases the cost for traffic control personnel (who often have other assigned tasks), and inconveniences the traveling public.

Noise and Air Pollution

Operation of the Klarcrete machine produced a noise level that was uncomfortable to persons in its immediate vicinity. For this reason, all machine operators should wear ear protection. No equipment was available for measuring machine noise, but, because no citizens complained, it must be assumed that the noise was absorbed by the environment to the degree that it was not a nuisance. It should be noted that, although a small town was nearby, the area is rural in nature; some means of muffling the noise might be necessary in a metropolitan area or for night work.

When the machine is operating on dry pavement, air pollution by dust can be great (Fig. 7). However, on wet pavement, no air pollution occurs. Figure 8 shows the machine operating after a downpour, but a water truck with a spray bar was employed at other times. In very hot weather, water evaporation is fast and the pavement has to be wetted often. The machine operates as well on wet pavement as on dry. A companion problem was that particles left by the machine had to be swept from the road with a mechanical sweeper that produced a dust cloud. The particles, nearly ¼ in. (6.35 mm) in depth, turned into a paste-like substance when sprinkled with water and could not be swept from the road. This problem was not solved at the test site and the particles were swept from the road while dry. A solution for this could be a vacuum type of street sweeper such as those used by some cities.

RESULTS OF EXPERIMENTS

Surface Alteration

The machine operated as it had been purported to do. In removing the entire surface to a depth of ⅛ to ¼ in., the riding quality of the road was not impaired and the noise level produced by vehicular traffic on the treated surface was not noticeably greater than that on the old surface. The freshly treated surface was regular and had no holes or indentations that would serve as traps for pools of water.

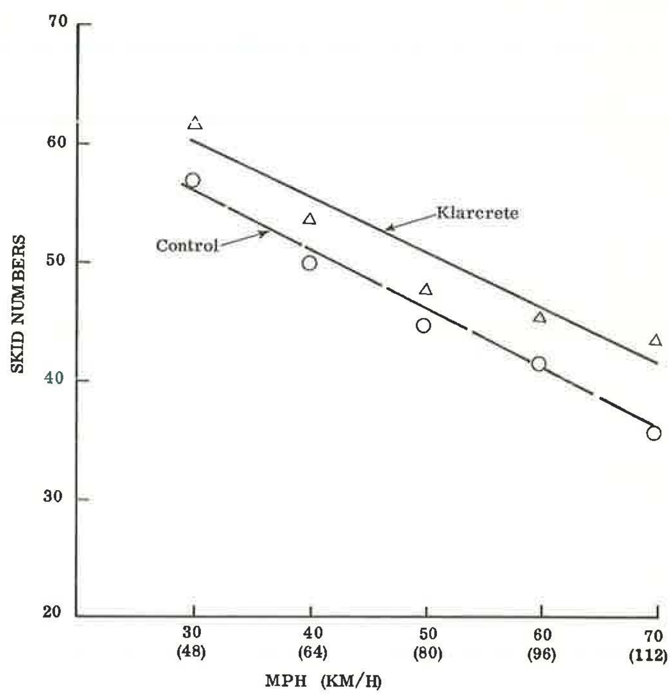
Figure 7. Dust produced by Klarcrete machine operating on dry pavement.

Figure 8. Klarcrete machine operating on wet pavement.

Figure 9. Wet pavement after treatment with Klarcrete machine. Note the ponding of water on the untreated portion.

Figure 10. The Virginia Highway Research Council's skid-resistance measurement vehicle.

Figure 11. Skid test results (traffic lane) with a new tire and 0.20-in. (0.508-mm) water film thickness.



The sharp surface of the granite aggregate protruded above the surrounding cement mortar to produce a texture that was coarse. The coarse texture allows considerable space for water to escape and also exposes a polish-resistant aggregate for contact with the tires of vehicles. Figure 9 shows the pavement after a heavy rain, when all of the pavement had been treated except the extreme right portion with the edge line marking.

Skid Tests

As previously mentioned, the purpose for removing the mortar and fracturing the large aggregate was twofold: (a) to provide a well-defined microtexture, particularly in the large granite aggregate, that was expected to improve the skid resistance of the pavement; and (b) to provide a surface macrotexture that would be less conducive to hydroplaning because it would facilitate the escape of water at the pavement-tire interface.

To determine if the expected improvements were realized, skid tests were performed with the Virginia Highway Research Council's skid trailer (Fig. 10) on the treated section and on a control section adjacent to it. The following tests were performed in both the traffic and passing lanes:

1. Conventional tests following ASTM Method E 274, made at 40 mph (64 km/hour) with 0.02-in. (0.508-mm) water film thickness. Tests were also made at 30, 50, 60, and 70 (48, 80, 96, and 112 km/hour) at the same water film thickness. These tests were performed with a new ASTM Standard E 249 tire.
2. The tests in 1 were repeated except that the ASTM Standard E 249 tire had been turned down to the point that it had no tread.
3. The tests in 1 were repeated except at a water thickness of 0.04 in. (1.016 mm).
4. The tests in 2 were repeated except at a water thickness of 0.04 in. (1.016 mm).

Figures 11 through 20 show the skid test data in graphic form. Each value is the average of five tests.

Figure 11 shows that the pavement not only had very good skid resistance before treatment when tested by ASTM Method E 274 but also had an acceptable skid number (SN) at 70 mph. Even so the Klarcrete treatment improved the skid number by about 4 units up through 60 mph and by about 8 units at 70 mph. If tests were performed at 40 mph only, it would be questionable if the increase in skid number from 50 to 54 would justify the expense of the treatment. However, the increase of 8 units, from 36 to 44, at 70 mph would justify the treatment if the site had a high wet-pavement accident history. Both curves in Figure 11 depict only a moderate loss in skid resistance with increased speed; this indicates no tendency toward hydroplaning.

Figure 12 shows results of tests using ASTM Method E 274 for the passing lane as opposed to the traffic lane. This lane had received less traffic, and it can be seen that no improvement was realized.

Results on the traffic lane with the bald tire are shown in Figure 13. The improvement in skid resistance is significant, even at the low speed of 30 mph, where the treatment caused an increase of 11 units. Since the curves are parallel and neither approaches zero, there is still no indication of absolute hydroplaning, although it is obvious that the channels in the pavement surface effectively provide for the escape of water when a bald tire is used, even when only a 0.02-in. (0.508-mm) water thickness is used.

In Figure 14, which shows results of the bald tire tests in the passing lane, two things should be noted. First, there is a smaller increase in the skid number as a result of treatment than there was in the traffic lane (8 units as compared to 11), and second, the skid number before treatment is about 6 units higher than that in the traffic lane before treatment. The latter fact indicates that the texture in the passing lane prior to treatment, although it was very fine and would probably be classified as microtexture, did provide for enough contact with the bald tire to generate skid values that would satisfy any minimum requirements.

All skid data reported graphically thus far resulted from tests performed with a

Figure 12. Skid test results (passing lane) with a new tire and 0.20-in. (0.508-mm) water film thickness.

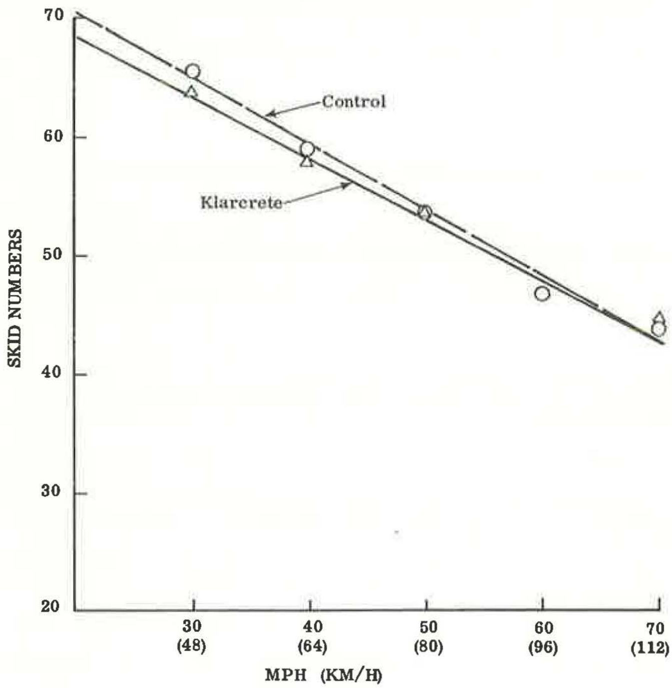


Figure 13. Skid test results (traffic lane) with a bald tire and 0.02-in. (0.508-mm) water film thickness.

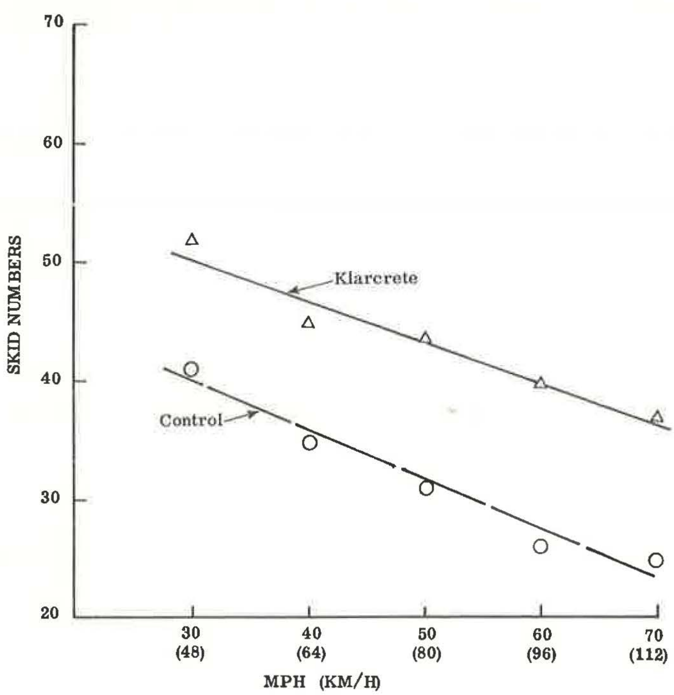


Figure 14. Skid test results (passing lane) with a bald tire and 0.02-in. (0.508-mm) water film thickness.

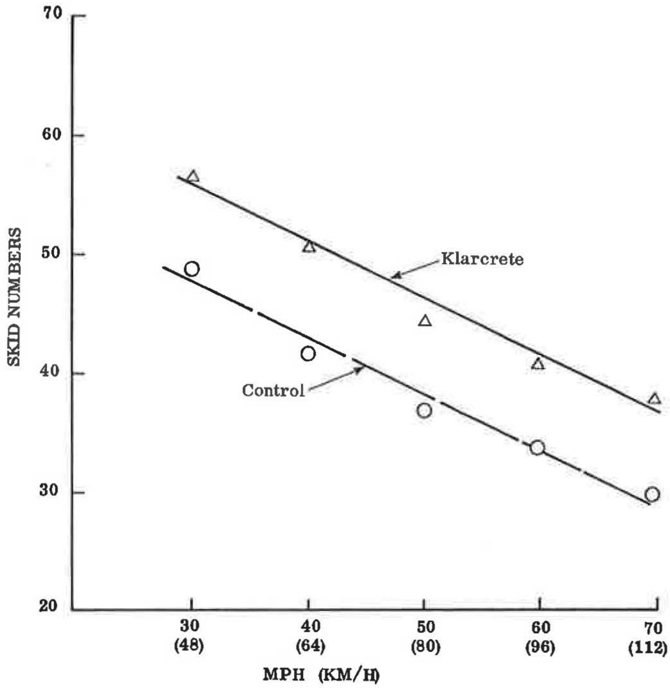
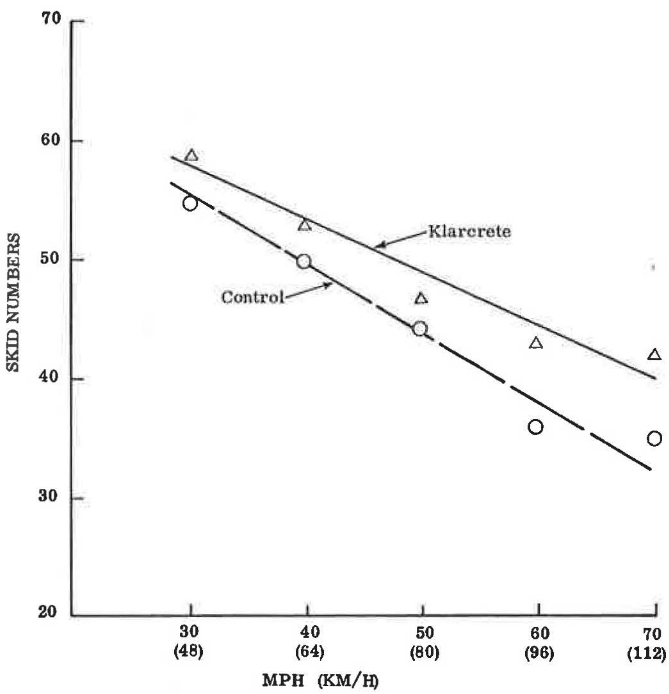


Figure 15. Skid test results (traffic lane) with a new tire and 0.04-in. (1.016 mm) water film thickness.



water film thickness of 0.02 in. The results in Figures 15, 16, 17, and 18 were obtained at a water film thickness of 0.04 in. (1.016 mm).

The values in Figure 15, obtained in the traffic lane with a new tire, are essentially the same as those shown in Figure 11, which were recorded in tests on half the water film thickness. This finding indicates that a film thickness of 0.04 in. is not enough to overtax a new ASTM tire and that, for realistic testing, the 0.02-in. film thickness prescribed by ASTM is sufficient.

Figure 16 shows the skid values obtained on the passing lane with the new test tire and a film thickness of 0.04 in. (Remember that in Figure 12, which showed tests with the same tire but half the amount of water, some values were higher for the untreated pavement than for the treated.) Figure 16 reveals the same phenomenon, which is accepted as insignificant or as a testing error because of the small amount of data. However, it could well be that a reduction in surface area under some conditions could reduce skid numbers.

Figure 17 differs from Figure 13 in that the tests were performed with a water film thickness of 0.04 in. The values for both the treated and untreated pavements with the increased water are lower by about 4 SN for the test speeds of 50, 60, and 70 mph. The decrease on the untreated surface was expected but that on the treated was not. This indicates that the greater water output resulted in a thicker film of water even on the rough-textured surface and that this additional water decreased the skid resistance at the higher speeds. This observation should be accepted as a possibility and not as a positive conclusion.

Figure 18 shows the data for the passing lane tests with bald tires and 0.04-in. water film thickness. Again there was a decrease in skid resistance on both the treated and untreated surfaces as compared to the results with 0.02 in. of water, but the decrease did not occur until the test speed reached 70 mph.

Figures 19 and 20 show data for 70-mph tests with 0.04 in. of water and six tire conditions ranging from new to bald. The values in Figure 19 are for the traffic lane and those in Figure 20 for the passing lane. These data clearly show that tread depth has no effect on the ASTM Standard E 249 tire until it reduces to less than $^3/_{32}$-in. (2.4-mm) tread depth for water depths as great as 0.04 in. In addition, if the 0.04-in. water depth can be accepted as representative of the films produced by many rains, the data suggest that a $^3/_{32}$-in. tread depth is sufficient for most wet-weather driving conditions.

Summary of Results of Skid Tests

As a result of the treatment, the skid resistance was raised in most cases; the exceptions are the test results from the passing lane when new tires were used. The absence of improvement in these cases is credited to the high skid resistance of the pavement before treatment and the drainage characteristics of the test tire. The improvements realized are a result of increased surface texture harshness, particularly on the large aggregate, and better provisions for drainage, especially for the bald tire.

Before testing, it was felt there was a possibility that the before and after tests using a bald tire, 0.04-in. water film thickness, and a test speed of 70 mph would demonstrate that the Klarcrete treatment would make the pavement less conducive to hydroplaning by providing a macrotexture that would facilitate the escape of water at the pavement-tire interface. However, although there is a tremendous difference between the curves for the $^3/_{32}$-in. tire tread depth and the bald tire (Figs. 19 and 20), in light of the slopes of the speed gradients of the curves (Figs. 11 through 18), the interpolation of rapid approach to absolute hydroplaning would be risky. Because no skid values were below 20, it is obvious that the test conditions were not conducive to hydroplaning. This does not imply that an automobile traveling at 70 mph with bald tires on the untreated section of this test site would not hydroplane, given certain water depth and driver handling conditions. Therefore, it can only be said that the test did not prove whether the treatment made the pavement less conducive to hydroplaning, but basic knowledge of the phenomenon coupled with the data would lead to a conclusion that the treatment will reduce the likelihood of hydroplaning.

Figure 16. Skid test results (passing lane) with a new tire and 0.04-in. (1.016-mm) water film thickness.

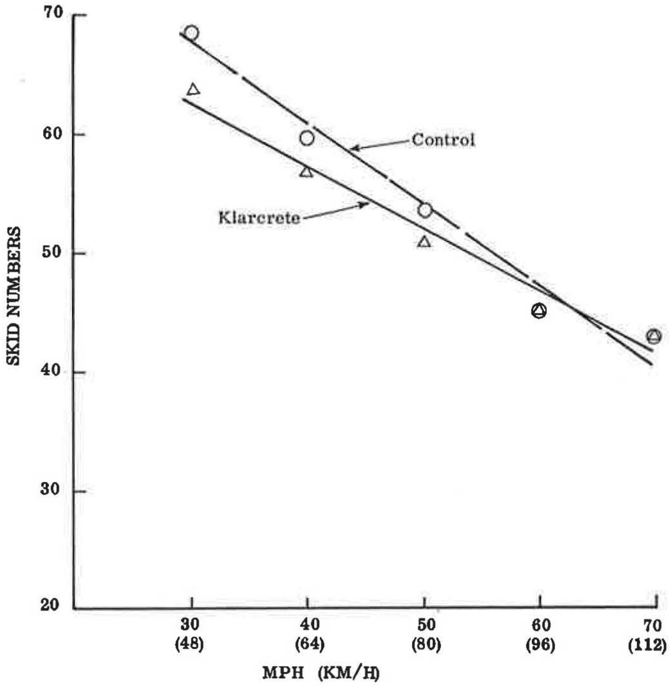


Figure 17. Skid test results (traffic lane) with a bald tire and 0.04-in. (1.016-mm) water film thickness.

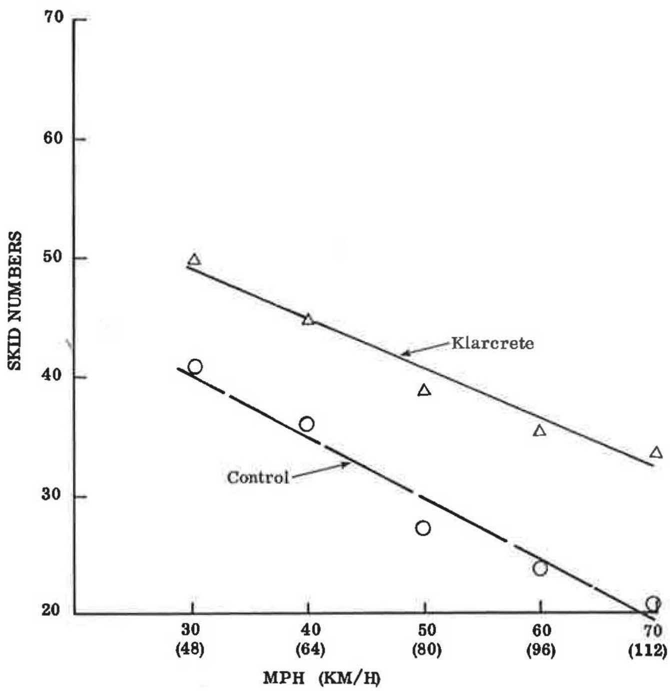


Figure 18. Skid test results (passing lane) with a bald tire and 0.04-in. (1.016-mm) water film thickness.

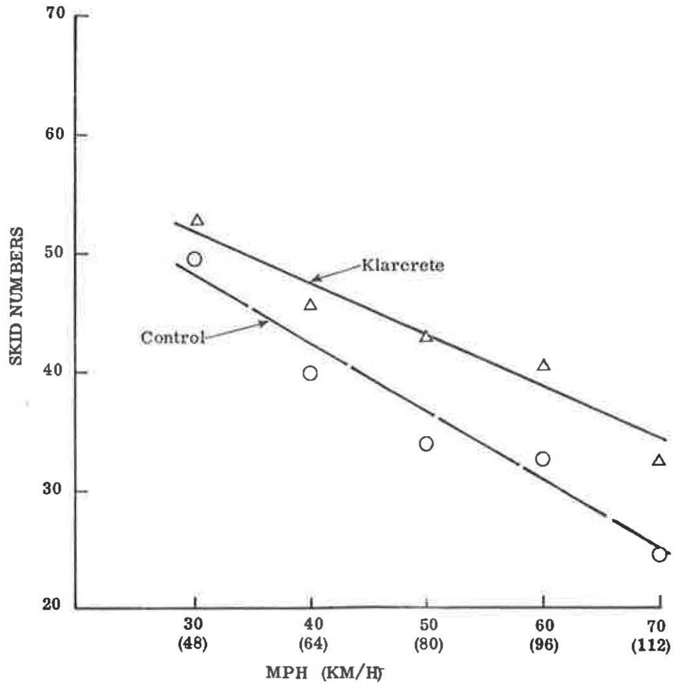


Figure 19. Effect of tire tread depth for tests (traffic lane) at 70 mph (112 km/hour) and 0.04-in. (1.016-mm) water film thickness.

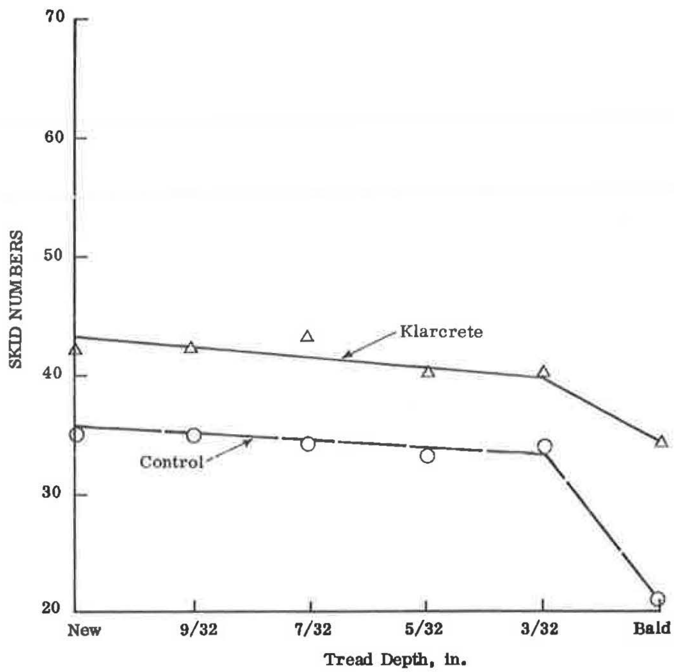


Figure 20. Effect of tire tread depth for tests (passing lane) at 70 mph (112 km/hour) and 0.04-in. (1.016-mm) water film thickness.

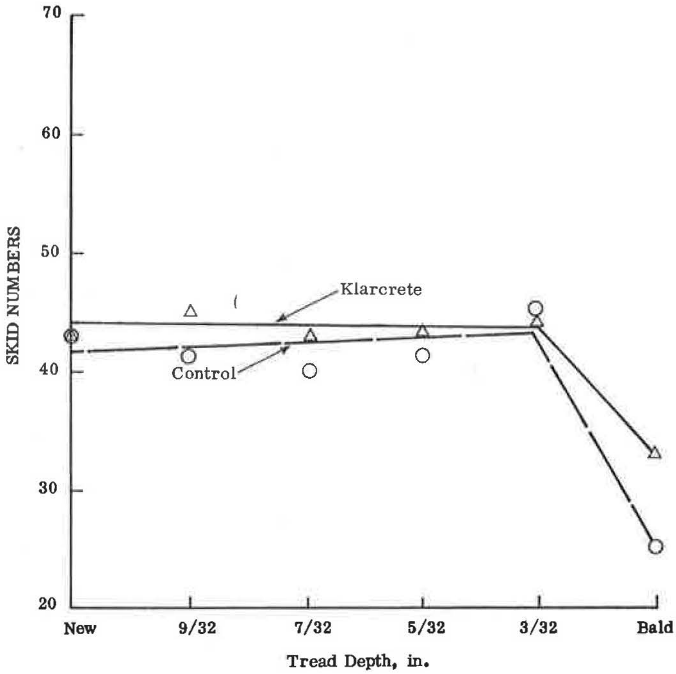
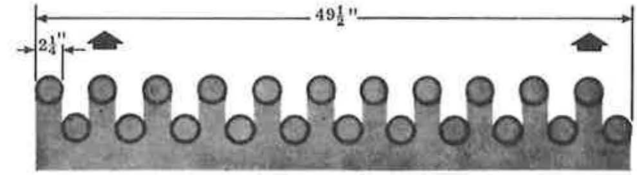


Figure 21. Long-range view of Klarcrete machine in operation on bridge deck.

Figure 22. The southbound bridge after cleaning.

Figure 23. Configuration of 22 cutting heads of new Klarcrete machine. (There will be no transverse motion of heads.)



Bridge Cleaning

Before sealing a bridge with epoxy it is necessary to completely clean the surface of foreign materials to give the epoxy a clean, sound surface to adhere to. Some bridge engineers feel it desirable to remove the surface down to the aggregate so that the fresh epoxy can adhere to it, the reason being that the surface mortar of an old bridge may have been weakened by deicing salts or other caustic agents to a degree that the new seal surface may scale off.

The Klarcrete machine did an excellent job of cleaning the bridge to a depth that exposed the coarse aggregate (Figs. 21, 22). It is faster and less expensive than sandblasting. From the results of this experiment it appears that the machine also holds real promise for cleaning bridges. Figure 21 shows the bridge cleaning operation, and the near white path directly behind the machine indicates the quality of work being performed by the machine. In some areas where the coal-tar epoxy was especially thick two passes were made. Figure 22 shows a portion of the bridge after cleaning was completed.

Cost

The cost of removing the surface and exposing the coarse aggregate from the approximately ¼-mile section of 24-ft pavement was $3,026.50, excluding the expense of traffic control. The total area, 30,934 ft^2 (2874 m^2), was treated at a cost of $0.10/$ft^2$ ($1.07/$m^2$). The cost of grooving in Virginia is about $0.20/$ft^2$ ($2.14/$m^2$). In comparison, the Klarcrete treatment costs about one-half as much. As previously noted, approximately 700 ft^2 (65 m^2)/hour of roadway were treated with the Klarcrete machine. This compares to about 1,000 ft^2 per hour (93 m^2 per hour) for grooving. Both the Klarcrete process and grooving provide means for water to escape from the pavement-tire interface, but the Klarcrete machine also exposes a new, skid-resistant surface.

A newer model Klarcrete machine, scheduled to be delivered to the United States in late fall or early winter of 1973, will double the rate of production and will, in fact, be considerably faster than grooving. The increase in production will be accomplished by having two rows of heads, with the second row offset 2¼ in. (57 mm) from the path of the first row. This will enable the machine to bush-hammer the 4-ft (1.2-m) swath without transverse movement of the heads and without increasing the compressed air requirements. Figure 23 shows the configuration of the heads of the new machine.

As noted earlier, the coal-tar epoxy on the bridges was more difficult to remove than the surface of the road, and in certain instances double passage with the machine was necessary. The total area on both bridges cleaned down to the coarse aggregate was 24,789 ft^2 (2302.9 m^2) and the cost was $5,187. This reduces to $0.21/$ft^2$ ($1.95/$m^2$). Because of the different sealant materials and thicknesses on different bridges, a comparison of this method with other bridge cleaning methods was not possible, but engineers from the Virginia Department of Highways state that the Klarcrete method was significantly less expensive and time-consuming than sandblasting.

CONCLUSIONS

The following conclusions were derived from the experimentation and subsequent skid tests.

1. The Klarcrete machine did an excellent job of removing the surface area to a depth of ⅛ to ¼ in. (3.175 to 6.35 mm) and was capable of removing a much greater depth.
2. After removal of the surface material, a coarse aggregate with sharp fractured surfaces was exposed above the surrounding cement mortar.
3. The cost of treating the roadway with the Klarcrete machine was approximately half of the cost that Virginia has had to pay for grooving.
4. The machine did an excellent job in cleaning the coal-tar epoxy from the bridges and was faster and cheaper than sandblasting.
5. In the experiment, approximately 90 percent of the downtime incurred was due to malfunctions of the compressors.

6. Although dust pollution can be a problem when the machine is operated on dry pavement, it is easily controlled by wetting the surface.

7. The riding quality of the pavement was not impaired by removing the surface and exposing the coarse aggregate.

8. The Klarcrete treatment provided a well-defined microtexture, particularly in the large granite aggregate, which made a substantial improvement in the skid resistance in the traffic lane.

9. Because of the existing high skid resistance in the passing lane, little improvement was indicated in the tests with new tires. The improvement with bald tires was not so great as was realized in the traffic lane.

10. The treatment facilitated the escape of water, but because of limitations on the test conditions, it was not proved that the hydroplaning potential was reduced. However, when these data are viewed in the light of basic knowledge, a judgment that the treatment would reduce the hydroplaning potential under prescribed conditions would seem valid.

11. The test lends validity to the selection of the 0.02-in. water film thickness by ASTM for its E 274 method, and the ASTM Standard E 249 tire seems to provide skid numbers without dropoff due to tread depth for treads as low as $^3/_{32}$ in. when ASTM Method E 274 is used.

ACKNOWLEDGMENTS

I would like to express gratitude to David C. Mahone, head of the Virginia Highway Research Council's Maintenance Section, who was responsible for the collection and analysis of the skid data and was the principal author of the section on skid tests in this report. I would also like to thank Mahone for his interest and advice throughout the project.

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TRAFFIC CONTROL FOR MAINTENANCE ON HIGH-SPEED HIGHWAYS

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Observations were made at lane closures on Interstate highways to compare effectiveness of yellow and orange signs. One sign scheme was used throughout the study. Driver obedience improved when new signs of either color were used; this finding implies that signs should always be maintained in good condition. Orange signs were slightly more effective than yellow signs in reducing traffic conflicts and merges near the traffic cones. Results of the study tend to support the adoption of orange as the standard color for signing construction and maintenance sites. However, differences between the two colors were rather small. Driver preference polls supported the orange signs more strongly. A degree of driver insensitivity toward signing was shown. In general, variables such as short sight distances, high volumes, poor condition of signs, and driver insensitivity produced unsafe situations at lane closures. However, the scope of the study did not permit observations at sufficient sites or at sufficient times to serve as a definitive exploration of such variables as weather, terrain, vertical and horizontal alignment, or level of service.

•MAINTENANCE WORK that requires barricading one or more lanes of a high-speed roadway creates a potential hazard to the unwary traveler and to the worker. The problem is twofold: First, the proper messages must be presented to the approaching driver far enough in advance to allow him time to decelerate and merge before reaching the actual work site; and second, the driver must obey the messages.

Standards for temporary signing have been rather difficult to develop and implement. Even well-prepared standards do not supplant judgment, discretion, and ingenuity in specific instances. Effective signing and barricading will surely cause a minimum of interference with the flow of traffic. A lane closure where all lanes operate at capacity during peak hours cannot operate effectively unless some of the traffic is diverted to alternate routes. Public announcements and advice to travelers have proved to be helpful in managing these situations.

This study is concerned only with left- and right-lane closures; shoulder closures and other maintenance activities were not observed. All data were taken during favorable weather conditions. The scope of the study did not permit observations at sufficient sites or at sufficient times to serve as a definitive exploration of variables such as weather, terrain, vertical and horizontal alignment, or level of service. It was inevitable that data from several sites be combined for purposes of comparison, even though different circumstances existed at most sites. The possibility of signing a "dummy" maintenance site was rejected from the outset of the study because of the unnecessary risks created for motorists and consequent liabilities.

Publication of this paper sponsored by Committee on Maintenance Operations.

PROCEDURE

During the summer of 1971, safety improvements were made on I-75 in Scott and Grant Counties and on I-64 between Frankfort and Louisville, Kentucky. Research personnel were able to observe and collect data at various lane closures. Cooperation of the contractors was excellent.

In Phase 1, observations were made at sites signed by contractors. In Phase 2, contractors' signs were replaced with new yellow signs and then with new orange signs. Phase 2 also included observation of the new signs at sites where other research activities required lane closures. Phase 2 provided direct comparison between yellow and orange signs. The new yellow signs were hung over the contractors' signs (Fig. 1), traffic was observed for 1 hour, new orange signs were superposed, and observations continued for another hour. At sites where other research activities required lane closures, care was taken to position signs according to the scheme shown in Figure 2. At all times, observers attempted to be inconspicuous to the motorists. Tables 1 and 2 give test data for right- and left-lane closures in Phase 1. Tables 3 and 4 give test data for right-lane closures in Phase 2, and Tables 5 and 6 give test data for left-lane closures in Phase 2.

Spot Speeds

Radar spot speeds were taken at the first sign at 2,500 ft (760 m) and again at the first traffic cone (Fig. 2). Walkie-talkies were used by the forward radar meter operator to relay identification of each vehicle to the second meter operator. Decreases in speed were used as indicators of effective signing and consequent driver awareness. Greater average decreases in speed were attributed to greater responsiveness to sign messages.

Traffic Conflicts

Traffic conflicts were categorized and defined as follows:

1. Abnormal brake application—a very rapid deceleration that causes "dipping" of vehicle's front end (tire squealing is noted separately).
2. Forced merge—a vehicle that changes lanes directly in front of a following vehicle and causes the following vehicle to apply its brakes; the first vehicle "forces-in" and risks possible contact.
3. Complete stop—driver waits too long to merge and is forced to come to a stop and wait for a gap.

Merging Maneuvers

Observers were able to record the location of merging maneuvers to the nearest 100 ft (30 m). For consistency of observation, the point of merging was considered to be where the left front tire crossed the centerline stripe when the vehicle merged to the left and where the right front tire crossed the centerline stripe when the vehicle merged to the right. These observations were later grouped according to percentages occurring in 500-ft (150-m) intervals. Greater percentages of vehicles merging near the traffic cones were considered undesirable and potentially dangerous to motorists as well as to workmen.

Turn Signals

Turn signals were counted and converted into percent of total lane changes. Smaller percentages of turn signal actuations were considered indicative of better signing because this showed less dependency on the turn signal in merging and thus greater driver awareness.

Figure 1. Research personnel positioning new signs over contractor's signs.

Figure 2. Lane closure detail showing sign scheme used.

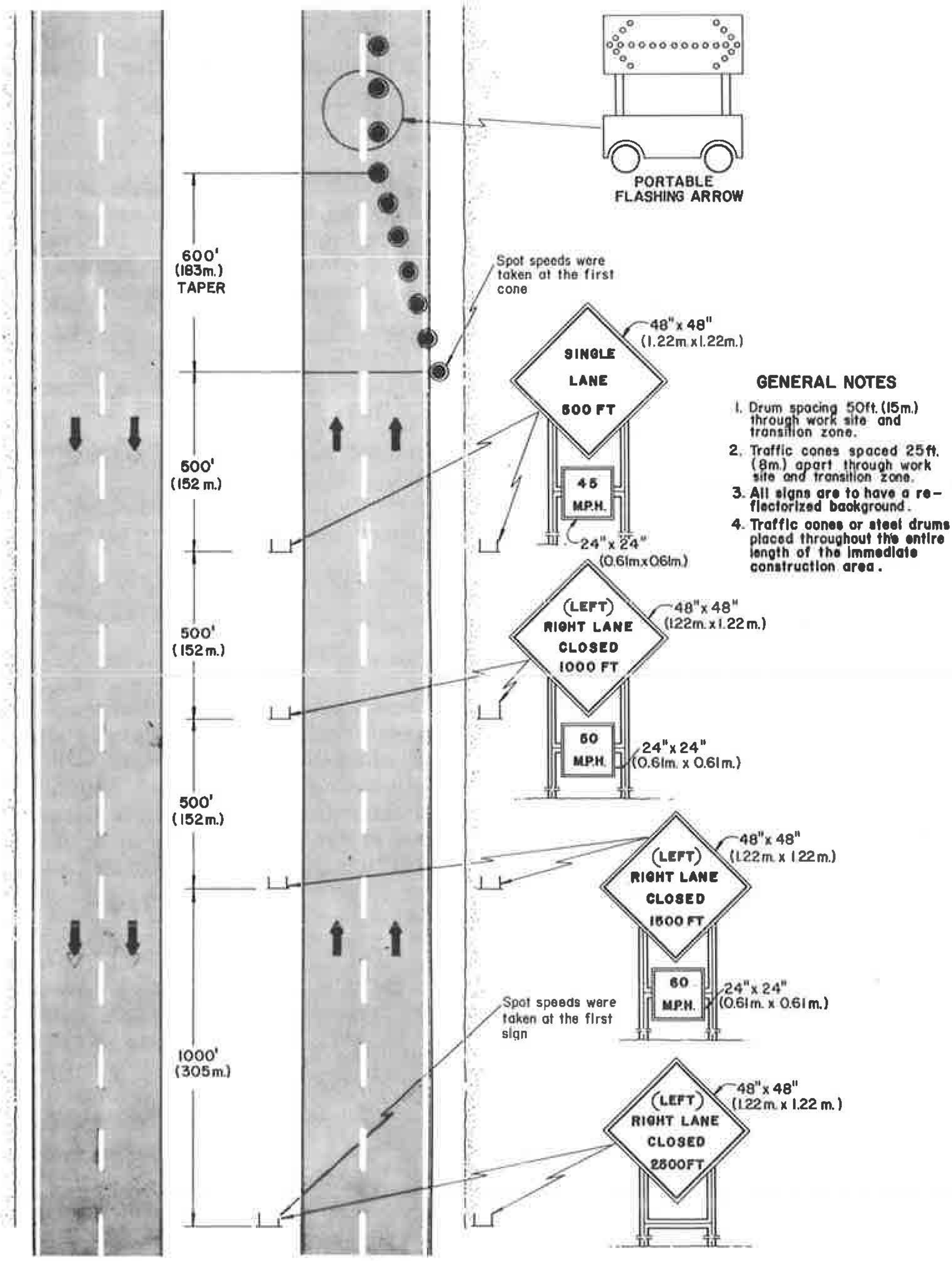

Table 1. Volume, design, and speed data for right- and left-lane closures (Phase 1).

Data Set Number	Volume			Grade	Curve	Sight Distance (miles)		Mean Speed (mph)					
								At First Sign		At First Cone		Decrease	
	Cars	Trucks	Total			To First Sign	To First Cone	Cars	Trucks	Cars	Trucks	Cars	Trucks
R 1.1	271	67	338	-	Lt	0.25		64.6	57.4	52.0	53.3	12.6	4.1
L 1.1	437	59	496	+	Tan	0.60	1.10	67.5	59.6	54.5	45.7	13.0	13.9
R 1.2	261	86	347	+	Tan	0.85		62.7	58.6	51.9	49.9	10.8	8.7
L 1.2	539	73	612	+ to -	Tan to Lt	0.40	0.50	65.5	56.1	53.9	53.5	11.6	2.6
R 1.3	616	64	680	+	Rt	0.60		66.7	50.3	52.8	42.5	13.9	7.8
L 1.3	513	87	600	-	Tan to Lt	0.25	0.35	67.1	56.6	60.0	56.7	7.1	+0.1
R 1.4	395	85	480	+	Tan	0.65	1.15	67.5	66.9	54.5	56.5	13.0	10.4
L 1.4	724	54	778	-	Lt			66.5	54.7	59.6	53.3	6.9	1.4
R 1.5	374	59	433	Level	Rt	0.65	0.30	64.5	52.4	56.4	50.6	8.1	1.8
L 1.5	532	54	586	+	Lt to Rt	0.60	1.00	70.0	64.9	48.1	47.6	21.9	17.3
R 1.6	578	54	632	+	Rt	0.50	0.40	66.2	60.2	55.1	46.9	11.1	13.3
L 1.6	480	63	543	+ to -	Tan to Lt	0.40	0.40	65.6	65.5	54.5	54.0	11.1	11.5
R 1.7	509	67	576	+	Tan	0.50	0.25	66.0	60.5	55.4	49.0	10.6	11.5
L 1.7	429	93	522	Level	Lt to Rt	0.70	0.55	67.8	62.6	58.5	55.4	9.3	7.2
R 1.8	421	88	509	- to +	Rt to Tan	0.30	0.55	70.4	65.1	59.0	54.7	11.4	10.4
L 1.8	218	49	267	-	Tan	0.15		64.3	56.9	57.4	51.8	6.9	5.1
R 1.9	540	68	608	Level	Tan	0.40	0.70	67.2	60.0	53.4	50.2	13.8	9.8
L 1.9	699	64	763	-	Lt	0.25	0.55	68.4	56.7	50.0	47.1	18.1	9.6

Note: 1 mile = 1.6 km; 1 mph = 1.6 km/hour.

Table 2. Conflict and merge data for right- and left-lane closures (Phase 1).

Data Set Number	Conflicts				Turn Signals	Merges With Turn Signals (percent)	Distance Between First Sign and First Cone (ft)	Merges (percent)[a]				
	Abnormal Braking	Forced Merges	Complete Stops	Total				0-500 ft	501-1,000 ft	1,001-1,500 ft	1,501-2,000 ft	2,001-2,500 ft
R 1.1	2	1	1	4	44	16.9	2,200	25.7	17.6	18.0	36.0	2.7
L 1.1	15	3	0	18	16	14.3	2,500	6.4	11.0	21.1	19.3	42.2
R 1.2	16	3	0	19	46	20.9	1,970	9.6	28.6	20.5	41.3	0.0
L 1.2	5	2	0	7	35	25.0	3,015	11.0	19.0	21.0	22.0	27.0
R 1.3	44	21	0	65	91	20.9	1,925	46.8	15.2	27.5	10.5	0.0
L 1.3	11	3	0	14	25	13.4	2,238	20.9	13.9	27.8	29.4	8.0
R 1.4	14	9	0	23	68	23.1	2,600	12.9	18.4	11.7	17.3	39.7
L 1.4	12	6	0	18	45	18.4	2,238	12.7	18.9	25.8	33.2	9.4
R 1.5	32	15	0	47	63	20.3	2,085	36.0	17.4	12.9	30.8	2.9
L 1.5	13	2	0	15	23	11.4	2,571	15.9	24.6	18.5	15.4	25.6
R 1.6	18	15	0	33	108	27.8	1,825	14.4	35.5	41.4	8.7	0.0
L 1.6	11	3	0	14	34	20.5	2,788	30.1	16.1	13.3	10.5	30.1
R 1.7	28	16	1	45	98	25.4	2,000	31.6	24.9	23.3	20.2	0.0
L 1.7	4	0	0	4	28	22.1	2,181	7.1	13.4	12.6	44.9	22.1
R 1.8	14	5	0	19	95	26.0	2,958	9.2	16.2	29.2	27.6	17.8
L 1.8	6	8	0	14	14	15.9	3,200	51.1	19.3	14.8	12.5	2.3
R 1.9	10	3	0	13	75	27.8	2,430	5.6	21.1	26.7	25.5	21.1
L 1.9	14	7	0	21	24	12.5	2,260	17.7	16.2	24.0	27.6	14.6

Note: 1 ft = 0.3048 m.

[a]Merges are measured from the first cone back toward the first sign.

Table 3. Volume, design, and speed data for right-lane closures (Phase 2).

Data Set Number	Sign Color	Volume			Grade	Curve	Sight Distance (miles)		Mean Speed (mph)					
									At First Sign		At First Cone		Decrease	
		Cars	Trucks	Total			To First Sign	To First Cone	Cars	Trucks	Cars	Trucks	Cars	Trucks
R 2.1	Yellow	304	77	381	Level	Lt	0.30		68.2	63.8	52.5	51.9	15.7	11.9
R 2.1	Orange	359	62	421	Level	Lt	0.30		67.3	63.3	50.2	50.2	17.1	13.1
R 2.2	Yellow	345	82	427	Level	Lt	0.40		68.5	64.0	49.7	48.9	18.8	15.1
R 2.2	Orange	322	65	387	Level	Lt	0.40		70.0	62.2	50.2	51.0	19.8	11.2
R 2.3	Yellow	165	40	205	Level	Lt	0.30		65.4	60.3	49.1	44.3	16.3	16.0
R 2.3	Orange	152	36	188	Level	Lt	0.30		66.2	57.8	52.3	49.0	13.9	8.8
R 2.4	Yellow	325	56	381	—	Lt	1.00	0.50	69.3	64.0	50.9	52.9	18.4	11.1
R 2.4	Orange	385	66	451	—	Lt	1.00	0.50	70.0	63.3	50.2	51.5	19.8	11.8
R 2.5	Yellow	299	61	360	—	Lt to Rt	0.55	0.20	70.4	66.3	52.6	50.9	17.8	15.4
R 2.5	Orange	360	98	458	—	Lt to Rt	0.55	0.20	67.3	61.5	51.0	45.9	16.3	15.6
R 2.6	Yellow	214	86	300	- to +	Rt	0.30	0.20	70.0	62.5	51.7	51.6	18.3	10.9
R 2.6	Orange	184	68	252	- to +	Rt	0.30	0.20	70.5	61.8	52.5	51.8	18.0	10.0
R 2.7	Yellow	148	72	220	+ to -	Tan	0.60	0.20	70.2	61.9	57.2	50.4	13.0	11.5
R 2.7	Orange	198	54	252	+ to -	Tan	0.60	0.20	70.4	60.8	57.1	51.8	13.3	9.0
R 2.8	Yellow	291	80	371	Level	Tan	0.30	0.80	69.9	62.5	52.8	51.5	17.1	11.0
R 2.8	Orange	291	56	347	Level	Tan	0.30	0.80	69.5	61.5	52.2	51.3	17.3	10.2
R 2.9	Yellow	327	88	415	+ to -	Rt to Tan	0.40	0.28	70.0	59.8	50.9	49.8	19.1	10.0
R 2.9	Orange	351	93	444	+ to -	Rt to Tan	0.40	0.29	69.7	60.2	50.9	50.1	18.8	10.1
R 2.10	Yellow	278	44	322	+ to -	Tan to Rt	0.85	0.35	65.5	48.8	48.5	47.3	17.0	1.5
R 2.10	Orange	286	40	326	+ to -	Tan to Rt	0.85	0.35	66.8	53.4	53.5	47.5	13.3	5.9

Note: 1 mile = 1.6 km; 1 mph = 1.6 km/hour.

Table 4. Conflict and merge data for right-lane closures (Phase 2).

Data Set Number	Sign Color	Conflicts: Abnormal Braking	Conflicts: Forced Merges	Conflicts: Complete Stops	Conflicts: Total	Turn Signals	Merges With Turn Signals (percent)	Distance Between First Sign and First Cone (ft)	Merges (percent)[a]: 0-500 ft	501-1,000 ft	1,001-1,500 ft	1,501-2,000 ft	2,001-2,500 ft
R 2.1	Yellow	2	0	0	2	22	7.0	2,500	2.2	8.9	16.5	20.3	52.2
R 2.1	Orange	3	2	0	5	32	10.2	2,500	2.6	6.1	15.0	21.1	55.3
R 2.2	Yellow	6	2	0	8	38	10.6	2,500	3.6	19.3	22.9	21.2	33.0
R 2.2	Orange	3	2	0	5	40	12.5	2,500	2.5	15.3	22.1	20.3	35.8
R 2.3	Yellow	5	2	0	7	20	10.4	2,500	16.6	30.1	19.2	11.4	22.8
R 2.3	Orange	0	0	0	0	24	14.1	2,500	28.2	18.8	21.2	11.8	20.0
R 2.4	Yellow	3	4	0	7	57	18.6	2,500	6.5	18.0	17.0	14.1	44.4
R 2.4	Orange	3	3	0	6	58	16.7	2,500	7.5	13.5	12.6	13.2	53.2
R 2.5	Yellow	10	3	3	16	22	7.4	2,500	20.0	12.0	7.4	12.4	48.2
R 2.5	Orange	8	0	0	8	40	12.0	2,500	9.0	13.2	7.8	16.8	53.3
R 2.6	Yellow	2	0	2	4	48	22.2	2,500	23.2	20.4	13.0	14.8	28.7
R 2.6	Orange	2	0	0	2	32	16.5	2,500	14.4	22.7	10.3	16.5	35.1
R 2.7	Yellow	2	0	0	2	46	23.7	2,500	11.3	18.6	13.4	14.4	42.3
R 2.7	Orange	0	0	0	0	34	18.1	2,500	17.0	24.5	17.0	12.8	28.7
R 2.8	Yellow	0	1	0	1	42	16.6	2,500	1.6	6.7	11.4	22.9	57.3
R 2.8	Orange	0	0	0	0	25	10.5	2,500	0.8	5.9	8.4	21.4	63.5
R 2.9	Yellow	11	0	2	13	45	14.0	2,500	2.5	13.4	18.7	23.1	42.4
R 2.9	Orange	25	1	1	27	41	13.2	2,500	2.9	15.5	16.4	18.7	46.5
R 2.10	Yellow	18	0	0	18	24	9.3	2,500	12.4	30.2	8.5	7.8	41.1
R 2.10	Orange	4	0	0	4	16	7.5	2,500	1.9	17.8	17.8	14.0	48.6

Note: 1 ft = 0.3048 m.
[a]Merges are measured from first cone back toward first sign.

Table 5. Volume, design, and speed data for left-lane closures (Phase 2).

Data Set Numbers	Sign Color	Volume: Cars	Volume: Trucks	Volume: Total	Grade	Curve	Sight Distance (miles): To First Sign	Sight Distance (miles): To First Cone	Mean Speed (mph): At First Sign: Cars	At First Sign: Trucks	At First Cone: Cars	At First Cone: Trucks	Decrease: Cars	Decrease: Trucks
L 2.1	Yellow	432	46	478	+ to -	Rt	0.85	0.35	67.4	56.2	53.8	45.3	13.6	10.9
L 2.1	Orange	462	40	502	+ to -	Rt	0.85	0.35	68.4	58.2	52.3	50.6	16.1	7.6
L 2.2	Yellow	326	46	372	+ to -	Tan to Rt	0.85	0.35	68.6	57.2	54.5	50.7	14.1	6.5
L 2.2	Orange	334	53	387	+ to -	Tan to Rt	0.85	0.35	69.5	58.4	54.1	52.5	15.4	5.9
L 2.3	Yellow	664	93	757	+	Tan	0.80		69.7	64.1	48.0	50.3	21.7	13.8
L 2.3	Orange	561	76	637	+	Tan	0.80		69.1	64.3	54.1	48.3	15.0	16.0
L 2.4	Yellow	456	48	504	-	Lt	0.30	0.40						
L 2.4	Orange	576	58	634	-	Lt	0.30	0.40	65.0	54.7	55.1	51.5	9.9	3.2
L 2.5	Yellow	538	54	592	- to +	Tan to Rt	0.30	0.30	71.3	65.1	47.4	49.7	23.9	15.4
L 2.5	Orange	532	58	590	- to +	Tan to Rt	0.30	0.30	69.9	64.0	50.9	50.8	19.0	13.2
L 2.6	Yellow	340	76	416	Level	Tan	0.40	0.90	66.8	62.0	51.1	45.8	15.7	16.2
L 2.6	Orange	375	57	432	Level	Tan	0.40	0.90	68.0	63.1	49.6	58.1	18.4	5.0
L 2.7	Yellow	556	54	610	Level	Rt to Lt	0.40	0.40	66.6	60.9	53.2	44.3	13.4	16.6
L 2.7	Orange	600	70	670	Level	Rt to Lt	0.40	0.40	67.2	60.1	49.3	49.6	17.9	10.5

Note: 1 mile = 1.6 km; 1 mph = 1.6 km/hour.

Table 6. Conflict and merge data for left-lane closures (Phase 2).

Data Set Numbers	Sign Color	Conflicts: Abnormal Braking	Conflicts: Forced Merges	Conflicts: Complete Stops	Conflicts: Total	Turn Signals	Merges With Turn Signals (percent)	Distance Between First Sign and First Cone (ft)	Merges (percent)[a]: 0-500 ft	501-1,000 ft	1,001-1,500 ft	1,501-2,000 ft	2,001-2,500 ft
L 2.1	Yellow	14	0	0	4	22	18.0	2,500	10.0	11.7	10.0	25.0	43.3
L 2.1	Orange	8	2	0	10	24	20.0	2,500	3.3	16.7	3.3	18.3	56.7
L 2.2	Yellow	17	1	2	20	10	11.5	2,500	5.8	10.3	17.2	23.0	43.7
L 2.2	Orange	15	4	0	19	12	14.5	2,500	8.4	7.2	12.1	19.3	53.0
L 2.3	Yellow	6	5	0	11	26	14.1	5,000	37.4	5.6	5.6	20.6	30.8
L 2.3	Orange	1	0	0	1	11	7.8	5,000	18.3	8.5	11.3	29.6	32.4
L 2.4	Yellow	0	0	0	0	14	7.9	2,700	28.4	12.2	13.5	14.9	31.1
L 2.4	Orange	0	0	0	0	29	14.9	2,700	12.1	6.4	13.4	24.8	43.3
L 2.5	Yellow	14	4	0	18	44	19.3	2,536	9.7	18.4	23.7	20.2	28.1
L 2.5	Orange	4	0	0	4	10	4.8	2,536	13.3	20.0	18.1	23.8	24.8
L 2.6	Yellow	1	2	0	3	10	9.6	3,170	6.8	17.6	37.8	17.6	20.3
L 2.6	Orange	2	0	0	2	10	11.0	3,170	11.8	22.1	19.1	19.1	27.9
L 2.7	Yellow					12	5.8	2,283	14.5	13.6	26.2	17.5	28.2
L 2.7	Orange					34	16.4	2,383	12.5	10.6	23.1	26.9	26.9

Note: 1 ft = 0.3048 m.
[a]Merges are measured from the first cone back toward the first sign.

FINDINGS

Spot Speeds

Tables 7 and 8 give the mean speeds and mean decreases in speeds. The contractors' signs (Phase 1) were the least effective; drivers did not decrease speed so much as they did with new signs. There was no significant difference in driver obedience toward the new yellow and new orange signs. Thus, the color of the signs had very little effect on speed (Fig. 3). The total effect is attributed to differences in quality or condition of the signs. Indeed, the condition of the contractors' signs was inferior to that of the new signs (Fig. 4). Unfortunately, contractors' signs are usually not adequately maintained, especially if the construction or maintenance continues in time and if the same signs are moved from one place to another.

Auto speeds at the first cone (Table 5) were approximately 6 to 10 mph (9.7 to 16 km/hour) higher than the advisory speed limit [i.e., 45 mph (72 km/hour)] that was posted 500 ft (150 m) before the first cone. The mean 85th percentile speed of all cars at the first cone was a little over 59 mph (94 km/hour). Table 9 gives all mean 85th percentile speeds.

Traffic Conflicts

Figures 5 and 6 show conflicts per 100 vehicles at each site (Phase 2) for right and left lane closures respectively. With volume effects excluded and everything else constant, it appears that orange signs involved fewer conflicts than yellow signs. When conflicts at sites signed by contractors were included in the analysis (Table 10), there was a statistically significant increase in the number of conflicts at right-lane closures. At left-lane closures, only orange signs were significantly lower. New orange signs were associated with fewer conflicts than new yellow signs, but this difference was not statistically significant. Signs used in Phase 2 yielded greater consistency of results, and, according to Hurst, Perchonok, and Seguin (1), greater consistency in these statistics indicates less driver confusion.

Most of the conflicts (about 87 percent) occurred within the half of the signed area nearest the cones. The most frequently recorded conflicts were abnormal brake applications.

Merging Maneuvers

Merging maneuvers were difficult to analyze because driver behavior and predisposition are integrally involved. Ideally, if motorists were adequately warned in advance of a lane closure, there would be relatively few merges within the last few hundred feet approaching the barricade. Adequate warning enables a driver to choose his own gap rather than be forced into the through lane at the last second. Fewer merges near the cones complement the safety of the work crew and flagmen as well as motorists. However, as traffic volume increases and as gaps become smaller, more drivers will be trapped in the closed lane and thereby delay otherwise normal merging and probably cause an increase in forced merging. Also, there are always some drivers who will stay in the closed lane longer than they should just so they can pass one or two more cars [that is, the more aggressive driver might remain in the closed lane to take advantage of the reduced lane volume at the cost of encountering higher risk when he ultimately changes lanes (2)]. Consequently, where traffic is not congested, those drivers who deliberately disobey the messages and those who are not attentive may account for most of the merging within the last 500 ft (150 m) approaching the barricade. Indeed, dangers increased at those sites where the merging in this last 500 ft was unusually high (Tables 1-6). In general, those sites were complicated by short sight distances, high volumes, or poor traffic control, but no one factor was consistently dominant. For example, in Phase 2 there were five instances in which more than 20 percent of all merges occurred within 500 ft of the barricade. The hourly volumes varied from 188 to 757; sight distances ranged between 0.2 and 0.8 mile (0.4 and 1.5 km); percentage of trucks varied from 9.5 to 28.7; and lengths of the sites were generally about 2,500 ft (760 m), but one site was 5,000 ft (1525 m) in length. Yellow signs were in use

Table 7. Automobile mean speeds and mean decreases in speed.

Phase	Sign Color	Lane Closed	Mean Speed (mph) At First Sign	Mean Speed (mph) At First Cone	Mean Decrease (mph)	Level of Significance	
1	Yellow	Right	66.2	54.5	11.7	0.005 (phases 1 and 2, yellow)	
2	Yellow	Right	68.7	51.6	17.1		0.005 (yellow and orange, phase 2)
2	Orange	Right	68.7	52.0	16.7		
1	Yellow	Left	67.0	55.2	11.8	0.05 (phases 1 and 2, yellow)	
2	Yellow	Left	68.4	51.3	17.1		0.05 (yellow and orange, phase 2)
2	Orange	Left	68.2	52.2	16.0		

Note: Left- and right-lane closures were not tested together. 1 mph = 1.6 km/hour.

Table 8. Truck mean speeds and mean decreases in speed.

Phase	Sign Color	Lane Closed	Mean Speed (mph) At First Sign	Mean Speed (mph) At First Cone	Mean Decrease (mph)	Level of Significance	
1	Yellow	Right	59.0	50.4	8.6	0.10 (phases 1 and 2, yellow)	
2	Yellow	Right	61.4	50.0	11.4		0.10 (yellow and orange, phase 2)
2	Orange	Right	60.6	50.0	10.6		
1	Yellow	Left	58.7	51.6	7.1	0.025 (phases 1 and 2, yellow)	
2	Yellow	Left	60.9	47.7	13.2		
2	Orange	Left	60.4	50.2	10.2		

Note: Left- and right-lane closures were not tested together. 1 mph = 1.6 km/hour.

Figure 3. Cumulative distributions of speeds at a site where both sign colors were used.

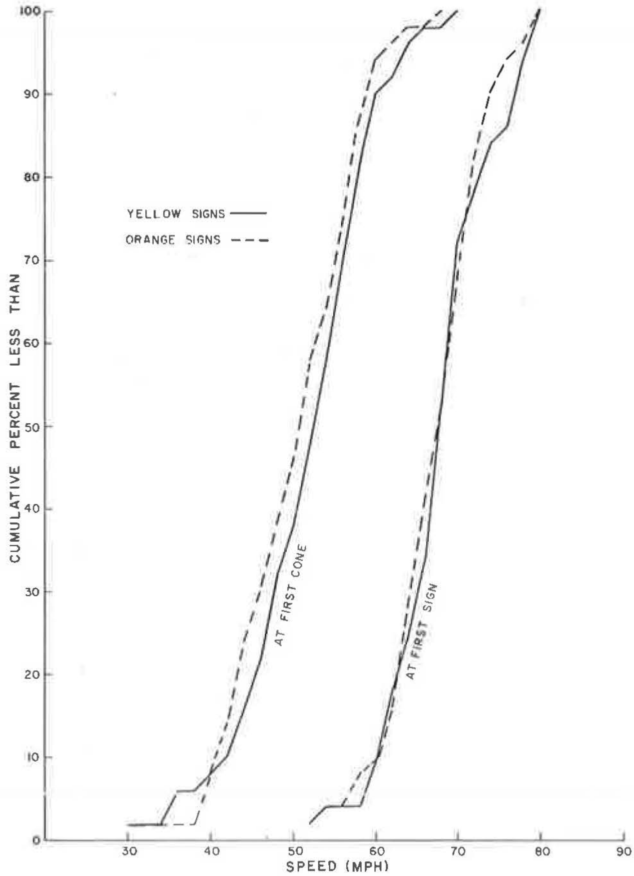

Figure 4. Contractor's sign (left) as contrasted with test sign.

Table 9. Mean 85th percentile speeds.

Phase	Sign Color	Lane Closed	Automobile Speed (mph) At First Sign	Automobile Speed (mph) At First Cone	Truck Speed (mph) At First Sign	Truck Speed (mph) At First Cone
1	Yellow	Right	70.7	60.5	64.6	55.3
2	Yellow	Right	73.3	58.8	65.5	55.6
2	Orange	Right	74.4	58.8	64.4	55.7
1	Yellow	Left	71.6	61.0	63.3	57.1
2	Yellow	Left	73.8	58.4	65.3	53.0
2	Orange	Left	73.4	58.1	64.8	56.1

Note: Left- and right-lane closures were not tested together. 1 mph = 1.6 km/hour.

Table 10. Mean conflicts per 100 vehicles.

Phase	Color	Lane Closed	Mean Conflicts per 100 Vehicles	Level of Significance
1	Yellow	Right	5.64	} 0.01 (rows 1–2); } 0.001 (rows 1–3)
2	Yellow	Right	2.33	
2	Orange	Right	1.37	
1	Yellow	Left	2.59	} 0.20 (rows 4–6)
2	Yellow	Left	2.25	
2	Orange	Left	1.37	

Note: Left- and right-lane closures were not tested together.

Figure 5. Conflicts per 100 vehicles at each study site (right-lane closures, Phase 2).

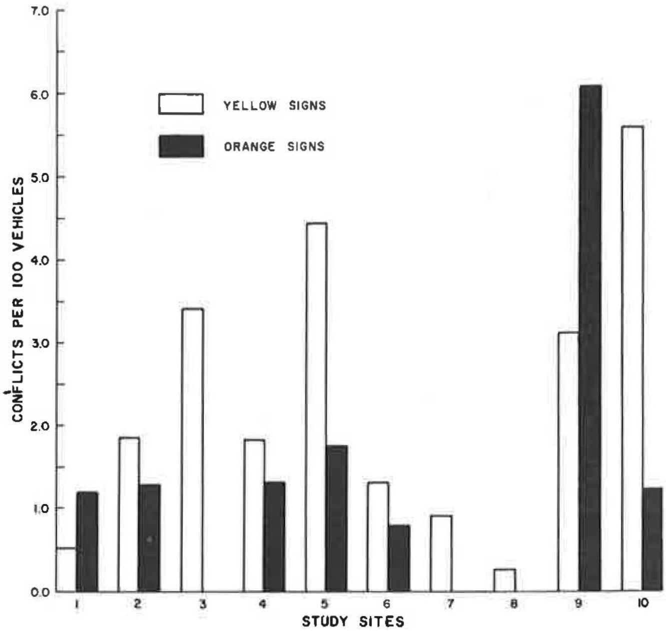

Figure 6. Conflicts per 100 vehicles at each study site (left-lane closures, Phase 2).

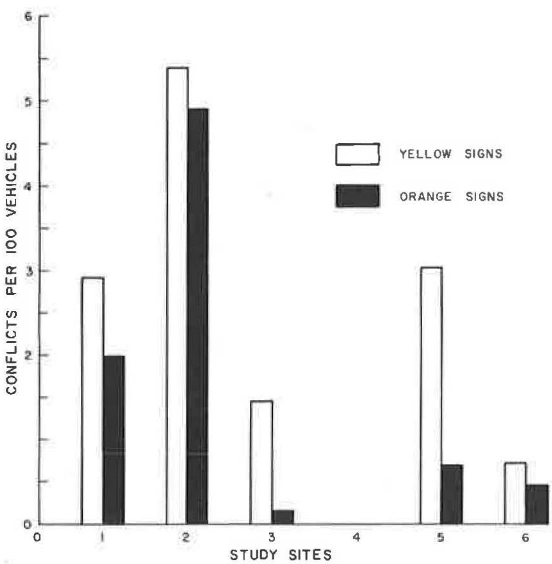

Table 11. Percentage of merges within 500 ft (152 m) of first traffic cone.

Phase	Color	Lane Closed	Merges Within 500 Ft of First Cone	Level of Significance
1	Yellow	Right	21.3	} 0.05 (rows 1–2); } 0.05 (rows 1–3)
2	Yellow	Right	10.0	
2	Orange	Right	8.7	
1	Yellow	Left	19.2	} 0.20 (rows 4–6)
2	Yellow	Left	16.1	
2	Orange	Left	11.4	

Note: Left- and right-lane closures were not tested together. 1 ft = 0.3048 m.

during four of the periods of observation, and orange signs were used during only one. Table 11 gives data that show that new signs are an improvement over the contractors' signs. Orange signs seem to be slightly superior to yellow signs in Phase 2 but not to a statistically significant extent.

Various frequency distributions were obtained by plotting distances (measured from the first cone) against the percentage of merges occurring at each distance. There were peaks in these distributions at or near the 1,000-ft (300-m) sign and near the first sign at 2,500 ft (760 m). Some distributions showed three peaks. No explanation for these behavioral modes is offered here, but some interesting possibilities may be found in the work by Roberts, Hutchinson, and Carlson (3) on high, intermediate, and low expressive self-testers (risk-takers). At sites where both sign colors were used, the two distributions roughly followed the same pattern (Figs. 7, 8, 9). Orange signs sometimes reduced the number of merges nearer the cones and, therefore, in some cases tended to skew the distribution slightly more to the right (Figs. 10, 11, 12).

Turn Signal Indications

Table 12 gives the mean percentage of turn signal indications for the various sites. The smaller percentages of turn signal actuations in Phase 2 may merely indicate the superior quality of the signs. There was no significant difference in turn signal use with respect to yellow and orange signs in Phase 2.

Driver Interviews

A total of 62 drivers were interviewed after they had passed through a lane closure. Sign colors were alternated so that drivers could make comparisons: 2,500-ft (760-m) and 1,000-ft (300-m) signs were yellow and 1,500-ft (460-m) and 500-ft (150-m) signs were orange. Of course, total recall would be most unlikely. The questions and replies are shown in Figure 13. Of the 62 people interviewed, 38 (61 percent) noticed two different colored warning signs. Of the 38 who noticed two colors, 27 (71 percent) said orange was more effective. This is assuming the 4 people who said red was more effective were actually referring to the orange signs. Ten people responded to the sixth question with one or more complaints. The most common complaint (given six times) was that there was not enough prior notice or advance warning. Two complaints were against flagmen. Other complaints, each occurring once, were that signs are spread out too much, flashing arrow should be nearer the beginning of the cones, and signs are often in place when no lane closure or maintenance is in progress. This last complaint could account for the fact that in the eighth question almost 20 percent of the people interviewed said that they wait until they see the actual lane blocked before merging.

DISCUSSION OF FINDINGS

No one factor was consistently responsible for undesirable conditions at the lane closures examined. High incidences of traffic conflicts and last-second merges were generally attributed to (a) short sight distances, (b) high volumes, (c) poor quality signs, and (d) driver insensitivity.

Adoption of the new AASHO Manual on Uniform Traffic Control Devices (4) provides, for the first time, a standard scheme for signing single-lane closures on Interstate highways. The manual specifies the use of orange signs at construction and maintenance sites. Results of this study tend to substantiate the change in color.

An example of deceptive signing is shown in Figure 14. Deceptive signs literally say there is road construction XXX feet ahead. However, the distance is actually measured to the beginning of a project or to the white "Your Highway Taxes at Work" sign, and thus the signs convey a false message to the road user because there may be no construction visible for several miles. This may cause a driver to doubt the validity of or to unconsciously disregard the next set of warning signs at an actual lane closure. The "Road Construction Next XX Miles" sign (Fig. 14), or several signs to this effect, would be adequate for the beginning of an extensive project. On several occasions during the course of this study, research personnel noticed warning signs in place but no

Figure 7. Merge distributions at site R 2.1.

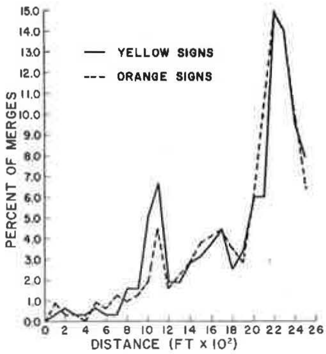

Figure 8. Merge distributions at site R 2.2.

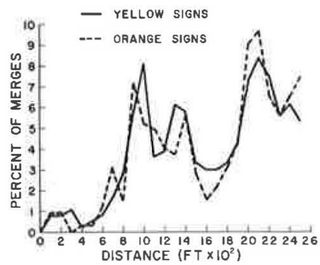

Figure 9. Merge distributions at site R 2.4.

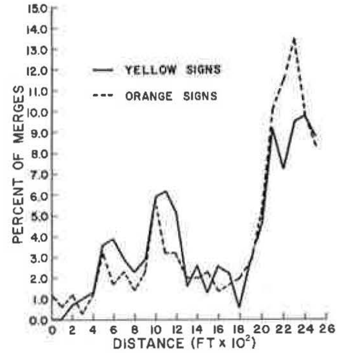

Figure 10. Merge distributions at site R 2.5.

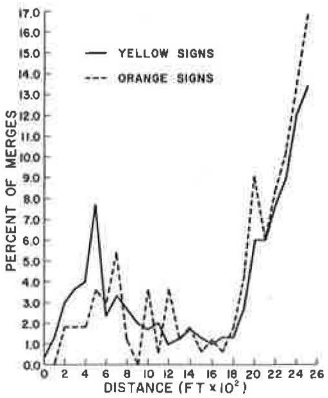

Figure 11. Merge distributions at site R 2.6.

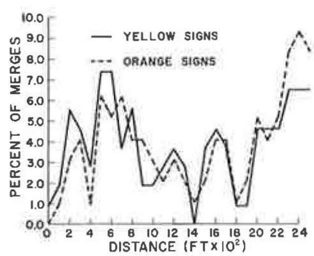

Figure 12. Merge distributions at site R 2.10.

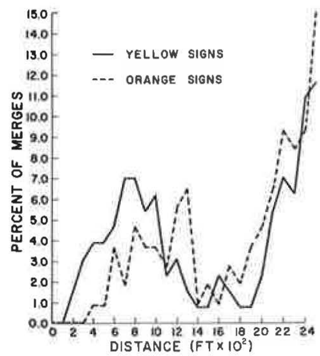

Figure 13. Questions and responses for driver interview.

1. Did you notice two different colored warning signs prior to the lane closure?

Yes	38
No	24

2. If yes, what colors did you notice?

Yellow	34
Orange	25
Red	13
Other	4

3. If only one color noticed, what was it?

Yellow	6
Orange	1
Red	1
Red-Orange	1
Other	1
Uncertain	14

4. If two colors were noticed, which one seemed more effective? (Only asked people who replied "yes" to question one).

Yellow	9
Orange	23
Red	4
Uncertain	2

5. Do you think you are adequately made aware that a lane is closed ahead at sites like this?

Yes	56
No	6

6. What is your biggest complaint about these sites?

Nothing	52
Other	10

7. Do you think the warning signs are usually spaced properly so you can rely upon what they say?

Yes	58
No	3
Uncertain	1

8. Do you actually merge into the open lane when you see the first warning sign, whenever you can, or when you actually see the lane blocked off?

First Sign	31
Whenever	19
Actual Lane Blocked	12

Table 12. Mean percentage of turn signal indications.

Phase	Sign Color	Lane Closed	Mean Percent of Merges With Turn Signal	Level of Significance	
1	Yellow	Right	23.2	0.0001 (rows 1–2)	0.00001 (rows 1–3)
2	Yellow	Right	14.0		
2	Orange	Right	13.1		
1	Yellow	Right	17.1	0.10 (rows 4–5)	0.10 (rows 4–6)
2	Yellow	Left	12.3		
2	Orange	Left	12.7		

Note: Left- and right-lane closures were not tested together.

Figure 14. Sign scheme preceding an extensive maintenance project (top photo shows no maintenance or construction in sight).

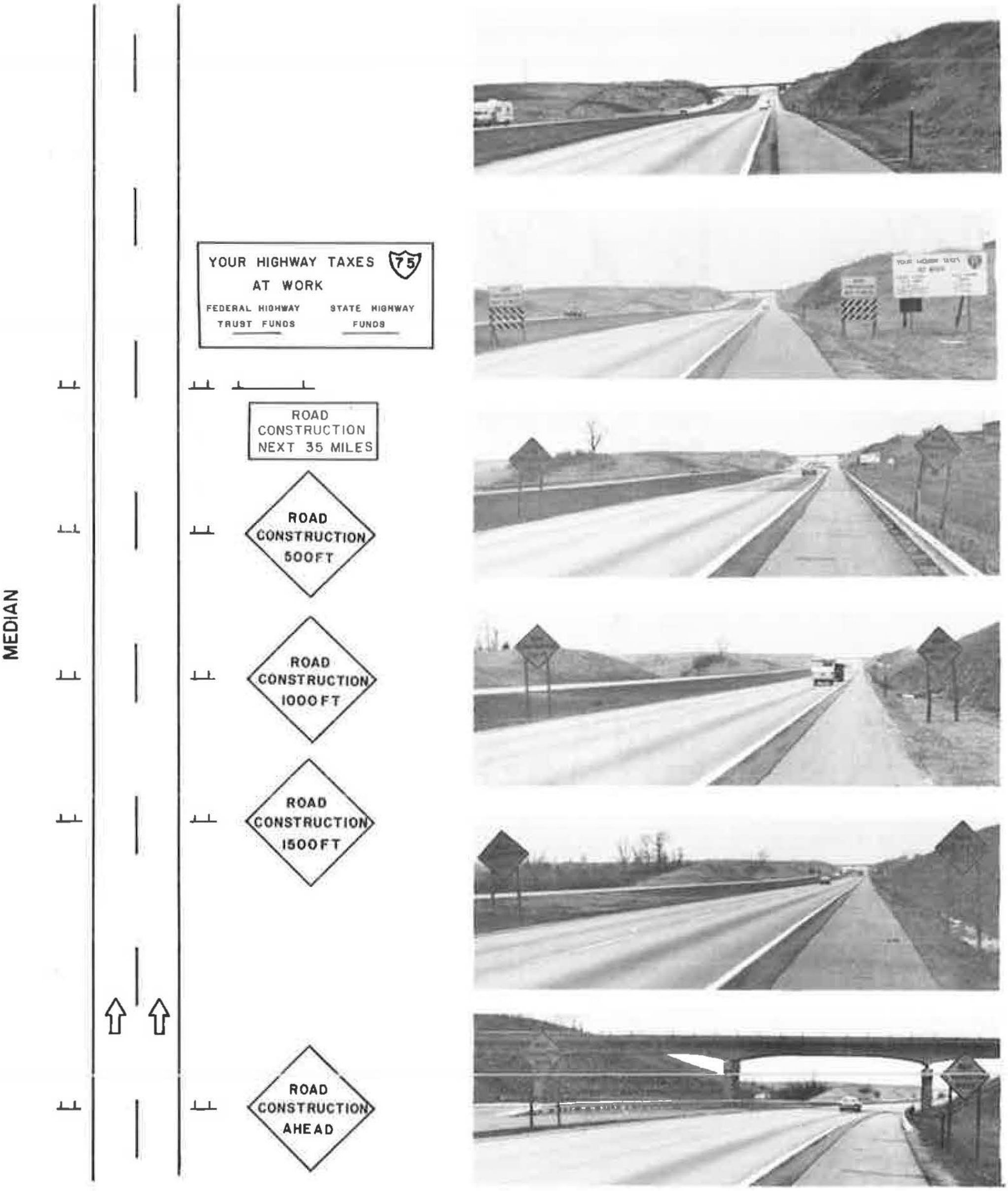

Figure 15. Errors that cause confusion and disrespect for warning signs.

maintenance or lane closure ahead. This practice also creates disrespect for maintenance signs. Such signs should be neatly covered or removed when work is suspended.

Other common errors in traffic control were observed during the data collection. Adjusting sign placement, i.e., lengthening distances between signs and between signs and cones, to compensate for poor sight distances is practical only to a certain extent. If the distances indicated by the signs are not within reason, drivers may tend to disbelieve the messages. Cone placement can be used to compensate for short sight distances. At one site (R 1.7), the contractor positioned a flashing arrow on the downhill side of a hill, and it did not come into view until the driver reached the crest of the hill. This accounted for the large number (45) of traffic conflicts recorded at that site.

The situation shown in Figure 15 could prove confusing. The overlay message had become unfastened on one side and presented an ambiguous choice as to where the construction actually was. It is a foregone conclusion that such errors must be avoided if safety and respect for warning signs are to be improved.

Because the new Manual on Uniform Traffic Control Devices specifies the use of orange signs for construction and maintenance sites, a distinction has been made from the standard stationary yellow warning signs (Merging Traffic, Fallen Rock Zone, Bridges Freeze Before Roadway, etc.) more commonly used on highways. The new manual should also create a higher degree of uniformity in traffic control at lane closures. However, it is the responsibility of field personnel to enforce the standards and to ensure that the signs are highly legible.

Perhaps the most astonishing finding from this research issued from the driver interviews. Approximately 20 percent admitted or confessed they deliberately delayed merging. This is willful disobedience and may be related to a driver attitude that results in speeds 5 to 10 mph (9.7 to 16 km/hour) greater than posted limits. Unfortunately, the conflict involvement rate of these drivers was not determined specifically and separately when field observations and interviews were conducted.

CONCLUSIONS

1. Orange signs produced a slight improvement over yellow signs in reducing traffic conflicts and merges near the barricade.
2. New signs of either color produced a significant improvement over signs of lesser quality. Presumably signs maintained in a like-new condition, or nearly so, would suffice.
3. Driver attitudes toward lane-closure signs appear to have compounded and confounded the total problem of effective signing. Other, more daring innovations may be needed. Temporary rumble strips, chatter bars, or other disquieting devices may be necessary to adequately impress the message on some drivers.

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