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16. Abstract Objective of this study was determination of efficacy of red, yellow and green turn arrow indications in traffic signals. Four basic study methods were: (1) history of traffic signals and use of arrows for traffic controls; (2) determination of current practices among traffic engineers throughout the Nation; (3) public understanding and acceptance of arrow indications in lieu of conventional circular lenses in traffic signals through the medium of questionnaires mailed in by highway users; and (4) "before" and "after" field studies, by time-lapse photography, to determine motorist response, accident experience and cost effectiveness at six experimental sites in Washington, D.C. and two sites in the suburban area of Montgomery County, Maryland All elements of the study are described in detail.

Arrows were found to be beneficial in some circumstances. Conclusions and recommendations, based on study effort are expressed. Guidelines for use of three color turn arrow displays have been developed, and a Users Manual to aid in implementing arrow displays, in lieu of conventional circular signal indication, is included.

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The authors also wish to thank the senior Traffic Engineers in the various State and Local jurisdictions who shared their experiences with, and opinions on, the use of the three color turn arrow displays.

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CHAPTER I. EXECUTIVE SUMMARY

A. Synopsis

This study investigated the efficacy of red, yellow, and green steady (non-flashing) turn arrows in traffic signals. Four basic study methods were employed. These were: (1) collecting historical data on their prior use; (2) determining the present practices and opinions of a selected group of senior Traffic Engineers in both State and Local jurisdictions throughout the U.S.A.; (3) obtaining the responses of randomly selected motorists to a written questionnaire designed to test their understanding of various possible arrow displays; and (4) "before" and "after" field tests to determine motorist response and accident experience at six Washington, D.C. and two suburban Maryland sites where turn arrow displays were installed on an experimental basis. All of these elements of the study are described in detail.

The arrows were found to be beneficial in some circumstances. Conclusions and recommendations based on the study effort are provided. Guidelines for the use of three color turn arrow displays have been developed, and a Users Manual to aid in implementing such arrow displays is included.

B. Conclusions

1. There has been quite wide, but still far from universal, adoption by the U.S. traffic engineering profession of yellow turn arrow signal indications, as a clearance interval indication for green turn arrows. The great bulk of the opinion of users is favorable to continued use of such yellow turn arrow clearance indications.

2. There has been substantial hesitation within the traffic engineering profession towards any widespread adoption of red turn arrow signal displays, particularly in the absence of a nationwide public education effort to familiarize the motoring public with the meaning of this control device. It should be noted that, while red and yellow arrows are included in the Manual on Uniform Traffic Control Devices, 1971 edition, they are not yet provided for in many State Motor Vehicle Codes. Their inclusion in the National Uniform Motor Vehicle Code was approved in July, 1975.

3. Of the relatively few jurisdictions that have tried red turn arrow indications some report successes and others report dissatisfaction. In general, the reported experiences had been worst at highly congested locations where motorists were experiencing long delays, and were best at less congested locations where some type of explanatory signing (e.g. "Turn on Green Arrow Only") was used with the signal displays.

4. At locations where a separate turning interval is employed, and where turning lanes which are completely separate from the through lanes are provided, it is common practice to aim, shield, or optically program the signals for the through and turn movements so that motorists can only see the signal that applies to their traffic movement. When this is done successfully driver confusion as to which signal applies to the movement he desires to make is avoided. In this situation a red ball indication can be used to stop the turning movement, and the need for a red turn arrow display to stop the turn without confusing drivers making other movements is reduced or avoided.

   Lack of a rigid signal head mounting (as in an unguyed span wire installation) may result in sufficient wind induced signal head motion to make use of aimed signals (with their visibility controlled to specific approach lanes) impossible. In addition, some intersections have approach geometrics which preclude use of aimed visibility signals. This was the case at the Newport Beach, California location (mentioned in Chapter IV, Current Practices) where a downgrade "S" curve into a 40 degree skewed intersection precluded effective use of aimed signal heads for the through and turn lanes.

5. Red, yellow and green turn arrow displays can be successful and beneficial if properly used. Three color turn arrows can be beneficial in three different types of location. These are:

   (a) On an intersection approach which has an exclusive lane for turning movements;

   (b) Where turning movements are "protected" from conflicting movements by other indications or by the signal sequence; and

   (c) Where all movements from an approach do not begin or end at the same time and where the indications for the turning movements will also be visible to traffic with other allowable movements.

6. A significant proportion of the motoring public does not understand that turns are prohibited when the signal display consists of a through green arrow and no other indications. Display of a red turn arrow in conjunction with such a through green arrow can significantly reduce the frequency of illegal turns on the through green arrow.

7. Comparison of "before" and "after" accident experience shows that the change to the three-color arrow indications was associated with a reduction in accident frequency at most study locations. None of the six Washington, D.C. experimental locations where this change was made showed an increase in accidents. The time periods available for the comparison of accident experiece were not long enough to permit high levels of statistical confidence in the results of such "before" and "after" comparisons. None the less, the Washington, D.C. experience strongly suggests that, when properly installed in conformance with the MUTCD, three color arrow turn indications can yield safety improvements at selected locations now using older types of displays. This finding is supported by the reported experience from Arizona, California and Delaware.

8. The attractiveness of the use of the three color turn arrow display is intimately related to the choice of the signal phasing for the location in question. Research on the relative attractiveness of alternative phasings in typical traffic situations appears strongly desirable. Warrants for the use of the various more restrictive types of phasing should be established.

C. Recommendations

1. Provision for the use of the three color arrow displays should be retained in the Manual on Uniform Traffic Control Devices.

2. The three color turn arrow display should be considered for use at three types of location. These are:

   (a) On an intersection approach which has an exclusive lane for turning movements;

(b) Where turning movements are "protected" from conflicting movements by other indications and/or by the signal sequence; and

(c) Where all the movements on the approach do not begin and/or end at the same time, and where the indications for the turning movement(s) will also be visible to traffic with other allowable movements.

3. In signal phasings in which a turn is "protected" during part of the signal cycle and is "prohibited" during another part while other movements are allowed from the same approach, a green through arrow should not be relied upon to carry the message that the turn is prohibited during the latter interval. A red turn arrow should be displayed simultaneously with the green through arrow during the interval when through movements are allowed and the turn is prohibited.

4. Additional research should be initiated to develop warrants for the selection of the optimum signal phasing for typical traffic situations.

5. The developed guidelines for the use of three color turn arrow displays presented herein should be forwarded to the appropriate technical subcommittee of the National Advisory Committee on Uniform Traffic Control Devices for their consideration and possible development of recommended revision of the Manual on Uniform Traffic Control Devices.

6. A nationwide educational campaign should be developed to improve driver understanding of arrow displays in traffic signals.

7. At locations where three color turn arrow signal displays are used, the signal head containing the turn arrows should be horizontally separated several feet from the signal head containing the through signal displays. Turn signal heads should be signed "Right (or Left as appropriate) Turn on Green Arrow Only".

8. Consideration should be given to the desireability of authorizing flashing red turn arrow, and flashing yellow turn arrow, signal displays. Lack of such authorization complicates the design of signal installations using arrows, since provision must be made for appropriate displays under flashing operation of the signals.

CHAPTER II. INTRODUCTION

A. Aims and Objective

"The objective of this research is to determine the effectiveness of using red and yellow arrow signal indications as traffic control devices at signalized intersections."

B. Purpose

In the 1971 Edition of the MANUAL ON UNIFORM TRAFFIC CONTROL DEVICES (1) (approved by FHWA as of November 13, 1970) the application of "steady RED ARROW, YELLOW ARROW and GREEN ARROW indications may be used in lieu of the corresponding circular indications" at six specified types of locations. However, although the logic of using red and yellow arrows in conjunction with green arrow indications is understandable, there was a lack of field experience with these displays. This prompted the interest of the Federal Highway Administration in having "real world" tests conducted to determine their "efficacy", i.e. do they produce the desired or intended results without undesireable side effects.

Underlying a study of this nature is recognition of the nature of the problem and the functions of traffic control signals as outlined below:

> "The intersection is the critical element in an urban traffic plan....most delays to traffic can be traced to conflicts at intersections. It is important to fully understand those conflicts and their effect if the intersection is to perform properly."(2)

The advantages and disadvantages of traffic control signals described in Section 4B - 3 of the MUTCD as follows:

"Traffic control signals are valuable devices for the control of vehicle and pedestrian traffic. However, because they assign the right-of-way to the various traffic movements, traffic control signals exert a profound influence on traffic flow.

Traffic control signals properly located and operated usually have one or more of the following advantages:

1. They can provide for the orderly movement of traffic.
2. Where proper physical layouts and control measures are used, they can increase the traffic handling capacity of the intersection.
3. They can reduce the frequency of certain types of accidents, especially the right-angle type.
4. Under favorable conditions, they can be coordinated to provide for continuous or nearly continuous movement of traffic at a definite speed along a given route.
5. They can be used to interrupt heavy traffic at intervals to permit other traffic, vehicular or pedestrian, to cross.

....The following factors can result from improper or unwarranted signal installations:

1. Excessive delay may be caused.
2. Disobedience of the signal indications is encouraged.
3. The use of less adequate routes may be induced in an attempt to avoid such signals.
4. Accident frequency (especially the rear end type) can be significantly increased."

Adequate consideration of these accepted concepts is an essential part of the purpose of this study.

CHAPTER III. RESEARCH PROCEDURES

A. Project Design

Section 4B-6 of the Manual on Uniform Traffic Control Devices (the MUTCD), 1971 Edition, specifies that where steady (i.e. not flashing) arrow indications are used in traffic signals:

"1. A steady Red Arrow indication shall be used only in a separate signal face which also contains steady Yellow Arrow and Green Arrow indications. It shall be used for controlling only a single traffic movement.
2. A steady Yellow Arrow indication shall be used following a Green Arrow indication (which has been displayed simultaneously with a Circular Red indication in the same signal face).
3. A steady Yellow Arrow indication may be used (in a separate signal face) following a Green Arrow indication, when that face is used exclusively to control a single directional movement.
4. A steady Yellow Arrow indication may be used to indicate the clearance interval following the termination of a Green Arrow indication (when displayed simultaneously with a continuing Circular Green indication in the same signal face).
5. A steady Green Arrow indication shall be used only when there would be no conflict with other vehicles or with pedestrians crossing in conformance with the Walk indication."

Section 4B-6 (4) of the MUTCD further specifies six types of locations where steady Red, Yellow and Green Arrow signal indications may be used in lieu of circular (ball) indications. These are:

"a. on an approach intersecting a one-way street;
b. where certain movements are prohibited;
c. where certain movements are physically impossible;
d. on an intersection approach which has an exclusive lane for turning movements;
e. where turning movements are "protected" from conflicting movements by other indications or by the signal sequence; and
f. where all the movements on the approach do not begin or end at the same time and where the indications for the turning movements will also be visible to traffic with other allowable movements."

For each of the above six types of location, a study location was selected which met all the requirements of that type and where a multi-color arrow signal display could be installed on an experimental basis. These six experimental locations were all within the city limits of Washington, D.C. At each of the experimental locations a study was made of traffic operations in the "before" condition; the signal operation was changed to give a multi-color arrow display; and traffic operations were studied in a comparable "after" period. Time-lapse photography was used to collect the data on traffic behavior for these studies. "Before" and "After" accident experience comparisons were made at these experimental locations to detect any changes in traffic safety. Control locations were also selected and studied in a similar manner in order to determine if some extraneous factor (e.g. a change in the proportion of tourists in the motoring population) had altered traffic behavior. All the Washington, D.C. locations studied had far side, post mounted traffic signal heads.

Factors considered in the selection of the study locations included:

a. availability of a suitable elevated viewing position for use in taking the time-lapse films to document traffic behavior;
b. freedom from interference by expected construction activities;
c. a fixed time signal operation so the cycle lengths and splits would be constant from one cycle to the next;
d. no plans for any changes in the signal operation during the study period; and
e. the expectation that the necessary signal modifications could be made within the limited time-frame available.

Two experimental locations in nearby Montgomery County, Maryland were also selected for study, on a cooperative basis with the local authorities, of "before" and "after" traffic operations at suburban locations where red and yellow turn arrow indications replaced circular turn indications. At one of these Montgomery County locations the signal heads were post mounted, while overhead (span-wire) mounted signal heads were used at the other. Both Montgomery County locations had fully actuated signal controllers with skip-phase capability.

Chapter VI presents the details of the study locations, their traffic operations in the "before" and "after" periods, the signal modifications required and their costs, and the "before" and "after" traffic accident experience.

B. Scope of Work

The research effort was contained, for the most part, in the following activities:

1. Solicitation of current and past experience with red and yellow arrows through mail inquiry to senior traffic and highway engineers of representative states and cities or comparable traffic control jurisdictions.
2. Determining the adequacy of communicating with drivers by use of a mailed-in questionnaire distributed at the sites of the experimentation; and
3. Field experimentation with red and yellow traffic signal arrows, in combination with a green arrow at selected locations. The effects of the signal changes on traffic behavior and accident experience were determined at each experimental location, and for control locations as well.

C. Data Collection and Analysis

Solicitation of Current and Past Experience in Other Jurisdictions

The practices currently in use together with any past experience in other jurisdictions was obtained by a personalized inquiry at the top professional level through the Assistant Director of the D.C. Department of Highways and Traffic. Other highway and traffic engineers in selected states and cities were solicited for comments with emphasis given to the following major aspects relating to the use of red and yellow arrows:

At what types of locations are they used? How successful are they? Any problems?
Do motorists really understand the meaning of red and yellow arrows? Is explanatory signing needed?
What type of mounting is best for turn arrows-post, span-wire, or mast arm?
What about separate signal heads?
Are there any formal or informal warrants governing installations of red, yellow, and green arrows?

The generally narrative form of response covering close to 50 separate jurisdictions gave not only many answers to specific questions but also subjective and objective data with respect to their use including some research study results and applicable state and local regulations.

Results of this inquiry are reported in Section C of Chapter IV - STATE-OF-THE-ART.

Communication with Drivers, including Understanding

Past experience in related research had proved that questionnaires distributed to motorists at appropriate locations would provide very helpful information when filled out and mailed back in. This technique therefore was used.

Drafts of a questionnaire were reviewed by FHWA representatives, including psychologists, then revised and finally submitted to the U.S. Office of Management and Budget for the required approval. The approved form was subsequently distributed to motorists at selected locations. Electronic data processing was used to analyze the replies according to several logical breakdowns. The questionnaire, and the study results are discussed in Chapter V - PUBLIC UNDERSTANDING AND ACCEPTANCE.

Operational Traffic Data

Traffic data for all "before" and "after" studies were gathered primarily by means of time-lapse photography using Super 8 mm color film (ASA25) shot at two frames a second with a Minolta Autopack D 10 movie camera having a 7 to 70 mm zoom lens with an attached intervalometer. Camera mountings usually have been on the roofs of nearby buildings. The dates and times of the data collection operations at the various locations are given with the detailed discussions of those locations in Chapter VI TRAFFIC BEHAVIOR - BEFORE AND AFTER.

At some locations it was difficult or impossible to see the signal operation adequately from the available filming location until a supplemental indicator light had been installed. This occurred at locations where: the camera was greater than about 300 feet from the studied signal; where the camera was significantly elevated above the street and the signal sunvisors blocked the camera's view of the signal changes; and/or where the filming position was behind the signal of interest. The supplemental indicator lights were standard outdoor floodlight lamps and their mountings, mounted on the tops of the signal heads, and wired into the signal controllers so as to be on when the signal of interest (e.g. the green arrow) was on. These indicator lights were aimed so as not to distract motorists but to be still visible from the camera locations. Figure 1 shows several views of typical installations of these indicator lights.

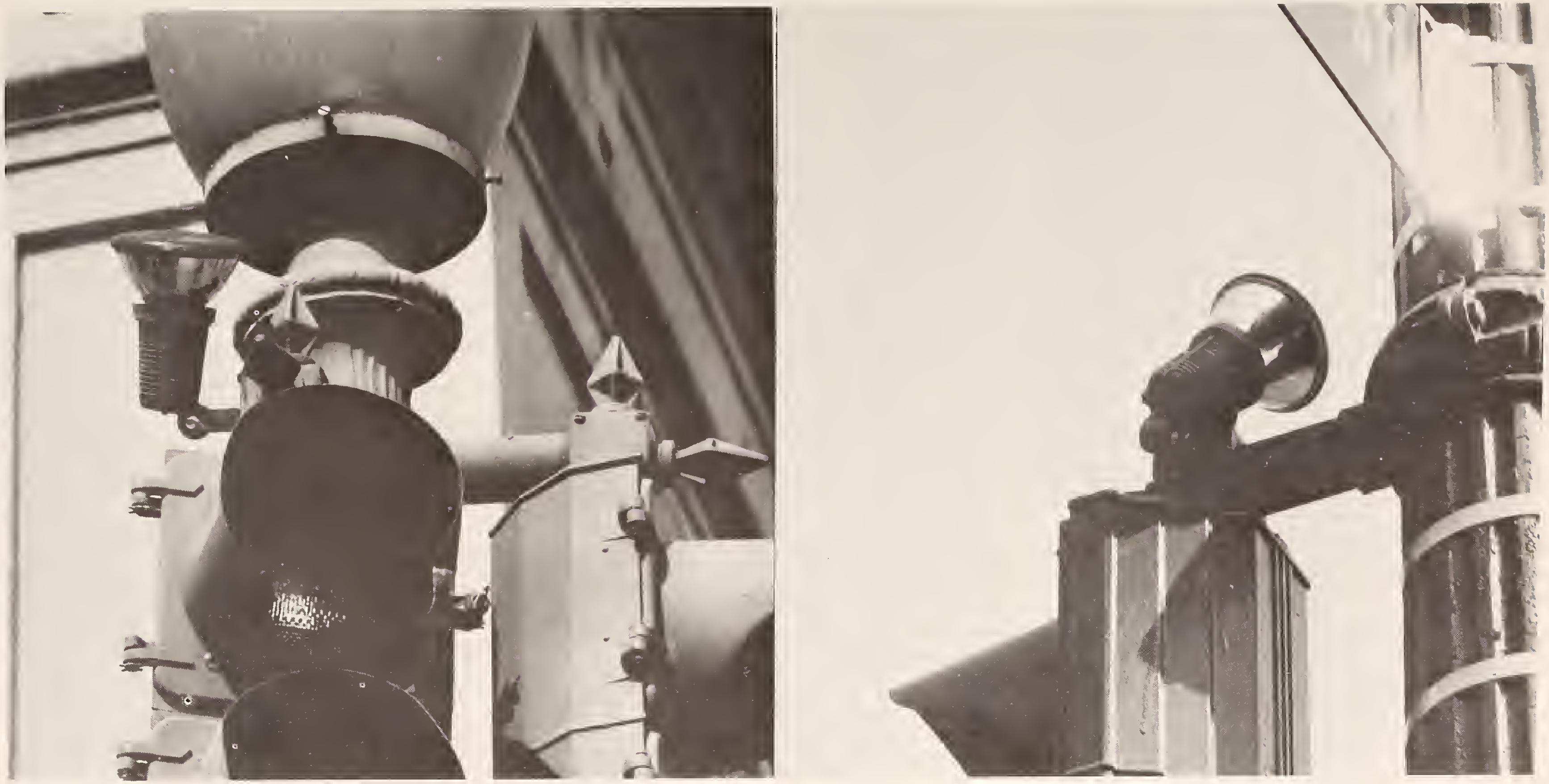


Figure 1

Views of typical installations of the indicator lights.

Film analysis was done with a Lafayette Super 8 Motion Analyzer Projector, Model AAP-904T. A film editor was also very helpful for quick previewing of film. To minimize any bias, both "before" and "after" film was obtained before the analysis for any location was begun. This allowed the same individual to code both the "before" and "after" films of any one location and allowed the "before" and "after" films to be mixed in the film scoring sequence so that the coders did not first score all the "before" film and then all the "after" films. This further reduced the possibility of bias within the film scoring operation. Data thus obtained was then analyzed through an ADP computer program. The data taken from the films included:

1. how many vehicles made the movement(s) under study;
2. how many of those were delayed, and for how long;
3. what kind of vehicles were involved;
4. how well the traffic signals were obeyed; and
5. whether the delays were due to the signals or to some other conflict (loading vehicles, pedestrians, etc.)

CHAPTER IV. STATE-OF-THE-ART

A. Historical Review of Arrow Indications in Traffic Signals

The earliest reference to the use of steady burning red arrow indications and steady burning yellow arrow indications in traffic signals found was in a report published under Technical Notes in the September 1963 issue of TRAFFIC ENGINEERING. This report was prepared by Committee 4D (61) - Application of Red and Yellow Arrows as Traffic Signal Indications, approved April 26, 1963 by the Technical Council, Institute of Traffic Engineers.

The earliest known installation of red and yellow arrows was in 1930 in Pittsburgh. Later, in 1945 and 1946, red arrows were installed in St. Louis and Detroit respectively. The 1963 I.T.E. report noted that most other recorded applications of red and yellow arrows had been made between 1957 and 1961. Inquiry by this committee established the use of either or both red and yellow arrow indications by only twelve cities-specifically, New York, Chicago, Detroit, St. Louis, Milwaukee, Pittsburgh, Cincinnati, Indianapolis, Dayton, Ft. Lauderdale, Wausau (Wisc.) and Kenosha (Wisc.)- while uses by a small number of others could not be confirmed.

Here it should be noted that these applications were neither uniform nor consistent and that most of them did not utilize the full red arrow, yellow arrow, and green arrow application. However, the Committee was able to isolate the applications into five distinct categories, as follows:

<u>Category A</u>- Complete three light signal heads with red arrow, yellow arrow and green arrow indications.
<u>Category B</u>- Steady burning yellow arrow indications (without red arrows).
<u>Category C</u>- Steady burning red arrow indications (without yellow arrows).
<u>Category D</u>- Flashing yellow arrow indications (without red arrows).
<u>Category E</u>- Flashing red arrow indications (without yellow arrows).

The use of the triple-arrow signal in Category A was comparable to many found today under Condition 5 of the Uniform Manual as applied to a "protected" left turn. Pittsburgh, Pennsylvania used (circa 1963) three color turn and through arrows to give a prohibited, then protected, left turn operation for (at least) one location. This is somewhat similar to locations where a lagging green is used to accomplish the same objective of a separate interval for a left turn, even though with lagging green the movement is not fully protected from pedestrian interference.

The most common application using a steady burning yellow arrow with a green arrow (Category B) was strictly for a clearance interval following a green arrow. Actually this was the same as the applications in Category A except that an illuminated message, NO TURN (red letters on an opaque background) was used in place of a red arrow lens. This particular usage seems to reflect the feelings of those who opposed the use of red arrows on the grounds that the basic meaning of red - STOP - conflicts with the basic meaning of the arrow - move.

In favor of the use of yellow and red arrows, however, were those who felt that motorists might react to a circular yellow and a circular red from a through-movement signal even when a separate LEFT TURN SIGNAL was operating favorable to that movement. Indecision or faulty reaction could create an accident hazard to vehicles following, which the use of yellow and red arrows could correct.

While the use of a steady burning red arrow (Category C) was insignificant and isolated, there was fairly extensive use of a flashing yellow arrow (Category D) to indicate that turns could be made with caution even when there could be potential conflict with other vehicles or an unusual pedestrian conflict.

A flashing red arrow (Category E) was used most often to permit a relatively safe right turn movement, after a stop, while all through movement was stopped. This was used at times for only a portion of the circular red phase and was particularly useful where a heavy right turn movement demanded additional capacity. Since these early uses of flashing red arrows, the increasing use of Right Turn on Red (after stop) regulations may, or may not, have reduced the need for a separate indication meaning "turn permitted after stop if safe".

For those interested in the details of some of the early applications of red and yellow arrows, reference can be made to the full ITE Report. (3)

This ITE report is valuable as background for study of the use of arrows. However, various applications were discontinued subsequent to initial application but the exact nature of these abandonments is not made clear. Also, evaluation of specific applications is not included although general comments and opinions are cited. For the most part these were based on subjective observations and generally were favorable and, in some cases, enthusiastically in support. These were some, however, who were equally contrary in their judgments.

Very little public relations work or attempts at driver education were undertaken. Consequently, the greatest success seemed to come from applications where the movement was a natural one and where the use left "practically no latitude for error by the driver".

The Committee also attempted to determine the quality of proper interpretations by motorists through a limited laboratory investigation. This resulted in an "unusually large number of misinterpretations". Thus, the Committee recommended field testing at actual sites such as is being carried out in this particular study.

One further weakness can be found in these early applications in that only in New York City was the use of red and yellow arrows covered by official Traffic Regulations although Detroit also covered the use of "red arrow (flashing)" in its Traffic Ordinance.

It might also be noted here that the District of Columbia did make legal provision for the use of red and yellow arrows under Part I, Section 11, Traffic Control Signal Legend of its Traffic Code, as of 17 March, 1972.

B. National Advisory Committee-Subcommittee on Signals

In the mid-1920's, through the activities of the National Conference on Street and Highway Safety, the American Association of State Highway Officials (now the American Association of State Highway and Transportation Officials) the American Engineering Council, and the American Standards Association, the need for greater uniformity and standardization of traffic signs, signals, and markings was recognized and action taken. First, AASHO developed a manual for rural areas; then, the National Conference on Street and Highway Safety developed one for urban streets. These two groups later combined their activities, forming a National Joint Committee on Uniform Traffic

Control Devices which was responsible for the original edition (1935) of the Manual on Uniform Traffic Control Devices for Streets and Highways.

The original manual was approved by AASHO and by the fourth National Conference on Street and Highway Safety. It also was approved as American Standard by the American Standard Association. (4)

The current edition of this manual with which we are concerned in this study was approved by the Federal Highway Administration as the National Standard for all Highways open to public travel as of November 13, 1970; it also was approved as an American National Standard by the American Standards Institute. It supercedes the 1961 edition.

The National Joint Committee on Uniform Traffic Control Devices thus has a long history of continuous and progressive activity supported with strong membership from the American Association of State Highway Officials, the Institute of Traffic Engineers, the National Committee on Uniform Traffic Laws and Ordinances, the National Association of Counties, and the National League of Cities. Staff Assistance is provided by the Federal Highway Administration.

The National Joint Committee, current referred to as the National Advisory Committee on Uniform Traffic Control Devices, carries on its continuous activity of review and revision through an organization of sub-committees, one of which-the Subcommittee on Signals- was responsible for the latest revision which included authorization for the use of red and yellow arrows in traffic signals.

Upon inquiry of the Committee, it appears that the decision to include red and yellow arrows in the Uniform Manual was based upon knowledge about their use among Committee members and upon the uses and findings of the ITE Committee discussed under Section A of this chapter. There also was a very definite feeling expressed that as long as traffic jurisdictions are going to use red and yellow arrows then there should be some authoritative guidance given to their use and official recognition given where needed. Results of further application and findings from research efforts such as this one would enhance the knowledge to a point where deletion, modification, or confirmation of the Advisory Committee's action would be indicated.

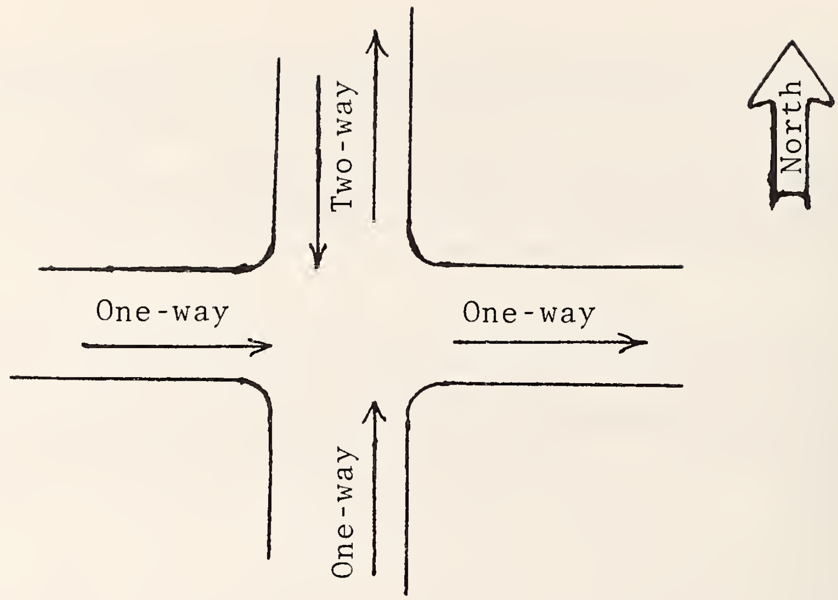
In addition to the foregoing overall viewpoint, additional comments directed to the six conditions under which these signal applications may be used were supplied by the Chairman of the Subcommittee on Signals, NAC (Mr. Wayne N. Volk, Madison, Wisconsin). These clarify the statement of the conditions, providing some of the reasoning in support of their acceptance, and are quoted below:

"I will try to comment on the six conditions listed in 4B-6.4 where arrows may be used in lieu of circular indications:

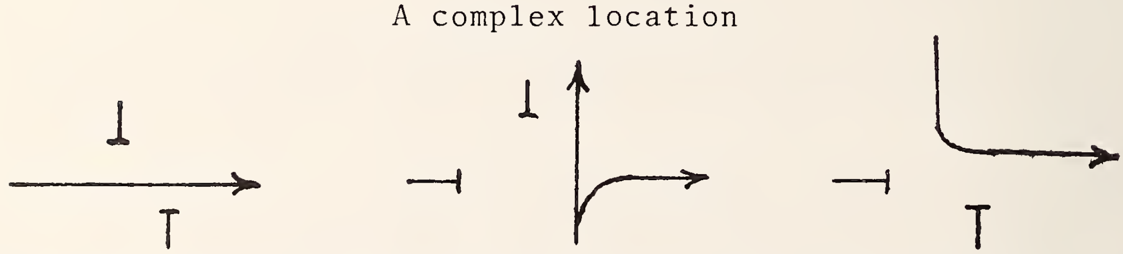
a. <u>On an approach intersecting a one-way street</u>. In this case many committee members felt that green arrows should be used where a turn was mandatory, either for physical or regulatory reasons. Where the approach is a one-way street and it intersects a one-way street, and it "heads into" a one-way street from the opposite direction, there is no choice but to turn into the intersected one-way street, and arrows would appear most appropriate. However, conflicting movements on green arrows would have to be avoided.

   Where the approach is one-way, and continues as a one-way street across the intersected one-way street, two arrows (one ahead and one pointed in the direction to turn into the one-way street) could be used. Of course, a circular green plus the appropriate "NO-TURN" sign could also be used. However, in this and all other cases where there are pedestrian conflicts, and especially WALK-DONT WALK indications, the arrows allowing a turn across the crosswalk would have to be sequenced to prevent vehicle-pedestrian conflicts, especially on the WALK indication.

   If the one-way approach to a one-way street terminates at that point in a two-way street on the opposite approach, greater problems result. In addition to avoiding pedestrian conflict problems, the vehicular indication sequencing would have to avoid showing a green turn arrow where a vehicular conflict would result if arrows were used. The green arrow shall always mean that the indicated movement has no conflicting vehicular movement. For instance, assume that...(an eastbound one-way street intersects a north-south street that changes from being one-way northbound to being two way at this intersection. The north leg of the intersection is two way. The east leg is one-way away from the intersection. The south and west legs are one way into the intersection. Such a location is shown in Figure 2) ... In that case the movements would have to be phased so that northbound traffic moved at a different



A complex location



A possible signal phasing for this location using arrow indicat-ions. NOTE: Either an exclusive pedestrian phase will also be required, or else the east crosswalk must be closed to pedest-rian use, in order to avoid pedestrian-vehicle conflicts.

A possible signal phasing for this location using circular (ball) signal indications.

Figure 2

A schematic comparison of possible signal phasings with arrow, and with circular, signal indications at a complex location.

time from southbound (left turning) traffic if arrow indications were used. However, if circular green indications were used, then theoretically both north and southbound traffic could have the green indication simultaneously. That would mean that southbound left-turning vehicles would have to yield to straight-through northbound vehicles. Under some circumstances, this might give better use of the green time than the arrows which would require more phases.

b. <u>Where certain movements are prohibited</u>. This is largely self-explanatory. Where right or left turns are prohibited, for example, the ahead arrow would normally be more effective than the circular green indication plus appropriate turn prohibition signs. This would probably be even more effective where the turn prohibitions are in force only at certain hours of the day.

c. <u>Where certain movements are physically impossible</u>. One example is an approach which is the stem of a Tee intersection. However, here again consideration must be given to pedestrians. A non-pedestrian-actuated WALK indication may use valuable time if it is required as the result of using a green arrow. A circular green, which requires yielding to pedestrians, but allows vehicles to move when there is no pedestrian conflict, might be much more economical of time. However, especially in suburban or rural areas where speeds are high, the circular green may delude motorists on the stem of the Tee into thinking the roadway continues ahead.

d. <u>On an intersection approach which has an exclusive lane for turning movements</u>. In this case, the thinking was that the arrow indications would be appropriate as they would be more clearly distinguishable from indications for through traffic. Some experience indicated, moreover, that as arrow indications for a protected movement from an exclusive lane become more common, motorists may think that a circular green for an exclusive lane is also a protected movement. (It was sometimes used that way in the past.) It is recognized that use of arrows for a left turn necessitates making this a separate phase or interval, whereas a circular green allows left-turning traffic to clear out during gaps in traffic from the opposite direction.

e. Where turning movements are "protected" from conflicting movements by other indications or by the signal sequence. This is pretty much self-evident. An example would be a protected left turn where the oncoming vehicles on the opposite approach receive a red indication. Signal phasing in which only non-conflicting vehicular movements are released simultaneously is another example (i.e., simultaneous left turns only). At one-way street intersections, signal sequence may have to be set up to eliminate conflicts.

f. Where all the movements in the approach do not begin or end at the same time and where the indications for the turning movements will also be visible to traffic with other allowable movements. An example of this case would be a "leading-left-turn" situation where the left-turn green arrow begins with the circular green (while traffic on the opposite approach is held), and the arrow terminates after which turns can be made on the circular green. Another example is when it is desirable to hold back right turns while allowing ahead vehicular traffic to go, and pedestrians to cross, after which the right (and possible left) turns are allowed by the appropriate arrow(s) or a circular green. It probably has its greatest use for leading (or lagging) left turns on a street with 4 or more lanes but no median."

"In conclusion, I'm very happy that you are undertaking this research as it should be really helpful to all of us and especially to the Subcommittee on Signals." (5)

C. Current Practices

During 1974, a letter of inquiry was sent to selected state and local traffic engineers to obtain information on their use of, and opinions on, triple-arrow (red, yellow and green arrow) traffic signal indications as provided for in the 1971 Edition of the MUTCD. Information was also solicited on the types of signal mountings used with arrow displays; the extent of motorists understanding of arrow indications; the need for supplementary signing to explain arrow indications; and whether the engineers considered such arrow applications as they had experience with to have been successful. If the engineers jurisdiction had a Right-Turn-On-Red law they were also asked how that affected their use of arrow indications.

Although the response was not universal, it was considered to quite representative. Also, since many replies were narrative in character, a fuller understanding was obtained than one based solely on statistical tabulations.

Because of many differences among state and local traffic operating conditions, as well as the varying influences exercised by states over local practices, discussion of current practices is separated for "state levels" and "cities and local jurisdictions".

1. State Levels

The reaction by state jurisdictions to the use of red, yellow, and green arrows as a triple lens installation ranges widely from (a) strong opposition or prohibition of its use, through (b) indifference or reluctance (not yet tried), then (c) a willingness for its use at specific locations, to (d) a general overall acceptance. Most of these reactions are related specifically to use of the RED ARROW; nearly everyone already is using greed arrows for left and/or right turning movements; and much use also is made of a yellow arrow as a clearance interval following a green arrow.

(a) Opposition

An initial example of opposition to tri-color arrows is North Carolina, where the 1973 State Interpretation of the MUTCD precludes use of red or yellow arrows within the State. (6) In an accompanying letter it was commented that "....motorists now have enough confusing situations to cope with, without adding to his confusion with these colored arrows. We have therefore prohibited their use in North Carolina."

In Illinois, the red arrow is not permitted although some use of the yellow arrow is considered valuable. "We do not believe the red arrow provides a totally understandable indication and therefore recommend it not be permitted in the National MUTCD; a circular red should be used to stop traffic whether turning or through."

Opposition also was strong in the state of Maine where a set of colored slides obtained from the Institute of Traffic Engineers had been shown to various groups (driver education schools, community service organizations, etc.) with little comprehension of their meaning: "in over ninety percent (90%) of the cases when these were shown, people had no idea what they meant and the general consensus in all cases was that with a green arrow the turn could be made with no conflict, with the yellow arrow the turn could be made with caution, and with the red arrow the turn could be made as soon as the vehicle had stopped". It also should be noted that Maine does have a RIGHT TURN ON RED law. How much this could have influenced the reaction to a red turn arrow is subject to conjecture.

West Virginia did try an application of a triple-arrow signal installation and then removed it after observing the operation and receiving complaints from local enforcement personnel. "The problem seemed to be that the motorists did not understand the red arrow....the yellow arrow caused no problem and the green was well understood. We did not erect any supplementary signs, but it seemed that the drivers turned regardless of the color on display. In fact, one of the local police officials called and frantically asked why the arrow kept moving up and down in the signal face. Apparently he did not recognize there was a change in color. After one week of use in one particular location it was determined that this configuration was not easily understood and it was removed."

(b) Indifference or Reluctance

No provision has yet been made for the use of RED ARROWS by California, Wisconsin, Michigan, Virginia, Washington, Iowa, and New Jersey. Whether this is due to disagreement or opposition was not made clear except in the cases of Iowa and New Jersey.

In New Jersey, during a series of seminars throughout the state to familiarize motorists with changes in traffic controls resulting from the 1971 Uniform Manual, the reaction to red and yellow arrows raised considerable question as to their suitability. The most common interpretations obtained were that "the yellow arrow meant to make the turn with caution, while the red arrow meant to stop and proceed with caution in the direction the arrow was pointing". The resulting conclusion was that "until we are able to implement a major publicity campaign concerning the meaning of these indications, we have no plans in approving them either for the local street system or installing them ourselves on the State Highway System." (Note: In New Jersey, all local installations must meet with State approval).

For Iowa, the State Highway Commission reports that it is "frankly reluctant" to approve any red arrow signal indications in the State. Only a very few yellow arrow signals have been used, an insufficient number to permit an evaulation of their effectiveness.

(c) Use Under Specific Conditions

While the Colorado Division of Highways has not yet made use of three-color arrow signal indications (yellow arrows are used for left-turn movements), a number of local jurisdictions have used them and "from our observations the three-color system is successful in urban areas...., especially where safe gaps in traffic are infrequent. Some questions are being raised about the meaning of the red arrow indication, but generally there has been no problem."

The Texas Highway Department has been "hesitant to use any red arrows", feeling that "the illuminated arrow pointing in the direction the motorist wants to go might override the prohibitive intent of its red color". Nevertheless, they seem to recognize that some cities might want to use them and therefore have taken the position: "We will not use red arrows unless a city uses red arrows in all similar signals within a city. Under these circumstances, we will consider using red arrows on an individual basis."

Limited use is found by the New York Department of Transportation almost exclusively "as left-turn lane indications where protected, non-permissive phasing is provided". This use was cited as necessary to comply with prohibitions in the Uniform Manual against the use of straight-through GREEN ARROW with CIRCULAR RED and CIRCULAR RED with CIRCULAR YELLOW. (section 4B-6, (5), (b), (c). Further comment indicated that "many motorists do not understand the meaning of red arrows" and that use may be made of an educational panel, NO TURN ON RED ARROW, as necessary. (Note: Such a panel was used with some success by the D.C. Department of Transportation with an installation at Wisconsin Avenue and M Street, N.W.).

The Arizona Highway Department has experimented with converting the left-turn signal display from red and amber balls to red and amber arrows with good results. Moreover, one such installation was subjected to a comprehensive study conducted in partial fulfillment of the requirements for the degree of Master of Science in Engineering at Arizona State University. This study had as its main objectives the determination of "how well the driver obeyed such a signal light and to what extent they understood the meaning of the arrow indications."

Observance of the triple-arrow signal installation was comparable to that obtained with the use of the red and yellow balls. Obedience was good with four out of five drivers understanding the meaning of the arrow indications, an understanding probably enhanced by the use of a sign LEFT TURN ON GREEN ARROW ONLY. Two out of every three drivers interviewed reported that they needed the sign to understand the meaning of the red arrow. Moreover, a fellow-up investigation by highway department staff found: "The considerable decrease in accidents after the signal conversion, the apparent lack of violation of the 'Red Left-Turn Arrow', and the smooth flow of traffic suggest that the 'Red Left-Turn Arrow' has not created any type of problems with regard to driver understanding and acceptance." However, it also was agreed that the sign message, LEFT TURN ON GREEN ARROW ONLY would be needed at every left-turn signal installation.

(d) General Acceptance

Only one state, Delaware, among those reporting, seems to accept the use of red, yellow, and green arrows without reservation. On the basis of information provided, judgement has been based primarily on accident experience: "As can be seen from our accident record at these locations, the situation could hardly be considered alarming. Twelve accidents at 11 intersections in 4 years is not a record which causes us great concern." A further comment is worthy of note: "We cannot help but wonder if traffic signals would be used at all if as much extensive study had been spent on the first traffic signal as is being spent in this one particular area.(9)

2. Cities and Local Jurisdictions

While urban and suburban areas generally offer many more potential applications for triple-arrow signal installations, there still seems to be a noticeable reluctance to adopt them as replacements for green arrows alone or green arrows with circular yellow and circular red. There has been fairly widespread use of the yellow arrow in conjunction with the green arrow, particularly with left turns using a "leading green".

The City and County of Honolulu reported that it is "contemplating the usage of these arrows in the near future". Tacoma, Washington uses yellow arrows but has only one red arrow. New York City did use red arrows to some extent before 1962 but found "poor acceptance" and "quite a bit of newspaper publicity"; they do not plan to use then again. Buffalo, N.Y. will use a few at T intersections. Phoenix, Arizona has installed red and yellow arrows at one location with "no significant misinterpretation of the meaning of the arrows".

A special application which "is generally considered successful" was found in the City of Newport Beach, California. Here, S and horizontal curves in a recreational area subject to extreme peak loads posed some serious problems. Green, yellow, and red arrows in a single face were used for exclusive left and right turn lanes with very acceptable results. No accidents during the first seven months could be credited to a misunderstanding of the arrow indications; "the signal is now accepted as 'normal' and traffic operation has obviously improved...." (10)

Replies to the inquiry indicated that RED ARROWS are not being used by the following cities:

St. Louis	Oklahoma City
Portland, Ore.	Cleveland
Los Angeles	Denver
Kansas City	Dallas
Boston	Richmond, Va.
Milwaukee	Minneapolis
Salt Lake City	Houston
Baltimore	Charleston, S.C.
Atlanta	New Orleans
Seattle	San Juan, P.R.
Toledo	New York City

Pertinent to this discussion is a comment received from Toledo, Ohio even though it relates to happenings involved where yellow arrows are used for phased right and left turn movements under lead situations. The reply indicated as follows:

> "Some motorists tend to continue the turning movement beyond the yellow clearance. This also happens at highly congested intersections where the amount of time per phase is not sufficient to accommodate the demand."

The above cites a problem identical to that experience in the District of Columbia (Wisconsin Avenue and M Street) where a right turn movement controlled by a triple-arrow signal was badly overloaded during rush hours to the point where the accumulation could not be cleared out within any single cycle. This resulted in a rather high proportion of the turns being made on yellow and red arrows (reallocation of cycle time for this movement to accommodate the overload was not practical). This problem will undoubtedly be found elsewhere.

3. RIGHT-TURN-ON-RED Law

The practice of permitting vehicles to make a right turn if safe after stopping for a red traffic signal may influence the extent to which red arrows are used in right turn signals. Unfortunately, an insufficient number of comments were received on this point to permit drawing any firm conclusions on the use of steady red arrows at locations with Right-Turn-On-Red. Interestingly, Michigan had several experimental locations where flashing red right turn arrows were being tested at right-turn-on-red locations.

CHPATER V. PUBLIC UNDERSTANDING AND ACCEPTANCE

A major consideration in the adoption and application of any new traffic control device, whether it be in the areas of signs, signals, or markings, is the matter of whether the motoring public will readily understand the meaning of the device and, in turn, accept it to the point of complying with the intended meaning. Such is the case here where there has been considerable question as to whether motorists would understand the meaning of red as "STOP" when used with a horizontal arrow in a traffic signal that might imply "movement." This point was cited in Chapter IV under Section A, Historical Review and Section C, Current Practices.

This study adopted a two-fold approach to answering this question: 1) actual installation of triple-arrow traffic signals at a number of experimental locations with an accompanying number of control locations (See Chapter VI), and 2) distribution of a questionnaire to a representative sample of motorists traveling through both the experimental and control locations while the field study was in progress. The results from the distribution of this questionnaire are discussed in this chapter.

A. Analysis and Review of Driver Questionnaire

For one measure of drivers' understanding and acceptance of RED ARROWS for controlling turning movements with traffic signals under selected conditions, a single-paged questionnaire was developed following consultation with representatives of the Federal Highway Administration. As required, it was approved by the U.S. Office of Management and Budget before distribution. The questionnaire showed various signal displays, which were printed in color, together with questions as to the respondents understanding of their meanings. The questionnaires were postage-paid, and were designed for a simple "check the answer and drop in the mail" type use, with which we had considerable success in an earlier study.

The questionnaires were distributed on a sampling basis at the six Washington, D.C. experimental locations, and at control locations matched to them by geometrics, signal operations, and area of the city. A minimum of 150 questionnaires were handed out at any location with the distribution divided between peak hour and midday off-peak times. A total of 1898 forms were distributed at experimental locations, and 1381 at other locations, for a total distribution of 3, 279 forms. From these, a total of 515 usable responses were received for a response rate of 15.7%. Of these 290 were from experimental locations.

The characteristics of the persons submitting usable replies are shown in Table 1 on the following page. Because the driver mix in the District of Columbia includes large numbers of drivers from nearby Maryland and Virginia, as well as many with out-of-the-area licenses, there were no distributions of characteristics with which the questionnaire respondent characteristics could be compared. A field study of three representative locations during similar hours showed that of 2,645 observed drivers, 79.6% or 2,106 were male, while 20.4% or 539 were female. There appears to be nothing unusual about the observed distribution of respondent characteristics and one must conclude they are reasonably typical and representative of area motorists. Moreover, the fact that over 90 percent either live in Washington, D.C. or within a normal commuting distance would indicate that traffic operational or control practices for jurisdictions other than Metropolitan Washington would not have any strong or bias effect.

In looking at the responses to the particular questions, the question arrises as to what percent of correct responses should be considered satisfactory. While the obivous goal is 100% understanding, when dealing with a new control device somewhat lower levels must be accepted during the motoring population's learning time. It will be remembered that there had been little or no nationwide educational program connected with the introduction of the three color arrow display. A 95% correct response would mean that 19 out of 20 respondents understood the control device, and the question, and had checked the correct answer. As a matter of engineering judgement it appears reasonable to accept a 95% or better correct response as "excellent". A response rate of 90% would indicate that, at least nine out of ten, but less than 19 out of 20 respondents understood the question and knew the correct answer. Therefore it appears reasonable to score response accuracy in the 90.0 through 94.9% range as "satisfactory" in view of the newness of the tested control devices. Rates in the 80.0 through 89.0% range would indicate that at least four out of five, but fewer than nine out of ten, people knew the correct answer. In view of the possible benefits of education and experience this 80.0-89.9 range may be judged "marginal". Rates below 80% correct responses were judged "completely unsatisfactory". While the above classification scheme is based entirely on judgement, and is admittedly arbitrary, it is believed that its use will be helpful in understanding the different levels of motorist understanding of the illustrated signal displays.

Table 1. Selected characteristics of the questionnaire respondents.

	Experimental	Control	All Responses
1. Frequency of Travel Through Location			
Less than once a week	21.7%	24.5%	23.3%
Once or twice a week	11.4	21.3	15.5
Daily or almost daily	61.7	48.4	55.2
No answer	5.2	5.8	6.8
2. Place of Residence			
In Washington, D.C.	34.8%	39.4%	35.3%
Within commuting distance	61.8	53.7	59.2
Elsewhere	1.7	6.9	4.5
No answer	1.7	-	1.0
3. Age of Motorist			
Under 24	11.7%	4.8%	8.7%
25-33	32.1	28.7	30.5
34-43	19.3	25.0	22.3
44-53	19.0	21.3	19.6
54-63	12.4	15.4	13.6
64 and over	4.8	3.7	4.5
No answer	0.7	1.1	0.8
4. Sex of Motorist			
Male	67.9%	72.4%	70.5%
Female	30.0	25.5	27.6
No answer	2.1	2.1	1.9

The Individual Questions and the Responses to Them

Questions 1 and 2

These two questions were an attempt to evaluate driver understanding of a signal display using a through green arrow on one far corner of the intersection with a green ball on the other corner. Such a display was considered for possible use to control approaches to an intersection where the cross street was one way. The intention was that the green arrow display would act to reinforce the conventional one-way signing and would further emphasize that the cross street was one-way so that a turn toward the corner with the arrow was illegal. Because of problems with the graphics and printing of the illustrations used for these two questions, they were hard to understand and the percentages of correct responses were completely unsatisfactory. The illustrations for these two questions are shown in Figure 3. In view of the severe problems with respondent understanding of these questions, it is perhaps best to make no judgement whatever, based on the questionnaire responses, as to the understandability or potential usefulness of such signal displays.

Figure 3. The illustrations for questions 1 and 2.

Question 3

The illustration for this question, shown in Figure 4, is a signal with two heads which are horizontally separated. Each head has three lights. Previous D.C. experience (7) had indicated that such horizontal separation was beneficial to motorist understanding of the signal. The left head showed a red left arrow, and the right head showed a through green arrow. Of the overall response (e.g. the response from both experimental and control locations) 89.1% understood that left turns were prohibited; only 74.6% understood that right turns were prohibited; and 96.7% understood that through movements were permitted. Thus the understanding of the red arrows left turn prohibition was a (high) "marginal", and the understanding of the green through arrows meaning was "excellent" for through movements, but "completely unsatisfactory" as a prohibition of right turns.

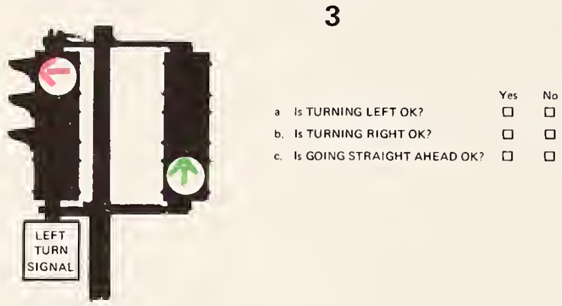


Figure 4. The illustrations for question 3.

Question 4

The illustration for this question, shown in Figure 5, is a signal with one head, with three lights. The display is a green through arrow (alone). That this display prohibited left turns was understood by 85.8% of the overall respondents, a "marginal" level of understanding. That right turns were prohibited on a through green arrow was understood by only 75.1% of the respondents a "completely unsatisfactory" level of understanding. That the display permits through movements was understood by 96.3% an "excellent" level of understanding.

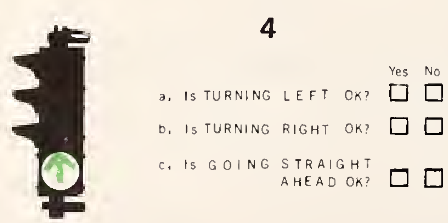


Figure 5. The illustration for question 4.

Question 5

The illustration for this question, shown in Figure 6, is a signal with one head, with three lights. The display is a red left arrow (alone). That this display prohibited left turns was understood by 88.2% of the respondents for a marginal understanding level. That the display prohibits right turns was understood by 77.5% for a "completely unsatisfactory" level of understanding. That the display also prohibits through movements was understood by only 76.3%, again a "completely unsatisfactory" level of understanding.

5

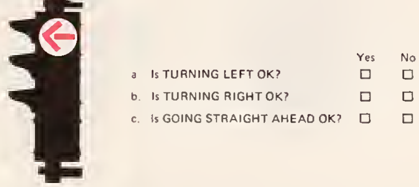


Figure 6. The illustration for question 5.

Question 6

The illustration for this question, shown in Figure 7, is a signal with one head, with three lights. The display is a green left arrow (alone). That this display permits a left turn was understood by 97.3% of the respondents, for an "excellent" level of understanding. That it prohibits right turns was understood by 85.4% for a "marginal" level of understanding. That it also prohibits through movements was understood by 86.8% of the respondents, again a "marginal" level of understanding.

6

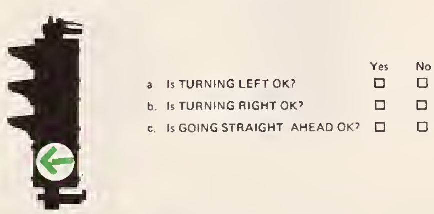


Figure 7. The illustration for question 6.

Question 7

The illustration for this question, shown in Figure 8, is a signal with two heads, each with three lights, closely spaced side by side. The left head shows a red ball display and the right head shows a red right arrow display. That this display prohibits left turns was understood by 96.9% of the respondents for an "excellent" level of understanding. That right turns were prohibited was understood by 89.7% for a (high) "marginal" level of understanding. That through movements were prohibited was understood by 94.0% for a "satisfactory" level of understanding.

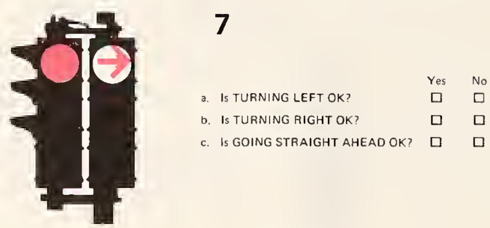


Figure 8. The illustration for question 7.

Question 8

The illustration for this question, shown in Figure 9, is a signal with two heads, each with three lights. The left head shows a green through arrow, the right head shows a red right arrow. That this display prohibits left turns was understood by 86.0% of the respondents for a "marginal" level of understanding. That the display prohibits right turns was understood by 88.0% for a better, but still "marginal" level of understanding. That through movements are permitted by this display was understood by 95.7% for an "excellent" level of understanding.

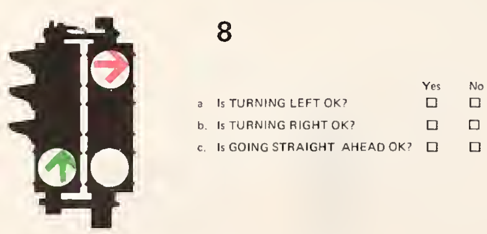


Figure 9. The illustration for question 8.

Question 9

The illustration for this question, shown in Figure 10, is a signal with two heads, each with three lights. The left head shows a red ball (circular) indication and the right head shows a green right arrow. That this display prohibits left turns was understood by 93.8% of the respondents for a "satisfactory" level of understanding. That the display permits right turns was understood by 92.2%, again a "satisfactory" level of understanding. That the display prohibits through movements was understood by 92.0%, also a "satisfactory" level of understanding.

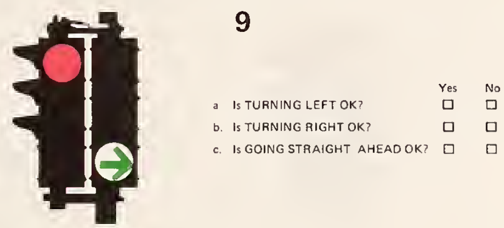


Figure 10. The illustration for question 9.

Question 10

The illustration for this question, shown in Figure 11, is a signal with two heads, each with three lights. The left head shows a red left arrow and the right head shows a through green arrow. That this display prohibits a left turn was understood by 91.3% of the respondents for a "satisfactory" level of understanding. That it prohibited right turns was understood by only 76.9% for a "completely unsatisfactory" level of understanding. That the display permits through movements was understood by 95.1% for an "excellent" level of understanding.

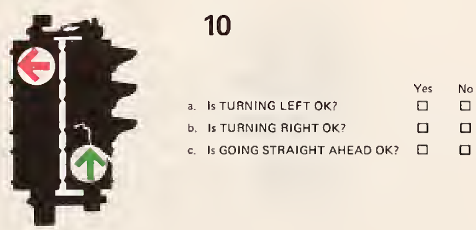


Figure 11. The illustration for question 10.

Question 11

The illustration for this question, shown in Figure 12, is a signal with two heads, each with three lights. The left head has a red left arrow indication and the right head has a red ball (circular) indication. That this display prohibits left turns was understood by 92.2% of the respondents for a "satisfactory" level of understanding. That it prohibits right turns was understood by 95.0% for an "excellent" level of understanding. That it also prohibits through movements was understood by 95.3% for an "excellent" level of understanding.

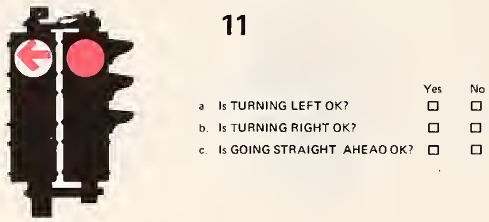


Figure 12. The illustration for question 11.

Question 12

The illustration for this question, shown in Figure 13, is a signal with two signal heads, each with three lights. The left head shows a green left arrow and the right head shows a green ball (circular) indication. Displays with both green turn arrow and green ball indications are often used with "protected then permitted" type movements to indicate when the turn is a "protected" movement. That the display permits a left turn was understood by 97.5% of the respondents an "excellent" level of understanding. That the display permits right turns was understood by only 74.4%, a "completely unsatisfactory" level of understanding. That through movements are permitted was understood by 91.7% for a "satisfactory" level of understanding.

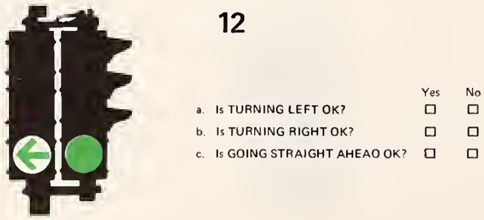


Figure 13. The illustration for question 12.

Question 13

The illustration for this question, shown in Figure 14, is a signal with two signal heads, each with three lights. The left head shows a red left arrow and the right head shows a green ball (circular) indication. It should be noted that displays in which a red turn arrow and a green ball indication are shown at the same time are prohibited by MUTCD Section 4B-6 (5.e.). That the display prohibits left turns was correctly understood by 89.9% of the respondents, a (very high) "marginal" level of understanding. However, that right turns were permitted by this display was understood by only 74.0%, a "completely unsatisfactory" level of understanding. That through movements were permitted was understood by 91.5%, a satisfactory level of understanding. It was most interesting that the red left arrows prohibition of left turns was quite well understood, but that combining it with a green ball indication appeared to seriously damage motorist understanding that they could make right turns on a green ball display. This may suggest that, without driver education as to the meaning of arrows, if any movement is controlled by an arrow indication, then all movements from that approach to that intersection should be controlled by arrow indications. Put another way, the response to this question suggests that mixing arrow and ball indications may lead to confusion by motorists making the movements to which the arrow does not apply.

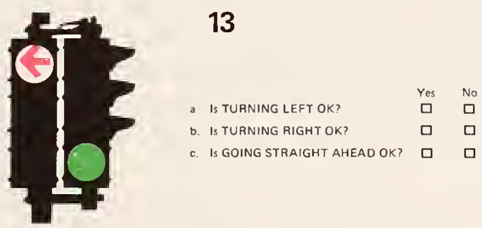


Figure 14. The illustration for question 13.

Question 14

The illustration for this question, shown in Figure 15, is a signal with two signal heads, each with three lights. The left head shows a green left arrow and the right head shows a green through arrow. That this display permits left turns was understood by 98.3% of the respondents, an "excellent" level of understanding and the highest level of correct understanding of all questionnaire responses. However, that the display prohibits right turns was understood by only 71.5% of the respondents for a "completely unsatisfactory" level of understanding. That the display permits through movements was understood by 96.1% for an "excellent" level of understanding.

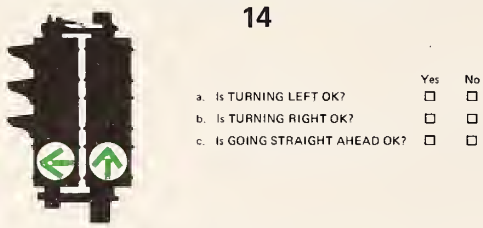


Figure 15. The illustration for question 14.

General Remarks on Question 1 through 14

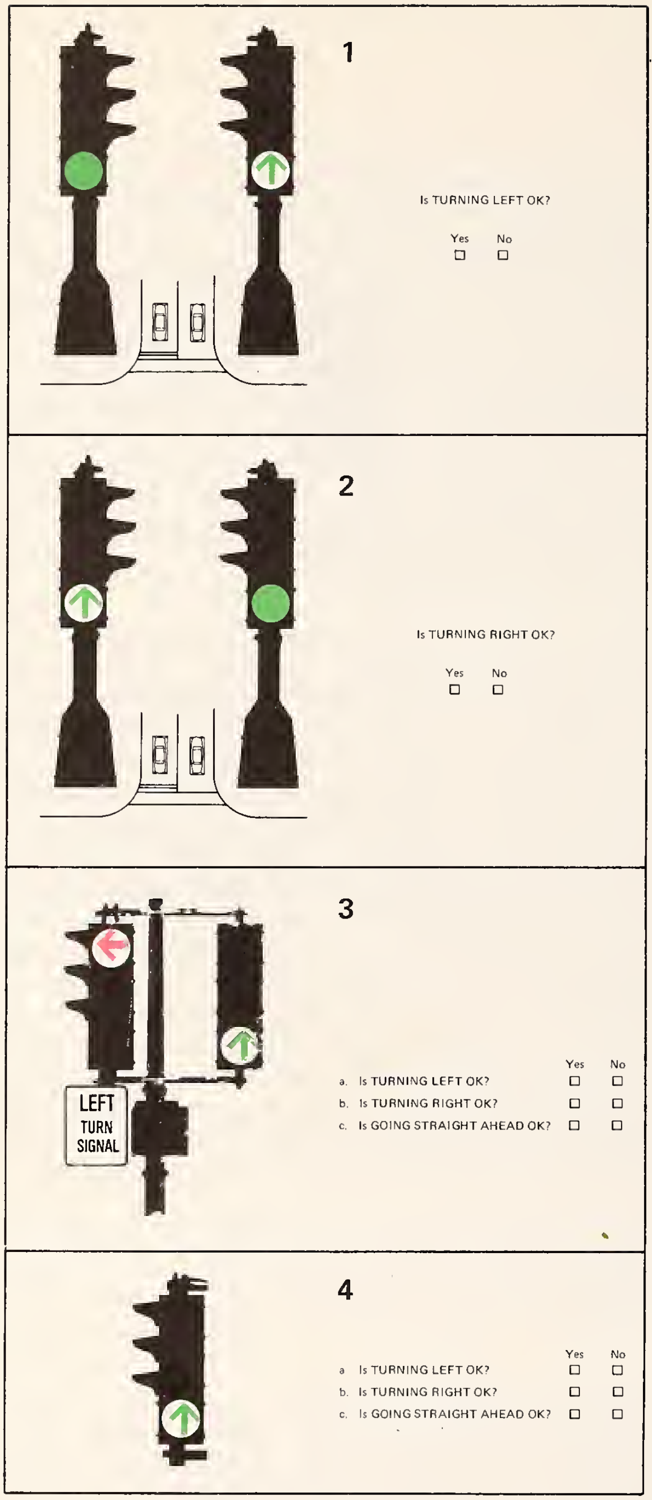
The questions and their illustrations, together with the correct responses and the levels of understanding in the overall responses are shown in Figure 16. The percentages of correct answers to each question are given in Table 2. That table shows the responses separated for the experimental locations and the control locations, as well as the overall responses. It should be noted that some respondents failed to answer some questions, creating a "no answer" response class, in addition to the desired "yes" and "no" answers. The frequency of such "no answer" responses varied widely between questions, ranging from from a low of 1.2% for questions 14A and 14C, to a high of 9.3% for questions 5C and 13B. On the conservative assumption that a "no answer" response to a question indicated uncertainty, all the "no answer" responses were grouped with the wrong answers in calculating the percentages of correct understanding.

The responses to these questions were definitely informative and perhaps even startling. This questionnaire was designed primarily to study motorist understanding of red turn arrows, but perhaps the most interesting responses have to do with green through (vertical) arrows.

Of the five displays where a red arrow alone controlled a turn (displays 3A, 5A, 8B, 10A and 13A) understanding was "satisfactory" for one (10A) and "marginal" for the rest. The percentages of correct understanding of these red turn arrows ranged from a low of 88.0% for the red right arrow of display 8B, to a high of 91.3% for the red left arrow of display 10A. All the red arrow understanding levels were grouped around the dividing line between "marginal" and "satisfactory" understanding. It should be remembered that these dividing lines were established (before the scores were examined) purely on a basis of engineering judgement.

Eight questions had "completely unsatisfactory" levels of understanding (3B, 4B, 5B, 5C, 10B, 13B, and 14B). Of these eight, seven involved the question "is turning right OK?" and four (3B, 4B, 10B and 14B) involved right turns on a thorugh green arrow. In every case where a through green arrow had been used to indicate a right turn prohibition, respondent understanding of that prohibition was "compeltely unsatisfactory", with understanding levels running from a low of 71.5% for 14B to a high of 77.5% for 5B. This strongly indicates that, despite many years of quite widespread use of green through arrows (in both Washington, D.C. and nationwide), roughly one motorist in four still believes a right turn is permitted on a through green arrow (displayed alone).

Section 4B-5 (1.b.) of the MUTCD states (p,217) that a green through arrow means that traffic "...may cautiously enter the intersection <u>only</u> (emphasis added) to make the movement indicated by such arrow, or such other movement as is permitted by other indications shown at the same time." Review of the responses to questions 3-14 strongly indicates that motorists understand the meaning of red and green turn arrows as <u>they apply to the turn they show</u> very much better than they <u>understand the above stated prohibition</u> against turns on a green through arrow displayed alone, or than they understand that an arrow for one movement (if displayed alone) prohibits other movements (i.e. that if the display is either a red left arrow alone (display 5) or a green left arrow alone (display 6) that both through and right turn movements are not permitted.) As noted in the discussion of Question 13, the mixing of arrow and ball (circular) indications in the same display appears to damage motorist understanding of the conventional ball displays. This effect was also noted in the responses to other questions, particularly question 12.



"Completely Unsatisfactory"

(problems with illustration graphics believed to void reliability of answer)

"Completely Unsatisfactory"

(problems with illustration graphics believed to void reliability of answer)

"Marginal"

"Completely Unsatisfactory"

"Excellent"

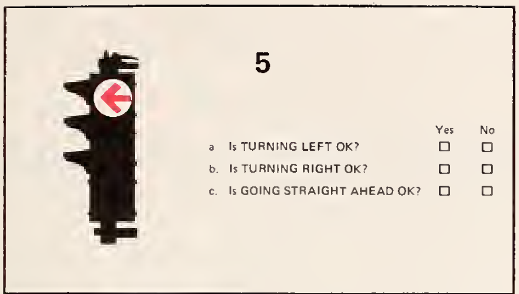
"Marginal"

"Completely Unsatisfactory"

"Excellent"

Figure 16.

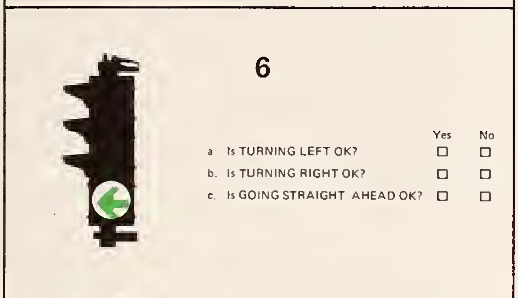
The question, their illustrations, correct answers and levels of correct understanding.



"Marginal"

"Completely Unsatisfactory"

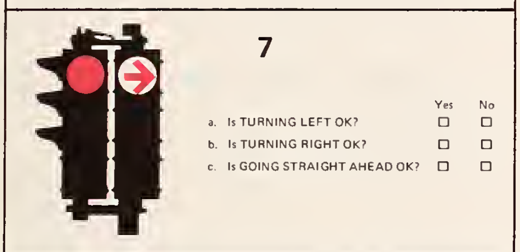
"Completely Unsatisfactory"



"Excellent"

"Marginal"

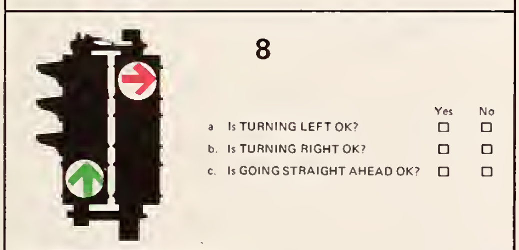
"Marginal"



"Excellent"

"Marginal"

"Satisfactory"



"Marginal"

"Marginal"

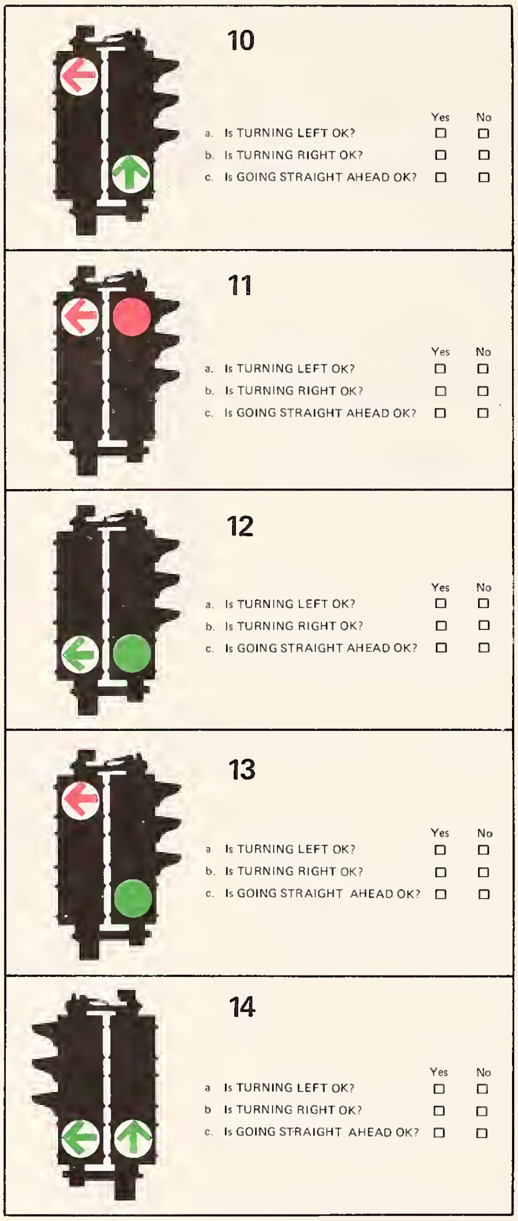
"Excellent"

"Satisfactory"

"Satisfactory"

"Satisfactory"

Figure 16 (continued)



"Satisfactory"

"Completely Unsatisfactory"

"Excellent"

"Satisfactory"

"Excellent"

"Excellent"

"Excellent"

"Completely Unsatisfactory"

"Satisfactory"

"Marginal

"Completely Unsatisfactory"

"Satisfactory"

"Excellent"

"Completely Unsatisfactory"

"Excellent"

Note: On the questionnaires that were distributed to the sample motorists, both the ball (circular) indications and the arrow indications were shown in color.

Figure 16 (continued)

Table 2. Percentages of correct answers by question and location.

Question	Experimental	Control	All Responses
No.1	51.7	58.5	56.1
No.2	61.7	73.9	67.4
No.3-A	89.7	87.2	89.1
B	74.1	74.5	74.6
C	95.9	97.9	96.7
No.4-A	84.5	86.7	85.8
B	72.8	76.6	75.1
C	96.2	95.7	96.3
No.5-A	88.6	86.2	88.2
B	76.2	78.2	77.5
C	73.8	78.7	76.3
No.6-A	97.6	96.3	97.3
B	84.8	85.1	85.4
C	84.8	88.8	86.8
No.7-A	97.6	95.2	96.9
B	91.4	86.2	89.7
C	94.2	93.1	94.0
No.8-A	86.9	85.6	86.0
B	87.9	86.2	88.0
C	96.9	93.6	95.7
No.9-A	93.1	94.1	93.8
B	92.1	92.0	92.2
C	91.0	92.0	92.0
No.10-A	91.0	89.9	91.3
B	76.6	77.1	76.9
C	94.5	95.7	95.1

Table 2. (continued)

Question	Experimental	Control	All Responses
No.11-A	93.1	89.9	92.2
B	95.9	92.6	95.0
C	96.6	92.6	95.3
No.12-A	97.2	97.9	97.5
B	70.7	77.7	74.4
C	89.7	94.1	91.7
No.13-A	89.3	89.9	89.9
B	69.7	79.3	74.0
C	89.7	93.1	91.5
No.14-A	97.9	98.4	98.3
B	69.0	73.4	71.5
C	96.2	96.3	96.1

Questions 15 and 16

These questions relate to the meaning of a yellow arrow and of a red arrow in traffic signals.

15. WHAT DOES A YELLOW ARROW IN A TRAFFIC SIGNAL MEAN TO YOU?

    SLOW DOWN, extra caution is required at this location when going in the direction shown by the Arrow. ____

    The Signal is Changing from GREEN to RED for traffic going in the direction shown by the ARROW. ____

    Both of the above ____

    None of the above ____

16. WHAT DOES A RED ARROW IN A TRAFFIC SIGNAL MEAN TO YOU?

    SLOW DOWN, extreme caution is required when going in the direction shown by the Arrow. ____

    STOP, then GO in the direction of the Arrow whenever it is safe. ____

    STOP, wait until the GREEN ARROW cames on before going in the direction the RED ARROW pointed. ____

    None of the above. ____

For question 15, with respect to the yellow arrow, only the second choice is correct. For all locations the percentage of correct responses was only 45.6%. However in the District of Columbia where motorists were allowed to keep moving through an intersection as long as they had entered it on a yellow indication, the first answer and the third might also be considered acceptable. If so, the percentages of "acceptable" answers for the experimental locations, the control locations, and all locations would be 92.4%, 88.9% and 91.2% respectively.

For the red arrow, only the third choice could be considered correct. The results here were 89.7%, 87.8% and 89.5% respectively for the the questionnaire distribution location groups. The percentages for those who felt they could stop and then make the turn when safe were low - 4.5%, 8.0% and 5.6% respectively. It was encouraging that those who were known to have had experience with red arrows (those who got their questionnaires at experimental locations where red arrows had been installed) had a lower error rate than control location motorists.

B. Need for Educational Program

Throughout the development process where significant changes have been made in uniform traffic control devices, whether signs, signals, or markings, it has always been found necessary to accompany these changes with extensive familiarization and educational programs. They must generally precede the introduction of changes and then carried on over an extended period to assure that the pertinent messages are received by all who might be affected or involved, whether motorists or pedestrians. Without attempting to outline the specifics of an educational program accompanying the use of red, yellow and green arrows, it should suffice to say that almost every available approach should be used-radio, television, newspapers, driver manuals, driver training schools, and the myriad of civic groups generally reachable. These approaches also must be supplemented by supporting explanatory signs with appropriate messages at the individual locations involved.

Such a need was pointed out in the Arizona experiment where a sign, LEFT TURN ON GREEN ARROW ONLY, was considered essential. Similar signs on the M Street approach to a right-turn arrow at Wisconsin Avenue in Washington, D.C. were effective in reducing the proportion of violations. The New Jersey Department of Transportation does not plan to approve the triple-arrow installation "until we are able to implement a major publicity campaign concerning the meaning of these indications".

While recognizing the essentiality of a well-planned, well executed educational program in connection with the use of red, yellow, and green arrows, there is the further need to assure a consistency in their use. Compatability and uniformity of their use within any community is essential. Impartial and effective enforcement of their regulatory status likewise should be considered an essential part of the educational program.

CHAPTER VI. BEFORE & AFTER FIELD EVALUATION

A. Introduction

A Washington, D.C. location which met each of the six conditions set out in the Manual on Uniform Traffic Control Devices, 1971 edition, Section 4b-6 Subsection 4, was selected for study. In addition two locations in nearby suburban Montgomery County, Maryland were also selected for study. The traffic signal displays at these eight experimental locations were modified during the late spring and summer of 1974 to include colored turn arrow indications. Traffic behavior with the "Before" and "After" signal display configurations was compared. Data on traffic performance at these experimental locations were obtained by time-lapse photography. Computer programs were developed to analyze the data resulting from scoring the time-lapse films. Control locations were also selected and observed to insure that some extraneous factor had not produced a significant change in traffic behavior between the "Before" and "After" observations. No such extraneous factor was discovered. At one of the Washington, D.C. locations (Location #05), where the intent was to evaluate the efficacy of arrow signal displays in indicating a rush-hour turn prohibition, the traffic observations were made during afternoon peak-hour conditions. At all the other locations the "Before" and "After" traffic observations were made during representative off-peak conditions.

The analysis process, the study locations, and the research findings at the various locations are described in the subsections which follow.

B. Definitions of Terms As Used Herein for Data Analysis

Time-Lapse Photography - Time lapse photography is the taking of movie films at a slower than normal number of exposures per second. The slower rate of taking the exposures (filming) means that a reel of film shot at time-lapse rates will cover a longer period of real (clock) time than a reel of film shot at normal speeds. The normal rate of filming Super 8 movie film is 18 exposures per second, and a 50 foot reel of film taken at that speed will last for roughly three minutes. In this study the filming rate was two exposures per second, and a 50 foot reel of film lasted approximately half an hour. Regardless of the rate at which the exposures were taken, each exposure produced one "frame" of film. Knowing the rate at which the exposures were taken, it was possible to calculate the amount of time that passed between two different events shown on the film, from the number of frames between the two events.

Film Scoring - Film scoring is the process of taking information on traffic behavior off of movie film, and recording it onto appropriate forms so that it can be keypunched for processing by a computer.

Signal Cycle - A traffic signal cycle is one complete sequence of all the indications of a traffic signal. The length of a signal cycle is the length of time it takes between when the indication for any given movement first goes green and when it goes green again. This is given in seconds, abbreviated as s. The "Number of Signal Cycles Observed" is given in cycles, abbreviated as c.

Signal Phase - A traffic signal phase is a part of the signal cycle allocated to any particular traffic movement (or to several non-conflicting movements) receiving the right-of-way.

Total Traffic Volume Observed - This is the number of vehicles using the studied intersection approach and on which data were obtained as to their movements. It is expressed in vehicles, abbreviated as v. At some locations data was taken on all vehicles using the studied intersection approach. At other locations, only vehicles making a specific movement, or using a preselected lane or lanes were observed. Consequently, at such locations the "total traffic volume observed" is qualified to reflect only those vehicles of interest. The descriptions of the study locations detail what vehicle movements were observed at each particular site.

Queue Position - Vehicles that were stopped when the signal turned green for the studied movement were numbered consecutively by lane. The first vehicle in each lane (the vehicle closest to the intersection in that lane) was given number one, the second number two, etc. Vehicles that waited more than one signal cycle to clear were given queue position numbers for the signal cycle in which they cleared.

Arrival of a Vehicle - If a vehicle moves through the studied intersection approach without ever coming to a full stop, it was said to have arrived at the intersection when its front bumper crossed the stop line. If a vehicle stopped before passing through the studied intersection, it was said to have arrived as of the first frame of film in which it stopped.

The stop-start-stop again creeping up in line that sometimes occurred was ignored, and the vehicle was considered to have arrived the first time it came to a full stop.

Clearing of a Vehicle - A vehicle was said to have "cleared" the approach when it crossed the (nearside) stopline. Vehicles that had stopped over the stopline were said to have cleared on the first film frame in which they started moving, and then kept moving through the intersection.

Delay - Delay is the length of time between when a vehicle "arrived" and when it "cleared". For a vehicle that arrived and cleared on the same frame the delay is zero. Note that delay is defined herein as the time between when a vehicle first stopped and when it cleared the intersection approach. Vehicles that never stopped were defined as having zero delay, even if they slowed while approaching the intersection. This avoided questions of what were the "normal" approach speeds for different types of vehicles making turns at intersections, problems in making measurements of speed, and subjective judgements in film scoring. Unless qualified "delay" means all the delay experienced by a single vehicle. It is expressed in vehicle seconds of delay time, abbreviated as v.s. Values for delay to a vehicle may be a positive number, or zero. A negative value for the delay to a vehicle is not possible.

Vehicle Experiencing Zero Delay - A vehicle experiencing zero delay is any observed vehicle which experiences zero delay while on the studied approach. The "Number of Vehicles Which Experienced Zero Delay" is given in vehicles, abbreviated v.

Total Delay to All Observed Vehicles - This is the result of summing the delays to all individual observed vehicles. It is expressed in vehicle seconds, abbreviated as v.s.

Mean Delay Per Vehicle for All Observed Vehicles - This is the result of dividing the "Total Delay to All Observed Vehicles" by the "Total Traffic Volume Observed". It is expressed in vehicle seconds of delay per vehicle, abbreviated as v.s./v.

Delayed Vehicle - A delayed vehicle is any observed vehicle which experienced any delay (greater than zero). The "Number of Delayed Vehicles" was determined by subtracting the "Number of Vehicles Experiencing Zero Delay" from the "Total Traffic Volume Observed".

Mean Delay Per Delayed Vehicle - The mean delay per delayed vehicle is the result of dividing the "Total Delay to All Observed Vehicles" by the "Number of Delayed Vehicles". It is expressed in vehicle seconds of delay per (delayed) vehicle, abbreviated as v.s./v.

Vehicles Delayed By Illegal Pedestrian Movements - Pedestrian movements were separated from the studied vehicular movements by the traffic signal phasing at all the study locations in the District of Columbia. Thus, any time a pedestrian was in the intersection in a position which would conflict with the studied movement, while the studied movement had its green signal, the pedestrian was violating the signal. All vehicles which were in such conflicts with pedestrians, and all vehicles which were in queues behind vehicles that had such conflicts with pedestrians, were defined as "delayed by illegal pedestrian movements."

Delay After Start of Green - Abbreviated as DASG - The delay after start of green or DASG, is the length of time between when the signal goes green for the traffic movement under study, and when the vehicle in question cleared the approach. It could also be described as "Clearing Time" - that is, the time it takes a vehicle to clear the intersection approach after the signal goes green for its traffic movement. In the case where a vehicle waits more than one signal cycle to clear the intersection approach, the DASG for that vehicle is calculated only for the signal cycle on which the vehicle cleared. That is it does not include the time the signal was green on earlier signal cycles. For vehicles that "jump the light" (violate the signal by going before it turns green for their movement) DASG was considered to be zero. This avoided potential problems with negative values for DASG. The DASG values were calculated individually for each vehicle. The DASG values are given in vehicle seconds of delay time, abbreviated as v.s.

Sum of DASG for All Vehicles - The total of the DASG values for all studied vehicles on the intersection approach. The value is given in vehicle seconds of delay time, abbreviated as v.s.

Mean DASG for Cars By Queue Position - This is the result of totaling the DASG values for each car which had the studied queue position, and then dividing the resulting sum by the number of cars that had that queue position. It is expressed in vehicle seconds of delay time per vehicle, abbreviated as v.s./v.

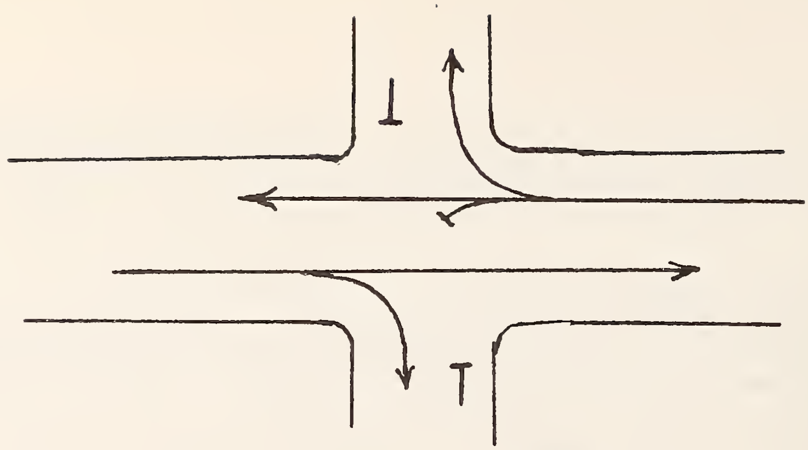
Length of Green Signal Indication for Studied Movement Per Signal Cycle - values are in seconds, abbreviated as s.

Signal's Green Time Per Vehicle - The mean amount of time the signal was green for the studied movement, per vehicle making that movement. It is calculated by first multiplying the "Length of Green Signal Indication for Studied Movement Per Signal Cycle" by the "Number of Signal Cycles Observed" to obtain the total amount of time the signal was green for the observed traffic movement; and then dividing that value by the "Total Traffic Volume Observed" to get the available green time per vehicle.

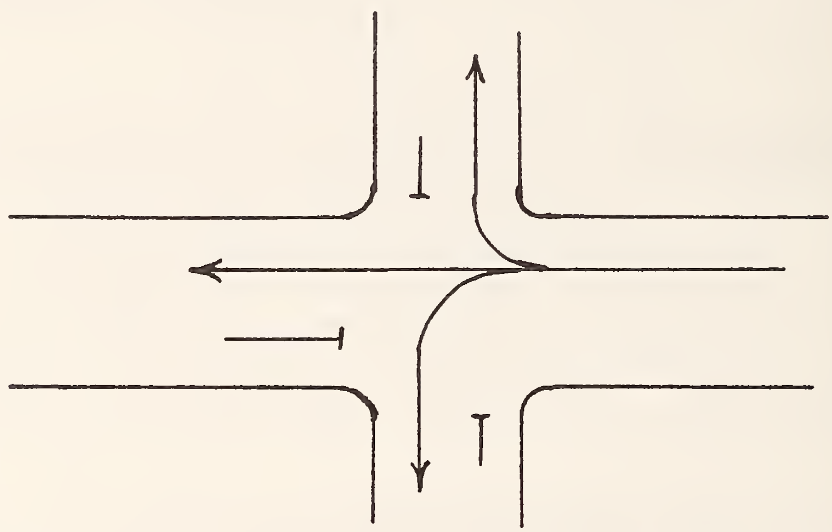
Traffic Signal Violations - The total number of traffic signal violations of all types by all the observed vehicles. It is expressed in vehicles, abbreviated as v.

Stretching the Yellow - One type of traffic signal violation. A vehicle "stretches the yellow" when it enters the intersection (that is clears the approach) just after the end of the yellow indication for the traffic movement it is making. In this study a vehicle was classed as "stretching the yellow" if it crossed the stopline five seconds or less after the end of the yellow indication for its movement. All "stretching the yellow" violations are included in the total number of violations for the location under study. It should be noted that entering the intersection on a yellow signal indication was not a violation.

Prohibited then Protected Operation - This refers to a type of traffic signal operation that first prohibits a specific movement (while other movements from its approach are allowed); and then allows the specific movement in question, while stopping any other movements that might conflict with it, thus "protecting" vehicles making the movement in question. For example, on a two-way street running east and west, left turns by westbound vehicles might be prohibited (held) while the westbound through and right turns (and the opposing eastbound through movement) receive their green indications. Then the opposing eastbound through and right turn movements would be cut off and the westbound left turn permitted. The cutting off (stopping) of the eastbound movements would "protect" the westbound left from traffic conflict. The westbound left is a "lagging" turn. Figure 17 illustrates such a "Prohibited then Protected" turning movement.



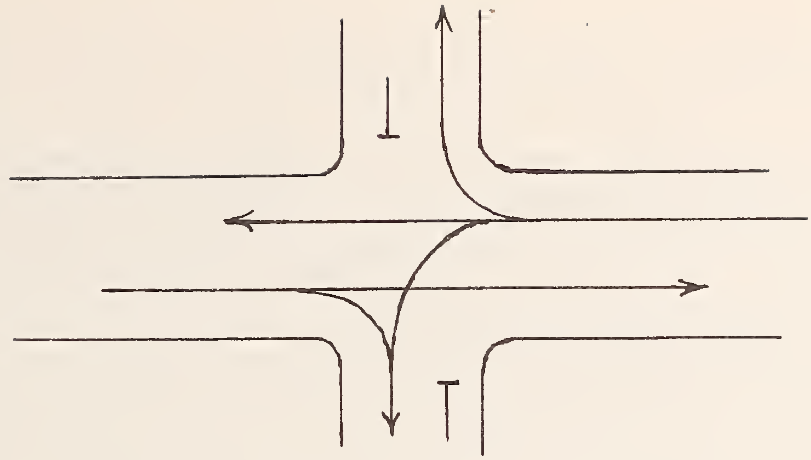
The traffic signal interval in which the westbound left turn is "prohibited", while other eastbound and westbound movements flow.



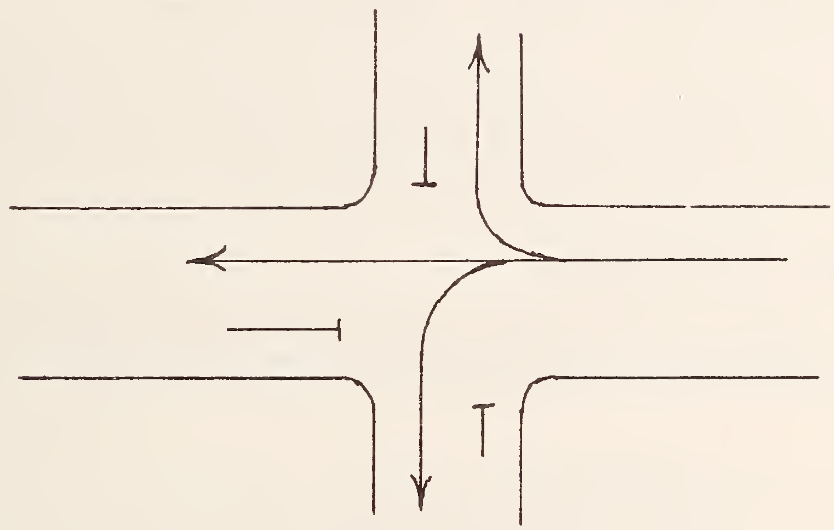
The traffic signal interval in which the westbound left turn is "protected" from conflicts by the stoppage of opposing movements.

Figure 17

A traffic signal operation in which the westbound left turn has a "prohibited then protected" operation.



The traffic signal interval in which the westbound left turn is "permitted" (subject to the normal right-of-way regulations), while other eastbound and westbound traffic movements also flow.



The traffic signal interval in which the westbound left turn is "protected" from conflicts by the stoppage of opposing movements.

Figure 18

A traffic signal operation in which the westbound left turn has a "permitted then protected" operation.

If the left turn cited in the above example came before the eastbound movements in the signal cycle (that is if it was a "leading" turn) then the turning movement would be described as having a "Protected then Prohibited" operation.

Permitted then Protected Operation - In this type of traffic signal operation the movement in question is permitted (subject to the normal right-of-way rules) at any time traffic from its approach can move, but is protected from conflicts with opposing movements during only part of that time. For example, on a two-way street running east and west, all movements by both eastbound and westbound traffic could be started at the same time. Then the eastbound movements could be shut off (stopped) to "protect" the "lagging" westbound left turn from conflicts. Figure 18 illustrates such a "Permitted the Protected" turning movement.

In the case where the signal interval in which the left turn was protected came before the start of the eastbound flow (a "leading green") the turn would be described as having a "Protected then Permitted" operation.

C. Data Analysis Procedures

A number of different characteristics of the traffic flow at the study locations could be analyzed. Some of the candidate characteristics were:

Violations;
Accident Experience;
Total Vehicle Delay;
Delay After Start of Green for All Vehicles;
Delay After Start of Green by Queue Position (Start Up Time);
Number of Vehicles per Signal Cycle;
Vehicle Classification;
Effect of Conflicts;
Various Measures of Travel Cost, such as Idling Cost, and Fuel Consumption, based upon vehicle delays.

All of the above can be calculated from time-lapse film observations of traffic. However, preliminary analysis of the time-lapse information indicated that some characteristics would provide a much more reliable and objective basis than others, for statistical tests to determine whether or not there were real differences between the traffic flow in the "Before" and "After" conditions.

The function of a traffic signal is to assign right-of-way. The degree to which the intended assignment is understood and observed must be a primary measure of the success or failure of any traffic signal display. Differences between the "before" and "after" conditions in signal observance can be detected by determining statistically whether or not there has been a change in the frequency of violations as a percentage of the observed traffic volume. Changes in safety can be measured by testing for changes in accident frequency. It was initially intended to make Total Delay, and the Sum of Delay After Start of Green for All Vehicles, two of the primary measures of whether or not there had been a change in traffic delays between the "before" and "after" conditions. However, analysis showed that both characteristics were very heavily influenced by random changes in traffic volume of the type that ordinarily occur between one day and the next in urban traffic. These normal fluctuations affect queue lengths at traffic signals in a random way, totally unrelated to any characteristics of the traffic signal display at the studied location. Numerically small changes in mean (average) queue length (e.g. from two to three vehicles per cycle) can have very marked effects on Mean Delay and on Mean Delay After Start of Green for All Vehicles. This means that the various cost of travel measures, which are calculated from vehicle delays and known vehicle operating characteristics, are similarly affected. It was therefore decided to use mean Delay After Start of Green (abbreviated herein as "DASG") <u>By Queue Position</u> as the measure of whether vehicle starting behavior was different in the "before" and "after" periods. The reader is cautioned that, while other delay data is presented as of possible interest, it is the DASG By Queue Position that shows whether or not there were real differences in traffic delays and their resulting costs between the "before" and "after" conditions at the study locations.

Because the traffic flow at the study locations was made up of a very high proportion of passenger cars, DASG by Queue Position was determined only for passenger cars. Thus, vehicles that were not cars, or which were queued behind vehicles that were not cars, were excluded from the population samples for which DASG by Queue Position was calculated. Since being behind a vehicle that entered the intersection before the studied movement got its green would tend to "cock" or "prime" a driver for a faster than normal start, all queues headed by a vehicle that entered the intersection ten or less seconds before the studied movement got its green were also excluded from the population sample used in calculating DASG by Queue Position for the studied movement. For example, at a location with a lagging left turn and having its left approach lane an optional through or left turn lane (a not uncommon situation on urban surface arterials), if the first car in a queue entered the intersection at time Zero and made either a through movement or an illegal left turn, then, if the left turn signal came on at time Zero Plus Ten Seconds or less, all vehicles in that queue would be excluded from the sample population used in calculating DASG by Queue Position for the left turn. Thirdly only vehicles that were stopped when the signal turned green were included in the population sample. This eliminated any influence of the extra warning (alerting) that might be provided to drivers who stopped at the back of a queue after the signal for their movement had already turned green but before the earlier arrivals had cleared. Finally, all vehicles that encountered conflicts (loading vehicles, pedestrians illegally in the intersection, intersection blockages, etc.) were excluded from the population sample. These various exclusions resulted in a population sample consisting exclusively of passenger cars (and light trucks with performance equal to passenger cars) that made the studied movement free from extraneous influences on their starting performance. The DASG by Queue Position was claculated from such population samples in the "before" and "after" conditions at the various locations.

Standard statistical tests were used to determine whether any observed differences between the "before" and "after" periods were due to chance or were the result of real changes in traffic behavior. For the differences in the proportion (relative frequency) of violations of the signals "before" and "after", a nul hypothesis that there was no difference was tested using the following formulas:

n_1 and n_2 = sample sizes in conditions one and two respectively;

x_1 and x_2 = number of violations in conditions one two repsectively;

$$f_1 = \frac{x_1}{n_1} \qquad f_2 = \frac{x_2}{n_2}$$

$$p = \frac{x_1 + x_2}{n_1 + n_2}$$

$$\sigma_f = \sqrt{(p)\ (1 - p)\ \left(\frac{1}{n_1} + \frac{1}{n_2}\right)}$$

$$Z = \frac{f_1 - f_2}{\sigma_f}$$

and a two tailed test at a 95% level of confidence. For the differences in DASG By Queue Position for the studied movements the test used involved "the standard error of the difference between two means" and the formula

$$\sigma_{\bar{x}} = \sqrt{\frac{(s_1)^2}{n_1} + \frac{(s_2)^2}{n_2}} \quad \text{and}$$

$$Z = \frac{\bar{x}_1 - \bar{x}_2}{\sigma_{\bar{x}}}$$

where $\bar{x}_1$ and $\bar{x}_2$ are the mean values of DASG for the queue position under study in the "before" and "after" periods respectively; and where s_1 and s_2 are the values of the standard deviations of those respective samples. These tests are described further in standard statistics texts such as reference (12). For the comparison of the accident experience, the well known Chi Square test was used. (12,13,14)

The statistical analysis of vehicle delays was done using the number of film frames as the unit of time. This avoided the inconvenience of decimal values, and the inaccuracy resulting from rounding off decimal values, that would have occurred had the units of time been converted from frames to seconds prior to the calculations. All the time-lapse filming was done at a nominal camera speed (filming rate) of two frames a second. For the three cameras used in this project the actual filming rates varied from one frame per 0.5195 seconds to one frame per 0.5298 seconds. This variation between cameras makes it desireable to use the same camera to take both the "before" and the "after" films at any one location.

At an early stage in the project it was decided to take two hours of time lapse film in each condition ("before" and "after") at each location. This decision was based on the judgement that, if a two hour sample was not large enough to show that there was a difference between the "before" and "after" conditions, then the difference (if there was any) would be relatively minor; and that even in the face of such possible events as accidents or temporary camera malfunctions as might occur during the course of the filming, that an adequate sample size would remain to permit finding any substantial differences that might exist in traffic behavior "before" and "after".

It was originally proposed that a substantial period of time would be allowed to elapse between the modification of the traffic signals at the experimental locations to the "after" condition and the taking of the "after" traffic observations. However, it was decided that the wisest course was to make the "after" observations fairly shortly after the signal modifications were completed. This would document any problems motorist might have adapting to the arrow type displays and would thus provide a "worst case" comparison. If arrow displays proved effective after only a brief motorist exposure (learning period) they should certainly prove at least equally effective after a longer motorist exposure.

D. The Experimental Locations in Washington, D.C.

The locations selected for study, the traffic signal operations "before" and "after" the experimental arrow displays were installed, and the effects of the signal modifications on traffic behavior, are described in the following subsections. The subsections are arranged in accordance with the six location cases where three color arrow displays may be used, as given in MUTCD Subsection 4B-6 (4).

1. Experimental Location on an Approach Intersecting a One-Way Street

The experimental location is the intersection of F and 10th Streets, N.W. This intersection of a two-way street with a one-way street is within the Central Business District of Washington, D.C. Tenth Street is one-way southbound, while F Street is two-way east and west. F Street has two lanes for traffic in each direction, plus one lane for parking in each direction. On each side of F Street parking is prohibited on the the intersection approach, to provide for near side bus stops. The signal operation includes an exclusive pedestrian phase, and is controlled by a fixed time, three dial, controller.

The traffic movement of interest is the left turn by westbound F Street vehicles desiring to go southbound on 10th Street. In the "before" condition no special signal display or interval was provided to expedite the left turn. Eastbound and westbound traffic flowed simultaneously, with westbound to southbound left turns restrained by the normal right-of-way rule that left turning vehicles yield to the opposing flow. In the "after" condition a "split-phase" operation was adopted and the left turn was signal controlled. In the first signal phase, westbound through traffic flowed simultaneously with eastbound through and right turning vehicles. Then the eastbound through and right turn movements were stopped, while the westbound through flow continued and the west-to-south left turn was permitted. In both the "before" and the "after" conditions pedestrians were held by a "Don't Walk" signal throughout the movement of F Street traffic, and were then given an exclusive pedestrian phase. Both approaches were controlled by post mounted traffic signals on each far-side corner.

In view of the change in signal phasing it was necessary to investigate traffic flow "before" and "after" on both the eastbound and the westbound approaches to this intersection. To avoid any possibility of confusion during film scoring or data analysis the two approaches to this intersection were given different location (reference) numbers. The approach on the east side of the intersection (carrying westbound traffic in Lanes numbers 1, 2 & 3) was numbered as Location 19. The approach on the west side of the intersection (carrying eastbound traffic in Lanes 4, 5 and 6) was given Location Number 09. The time-lapse films of traffic flow at this intersection were analyzed and scored separately for the two approaches.

The shift to a protected turn required rephasing and retiming the signal operation between the "before" and "after" portions of the study. For operational reasons the length of the exclusive pedestrian phase was also changed between the "before" and "after" portions of the study. In order to provide for the protected left turn, it was necessary to run additional electric circuits between the signal heads required for this more complex display. Due to a lack of surplus circuits in the originally installed signal controller it was necessary to change to a new and more powerful signal controller to handle the increased number of signal intervals required to provide for the protected left turn. Because of a lack of surplus space in the signal wire conduit to handle the necessary additional circuits, changes in the conduit leading into the controller box, and in the controller box mount, were also required. The total cost of the signal modifications at this location to convert to the experimental arrow display was $3,230. The need for the various changes listed above made this installation very much more expensive than was conversion to an arrow display at other locations where sufficient surplus capacity existed in the "before" condition to allow change to the "after" display without major changes in signal equipment. It should be particularly noted that the high cost of the signal modifications at this location was the result of the shift to "split phase" operation with a prohibited and then protected movement. The high cost of the signal modifications would have occurred with <u>any</u> signal display chosen for such operation; it was <u>not</u> the result of the use of arrow displays per se.

The "before" time lapse films were made on May 1, 1974 from 12:22 to 2:29 P.M. The signal modifications were completed September 10, 1974, and the "after" time-lapse films were made on September 27, 1974 between 12:25 and 2:39 P.M.

<u>The Eastbound Approach (Location Reference Number 09)</u>.

The Annual Average Daily Traffic (AADT) on this approach is 3,250 vehicles per day and running speeds are in the 25 mph range. Figure 19 shows the location. Figure 20 shows its signal operations in the "before" and "after" conditions.

In the "before" condition, traffic on the eastbound approach was controlled by conventional three light signal heads, with all eight (8) inch ball type (circular) lenses, post mounted on each far-side corner.

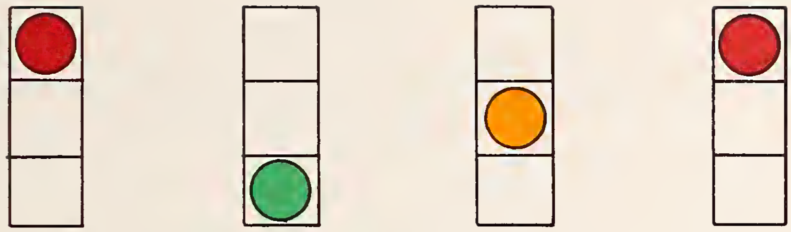
In the "after" condition, traffic on this approach was controlled by a pair of five light signal heads, one of which was post mounted on each far side corner. The signal lights were installed in a "house" type arrangement. This had two vertical pairs of lights mounted side by side for the yellow and green indications, and a single light with a red ball lens centered above the two pairs. The left (green and yellow) pair controlled the through movement, and the right pair

Figure 19

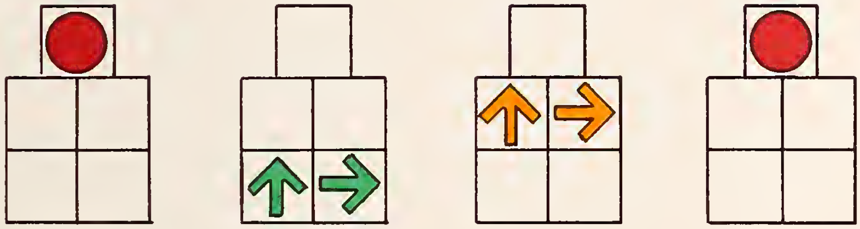
Eastbound views of the intersection of F and 10th Streets, N. W.
(location # 09)

The "after" condition.

Figure 19 (Continued)



The signal operations in the "before" condition.



The signal operations in the "after" condition.

Figure 20

Signal operations on eastbound F Street at 10th Street, N. W. in the "before" and "after" conditions.

controlled the right turn. (Reference to the illustrations of this operation provided in Figure 20 may be helpful.) All signals had 12 inch lenses. The signal indications cycled through: a red ball display; a green through arrow plus a green right arrow (pedestrians having a "Don't Walk" throughout the east and westbound movements, and then having an exclusive pedestrian phase); a yellow through arrow plus yellow right arrow; and then back to the red ball display. No signing was provided to explain the arrow signal indications.

Selected data for the "before" and "after" conditions is presented in Table 3.

Table 3

Selected "before" and "after" data for eastbound F Street at 10th Street, N.W. (location 09).

	"Before"	"After"
Number of Signal Cycles Observed.	90 c.	45 c.
Total Traffic Volume Observed on this approach.	647 v.	277 v.
Approach Traffic Volume Per Signal Cycle Observed.	7.2 v./c	6.2 v./c.
Number of Vehicles Which Experienced Zero Delay.	136 v.	4 v.
Percentage of Vehicles on this approach Which Experienced Zero Delay.	21%	1.4%
Total Delay to All Observed Vehicles on this approach.	18,007.3 v. s.	16,710.0 v.s.
Mean Delay Per Vehicle for All Observed Vehicles.	27.83 v.s./v.	60.32 v.s./v.
Mean Delay Per Delayed Vehicle.	35.24 v.s./v.	61.21 v.s./v.
Number of Vehicles Delayed by Illegal Pedestrian Movements.	297 v.	69 v.
Percentage of Approach Vehicles Delayed By Illegal Pedestrian Movements.	46%	25%
Sum of DASG for All Vehicles on this approach.	5,423.4 v.s.	2,192.6 v.s.

Table 3 (continued)

Selected "before" and "after" data for eastbound F Street at 10th Street, N.W. (location 09).

	"Before"	"After"
Length of Green Signal Indication for Studied Movement per 80 second signal cycle	24.0 s.	11.2 s.
Signal's Green Time Per Vehicle on this approach	3.339 s./v.	1.820 s./v.
Mean DASG for Cars By Queue Position:		
Queue Position one;	4.93 v.s./v.	4.21 v.s./v.
Queue Position Two;	8.49 v.s./v.	7.31 v.s./v.
Traffic Signal Violations:		
Total (# and %);	8 = 1.24%	11 = 3.97%
"Stretched Yellow" (# and %)	6 = 0.93%	11 = 3.97%

Study of the data in Table 3 shows that the change in signal operations from the conventional simultaneous east and westbound flows of the "before" condition, to the split-phase operation of the "after" condition, produced a substantial alteration in traffic operations. The increase in the time provided for the exclusive pedestrian phase from 23 seconds per signal cycle in the "before" condition to 26.4 seconds in the "after" condition is a fairly small change (as a percentage of the 80 second cycle) and does appear to have resulted in a reduction in the percentage of eastbound vehicles delayed by pedestrians illegally in the crosswalk while the eastbound vehicles had their green indication. The great bulk of the reduction in eastbound F Street's green time (from 24 seconds in the "before" condition to 11.2 seconds in the "after" condition) resulted from the need to take time out of the F Street movement for the protected left turn for westbound (7.2 seconds) and for a second clearance interval (4.0 seconds). The length of the eastbound green time in the "after" condition is only 47% of that in the "before" condition. The observed traffic volume on the eastbound approach went down from 7.19 vehicles per signal cycle in the "before" condition to 6.16 vehicles per cycle in the "after" condition. The "after" volume is 86% of the "before" volume. Since the reduction in green time is much more severe than the drop in volume (demand), the number of seconds of the signal's green time available per vehicle on this approach declined sharply from 3.34 s./v. in the "before" condition to 1.82 s./v. in the "after". The percentage of vehicles with no delays, and the mean delay per vehicle for all observed vehicles were both substantially worse in the "after" condition with its split-phase operation. This overrode the statistically significant shortening of the mean DASG (delay after start of green) for queue position one and two vehicles, which was observed in the "after" period, and which may have resulted from elimination of conflicts between the eastbound traffic and westbound left turners trying to make their turn on the beginning of the east-west green before the opposing eastbound traffic got moving. The percentage of violations was worse by a statistically significant amount in the "after" phase (the "Z" statistical test score is - 2.68). The increase in violations was of the "stretching the yellow" type, where vehicles entered the intersection within five seconds after the end of the yellow indication. For this approach the clearance indication was a through and a right yellow arrow, and the stop indication was a red ball. It is suspected that most of the "stretching the yellow" violations in the "after" period were intentional, and resulted from motorist frustration at the increased average delays; and that, for most, if not all, motorists this increase does not indicate a failure to understand the signal displays. This view is supported by the fact that there was no significant change in the frequency of violations other than "stretching the yellow" (that is violations more than five seconds after the start of the red for eastbound). It seems doubtful that the violators would have musunderstood the completely conventional red ball stop indication. (No red arrow is used on this approach.)

The Westbound Approach (Location Reference Number 19).

The AADT on this approach is 5,125 vehicles per day and running speeds are in the 25 mph range. Figure 21 shows the location, and Figure 22 shows its signal operations in the "before" and "after" conditions.

In the "before" condition traffic on this approach was controlled by conventional three light signal heads, each with all eight (8) inch ball (circular) type lenses, which were post mounted on each far-side corner.

In the "after" condition westbound traffic (using lanes one through three on the approach coded as Location # 19) was controlled by two pairs of three light signal heads, one pair on each far corner. The left side three light head of the six light assembly controlled the turn, while the right side three light head controlled the through movement. As can be seen from Figure 22, the signal indications cycled through: A red left arrow plus red ball display; a red left arrow plus green through arrow display; a yellow left arrow plus a yellow through arrow display; and then back to the red left arrow plus red ball display. All signals had 12 inch lenses. No signing was provided to explain the meaning of the arrow signal indications.

Selected data for the "before" and "after" conditions is presented in Table 4.

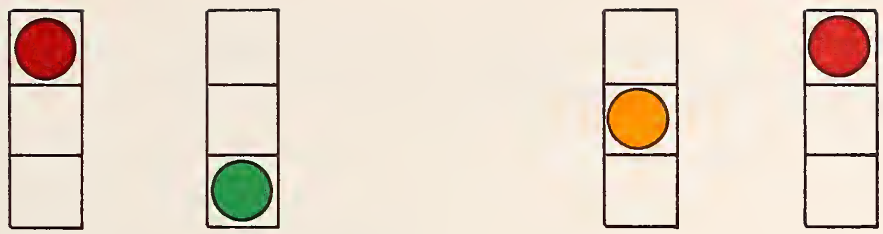
Figure 21

Westbound views of the intersection of F and 10th Streets, N.W. (location 19)

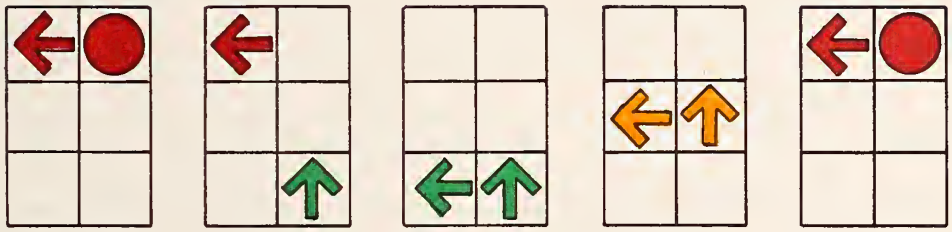
"Before"

"After"

Figure 21 (Continued)



Signal displays in the "before" condition.



Signal displays in the "after" condition.

Figure 22

Signal operations on westbound F Street at 10th Street, N. W. in the "before" and "after" conditions.

Table 4

Selected "before" & "after" data for westbound F Street at 10th Street, N.W. (location 19).

	"Before"	"After"
Number of Signal Cycles Observed	89 c.	82 c.
Total Traffic Volume Observed on this approach	748 v.	676 v.
Approach Traffic Volume Per Signal Cycle Observed	8.40 v./c.	8.26 v./c.
Number of Vehicles Which Experienced Zero Delay	86 v.	215 v.
Percentage of Vehicles on this approach Which Experienced Zero Delay	11.5%	31.8%
Total Delay to All Observed Vehicles on this approach	31,433.8 v.s.	21,412.6 v.s.
Mean Delay Per Vehicle for All Observed Vehicles on this approach	42.02 v.s./v.	31.68 v.s./v.
Mean Delay Per Delayed Vehicle on this approach	47.48 v.s./v.	46.45 v.s./v.
Number of Vehicles Delayed By Illegal Pedestrian Movements	386 v.	107 v.
Percentage of Approach Vehicles Delayed By Illegal Pedestrian Movements	52%	16%
Sum of DASG for All Vehicles on this approach	7,917.5 v.s.	3,825.2 v.s.

Table 4 (Continued)

	"Before"	"After"
Length of Green Signal Indication for Studied Movement per 80 second signal cycle	24 s.	22.4 s.
Signal's Green Time Per Vehicle on this approach	2.857 s./v.	2.710 s./v.
Mean DASG for Cars Going Straight Through, By Queue Position:		
Queue Position One;	4.77 v.s./v.	4.46 v.s./v.
Queue Position Two	7.81 v.s./v.	8.02 v.s./v.
Mean DASG for Cars Turning Left, By Queue Position:		
Queue Position One;	9.06 v.s./v.	3.25 v.s./v.
Queue Position Two	16.31 v.s./v.	6.00 v.s./v.
Traffic Signal Violations:		
Total (# and %);	15 = 2.01%	29 = 4.29%
By Turning Vehicles (# and % of turning volume)	4 = 5.48%	14 = 15.38%
Left Turning Traffic Volume Observed	73 v.	91 v.
Left Turning Volume, as a percentage of Total Traffic Volume on this approach	9.76%	13.44%

Study of the data in Table 4 shows that the change in signal operations also had a major effect on westbound traffic. Here again, the small increase in the time for the exclusive pedestrian phase appears to have resulted in a worthwhile reduction in vehicle conflicts with pedestrians in the intersection on the vehicular green. The split-phase operation did not result in a substantial reduction in westbound through green time. The changes in the mean DASG for cars going straight through from queue positions one and two were not statistically significant. This means that the observed difference is small enough to be reasonably believed to be due to nothing more than chance fluctuations, and that there is no convincing evidence that the mean DASG time of through vehicles were actually any different "before" and "after". While the sample sizes for the mean DASG times for the left turning vehicles were too small for statistical tests with high confidence levels (n =6 in the "before", and 11 in the "after" for queue position one) inspection suggests that they have changed. In the "before" condition, the DASG times for queue position one appear to have had a bimodal distribution. Some vehicles cleared very shortly after the start of the green (in effect making their turn before the opposing flow got moving), and the rest waited until the opposing flow had cleared before turning. Queue position two left turning vehicles in the "before" condition normally waited until the opposing flow had cleared. In the "after" mode, with its prohibited then protected left turn phasing, the DASG times for turning vehicles were both shorter and had smaller standard deviations (that is, they were more uniform).

Violations increased with the adoption of the split phase operation and three color arrow displays. The overall frequency of violations by all vehicles on this approach; and the frequency of violations by turning vehicles as a percentage of the turning volume; were both worse in the "after" period by amounts that were too great to reasonably be explained by chance (the differences were statistically significant at the 98% and 95% percent levels respectively). There was also some change in the violation frequency of through vehicles as a percentage of the through volume (from 1.63% "before" to 2.56% "after") but that change can reasonably be explained by chance.

The introduction of a protected turn phase for the westbound to southbound left turns also resulted in a statistically significant (Z value of - 2.175) increase in the percentage of westbound approach traffic that makes the turn.

<u>Summary for Both Approaches Combined</u>

A summary of selected "before" and "after" data for both approaches combined is presented in Table 5.

Table 5

Selected data for the combined eastbound and westbound approaches to the intersection of F and 10th Streets, N.W. in the "before" and "after" conditions.

	"Before"	"After"
Total Traffic Volume Observed on both approaches.	1,395 v.	953 v.
Total Delay to All Observed Vehicles on both approaches.	49,441.1 v.s.	38,122.6 v.s.
Mean Delay Per Vehivle for All Vehicles on both approaches.	35.4 v.s./v.	40.0 v.s./v.
Sum of DASG for All Vehicles on both approaches.	13,340.9 v.s.	6,017.8 v.s.
Traffic Signal Violations on both approaches.	23 v.	40 v.
Signal Violations as a Percentage of Total Traffic Volume Observed.	1.65%	4.20%
Number of Reported Traffic Accidents.	2 (Sep'73-Mar'74)	1 (Sep'74-Mar'75)

Study of the data in Table 5 shows that adoption of the split-phase signal operation with an arrow display, was followed by an increase in both violations and the mean (average) total delay per vehicle. Elimination of the conflict between eastbound through vehicles and westbound turning vehicles did result in a reduction in the mean DASG (delay to a vehicle after it received its green indication). Reported accident experience showed no change that can not reasonably be attributed to chance. It was not clear to what extent the observed changes in traffic behavior resulted from the change to split-phase traffic signal operation, and to what extent they were the result of the arrow display. It was the impression of one of the researchers that the change in the signal operation would probably have produced largely similar delays regardless of whether arrow, or conventional, signal displays were used, and that there appeared to be a causal relationship between the increase in delays and the increase in violations. It was not possible to confirm or quantify these impressions. It should be noted that the purpose of this research project was to evaluate the efficacy of red, yellow and green arrow displays in traffic signals, and that determination of the desireabilility of prohibited then protected movement, split-phase signal operations was beyond the scope of this project. The circumstances under which various types of signal operation are effective and warranted (e.g. normal two direction with the standard right-of-way rule controlling turns; protected then permitted turn operation; protected then prohibited turn operation; exclusive pedestrian phases; and leading vs lagging protected turns) appears a fruitful are for future study. References (15) and (16) bear on this problem.

2. <u>Experimental Location where Certain Movements are Prohibited</u>

The experimental location is the intersection of New York Avenue and 13th Street, N.W. This intersection of two arterial routes is near the edge of the Central Business District of Washington, D.C. Both routes are two-way. At this intersection a left turn by east-north-eastbound New York Avenue traffic onto northbound 13th Street is prohibited during the A.M. (7:00 - 9:30) and P.M. (4:00 - 6:30) peak periods on weekdays. The turn is permitted at other times when it functions under the normal right-of-way rule that "left turning traffic must yield to opposing traffic". It should be noted that all traffic desiring to turn right (south) leaves New York Avenue at a "Y" type intersection (with H Street) just upstream (west) of this location. This means that there are essentially no right turns from the studied approach onto 13th Street. In the film scoring and computer data analysis operations, this location was designated by location reference number 05. Figure 23 contains illustrations of the studied intersection approach. Figure 24 shows the signal operations in the A.M. and P.M. peak hours for the "before" and "after" conditions.

Raised medians are provided in New York Avenue on both sides of the intersection. On the east side of 13th Street (the downstream side) the median has been widened to include plantings, benches, etc.

On the west (near and upstream) side of the intersection, New York Avenue has four east-north-eastbound lanes. On the east (far and downstream) side it has three lanes due to the wider median on that side. The median lane on the west side (referred to in this study as Lane #1) is the lane which is dropped. The nose of the median is smoothed to allow reasonable merges by Lane #1 vehicles into the through lanes east of the intersection. Nevertheless, because of the lane drop the lane volume of through vehicles approaching the intersection in Lane #1 was significantly lower than the lane volumes for the other lanes.

In the "before" phase of the study, traffic on this approach was controlled by a three light signal head, with all 8 inch ball display lenses, post mounted on the right far side of the intersection. The rush hour turn prohibition was indicated by a conventional painted sign mounted immediately below the signal head.

In the "after" portion of the study, the intent was to use an arrow display to call attention to the rush hour turn prohibition. Consequently a five light signal head with a "house" type arrangement of the lights (two side-by-side vertical two light pairs for the yellows and greens, with a single light for the red centered above those pairs) was installed. All lenses are 12 inch. The left (north) side pair of lights has green and yellow through arrow lenses. The right (south) side pair of lights has green and yellow ball display lenses. During periods when the left turn prohibition

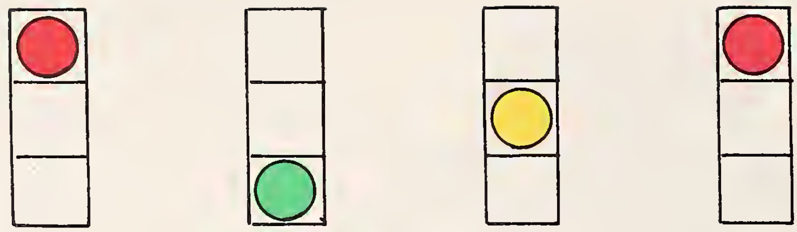
Figure 23

Views of the eastbound approach of New York Avenue to 13th Street, N.W.

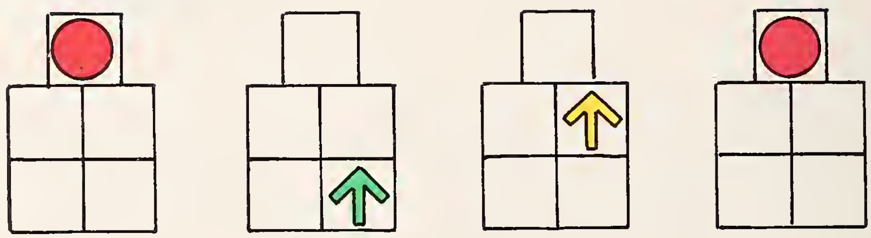
"After" display during peak hours.

"After" display during off-peak hours.

Figure 23 (Continued)



The eastbound signal displays in the "before" condition.



The eastbound signal displays in the "after" condition.

Note: In the "after" condition, during offpeak hours, conventional green and yellow circular signal indications are shown in the two lower left lens positions. The difference in the operations during peak and offpeak periods is shown in Figure 23.

Figure 24

Signal operations during the A.M. and P.M. peak hours for eastbound New York Avenue at 13th Street, N. W.

is not in force, the left side pair is dark, and the signal display uses the top red ball plus the right side pair. At such times the signal display cycles through: A red ball indication; a green ball indication; a yellow ball indication; and then back to the red ball. During the times when the turn prohibition is in effect, the right pair of lenses is switched off, and the left pair operate. This gives a display that cycles through: A red ball indication; a green through arrow; a yellow through arrow; and then back to the red ball indication. The turn prohibition sign, as used in the "before" period, was retained in the "after" period. No additional signing was installed.

It should be noted that a red arrow indication was not used at this location. The Manual on Uniform Traffic Control Devices, 1971 edition, states (Section 4B-6 subsection 4, part a. of the second paragraph, page 219):

> "A steady red arrow indication shall be used only (emphasis added) in a separate signal face which also contains steady yellow arrow and green arrow indications. It shall be used for controlling only a single traffic movement."

That provision was interpreted as prohibiting use of a steady burning red arrow display throughout the signal cycle (in other words a red arrow that did not change to green) to indicate a turn prohibition.

The "before" and "after" traffic observations at this location were made during the P.M. rush periods (4:00 - 6:30) on April 10 and September 12, 1974, respectively. Making the observations in the rush periods was necessary since the turn prohibition was only in force during the A.M. and P.M. peaks, and the intent of the study at this location was to evaluate the efficacy of an arrow display in indicating a turn prohibition.

The cost of the signal modifications at this location was $1,500.00 and the work was completed on August 19, 1974. The cost of the signal modifications necessary to create the "after" signal display used at this location was substantially increased by the necessity to pull additional cable to provide the extra electric circuits required for this more

Table 6

Selected "before" and "after" data for median lane of eastbound approach of New York Avenue to 13th Street, N.W.

	"Before"	"After"
Number of Signal Cycles Observed.	47 c.	67 c.
Total Traffic Volume Observed in this approach lane.	45 v.	81 v.
Approach lane's Traffic Volume Per Signal Cycle Observed.	0.96 v./c.	1.21 v./c.
Number of Vehicles in this Lane which experienced Zero Delay.	37	62
Percentage of Vehicles in lane which experienced Zero Delay.	82%	77%
Total Delay to All Observed Vehicles in this lane.	253.7 v.s.	290.0 v.s.
Mean Delay Per Vehicle for All Observed Vehicles in this lane.	5.6 v.s./v.	3.6 v.s./v.
Mean Delay Per Delayed Vehicle in this lane.	31.7 v.s./v.	15.3 v.s./v.
Sum of DASG for All Vehicles in this lane.	27.0 v.s.	151.0 v.s.
Mean DASG for Cars in this lane	0.6 v.s./v.	1.9 v.s./v.
Length of Green Signal Indication per 80 second signal cycle.	25.6 s.	25.6 s.
Signal's Green time per Vehicle approaching in this lane.	26.7 s./v.	21.2 s.v.

complex signal operation. Had sufficient surplus (unused) circuits been available in the "before" condition, the costs of the signal modification would have been much lower.

Selected data for the "before" and "after" conditions on the studied approach to this intersection is presented in Table 6. Since the study was intended to evaluate the efficacy of the arrow display in indicating the turn prohibition, the analysis was restricted to the approach lane from which the illegal turns would be made (the median lane). No left turns were observed from any other lane.

Review of the data presented in Table 6 shows that traffic volumes in the studied lane and the frequency of illegal left turns were both somewhat higher in the "after" period (with the green and yellow through arrows) than in the "before" period (with all circular "ball" signal displays). A statistical analysis showed that the difference in the frequency of the illegal turns "before" and "after" was not so large that it could not most reasonably be ascribed to simple chance fluctuation (the Z value was - 0.433). Thus there was no reason to believe that the change in the signal display resulted in any real change in the frequency of illegal turns. The Z value for the change in the mean delay to delayed vehicles was 1.57 which means that chance may explain the change.

Because of the low lane volumes it was not possible to make a meaningful analysis of DASG by queue position at this location.

Traffic accident experience in the September, 1973 through March, 1974 "before" period was compared to that in the September, 1974 through March, 1975 "after" period. There was one property damage accident involving this movement in the "before" period. There were no relevant accidents in the "after" period. The difference in accident frequency is small enough to be due to chance.

3. Experimental Location Where Certain Movements are Physically Impossible.

The experimental location is the "T" intersection of East Executive Avenue with E Street, N.W. In film scoring and computer data analysis this location was designated by location reference number 07. A channelization island divides the southbound flow on East Executive, so the southbound East Executive traffic desiring to turn left and proceed eastbound on E Street moves on one side of the island, while the traffic desiring to turn right and head west on E Street travels along the other side of the channelizing island. In this study the movement of interest is the southbound to eastbound left turn. Two lanes are provided for this turn, and both are mandatory left turn lanes. A park (the "Ellipse") lies to the south of this "T" intersection. The location is shown in Figure 25. Its signal operations in the "before" and "after" conditions are shown in Figure 26.

In the "before" condition, the left turn was controlled by a pole mounted, far side signal with four 8 inch lenses. The vehicular signal display sequence was: red ball; green left arrow; yellow ball; and then back to the red ball. The fourth (and lowest) lens in the four light signal head was not used.

No changes in signal timing or signal placement were made between the "before" and "after" conditions. In the "after" condition the signal had been converted to a four light head with all 12 inch lenses. The vehicular signal display was: red left arrow; green left arrow; yellow left arrow; and then back to red left arrow. The fourth (and highest) lens was a red ball which was used only in flashing operation during late night, malfunction, or emergency conditions. This fourth (ball) lens was required because flashing a red arrow is not authorized by the M.U.T.C.D., and because our interpretation of M.U.T.C.D. Subsection 4B-18 is that it requires all traffic signals to be operable in the flashing mode. No special signing was provided to explain the arrow signal indications.

In both the "before" and "after" conditions the signals were operated by a fixed time, three dial signal controller. Pedestrians were provided with a signalized crosswalk to the west of this "T" intersection so that those who used the marked crosswalks would not be in conflict with the left turning vehicles.

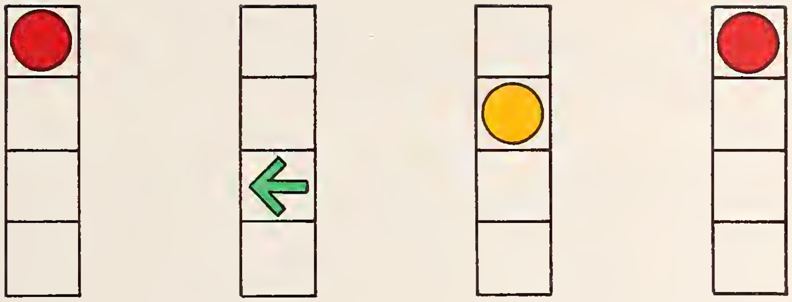
Figure 25

Views of the intersection of East Executive Avenue with E Street, N.W. (location 07)

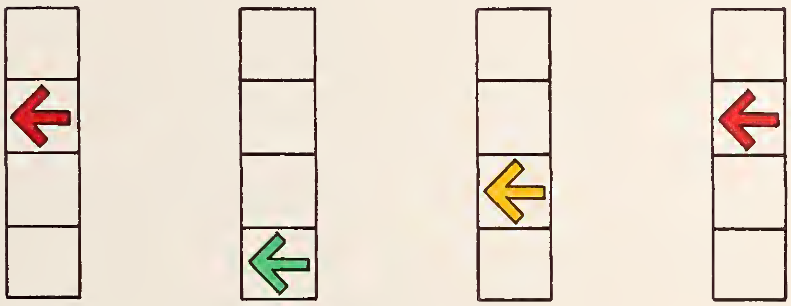
The "Before" condition.

The "After" condition

Figure 25 (Continued)



Signal displays in the "before" condition.
(Note: Lowest light not in service.)



Signal displays in the "after" condition.
(Note: Top lens (a red ball) used only during flashing operation.)

Figure 26

Signal operations in the "before" and "after" conditions on East Executive Avenue at E Street, N. W.

The "before" traffic observations were made on May 14, 1974 between 9:48 A.M. and 12:26 P.M. The "after" traffic observations were made on July 24, 1974 between 9:54 A.M. and 12:03 P.M. The signal modifications to convert from the "before" to the "after" signal display were made on June 1, 1974 at a cost of $305.00.

Table 7 presents selected data for the "before" and "after" conditions. A statistical test shows that the minor improvement in the frequency of traffic violations is not nearly large enough to suggest that it was anthing more than the result of simple chance fluctuation. The Z value was 0.224. Consequently there was no reason to believe that changing from the "before" to the "after" signal display changed the actual frequency of signal violations. Other statistical tests showed that there was no statistically significant change in the DASG times of queue position one vehicles (the Z value was - 0.572), but that the DASG times for queue position two vehicles were worse in the "after" condition by an amount that was too large to be reasonably explained by chance. The Z value was -3.471. This proved that the second vehicles in queue (but not the first) did take longer to clear the intersection approach after the signal changed with the all-arrow display used in the "after" condition. The Z value for the change in the mean delay per delayed vehicle was -3.254. Traffic accident experience at the location was analyzed for the June, 1973 through March, 1974 "before" period, and for the June, 1974 through March, 1975 "after" period. There were no reported traffic accidents involving vehicles making the studied movement in either period.

Both the mean delay per vehicle for all observed vehicles, and the mean DASG were much greater (worse) in the "after" condition. Review of the records of the individual vehicle arrivals suggests that this increase in delays was not completely the result of the change in signal displays at this intersection. There were major differences between film reels of the same condition in the levels of delay observed. For example, Reel 3 of the "before" condition showed 183 vehicles having a total of 2,122.8 vehicle seconds of delay, for a mean delay of 11.60 vehicle seconds per vehicle. Reel 4 of the "before" condition showed 186 vehicles having a total of 791.9 vehicle seconds of delay, for a mean total delay of 4.26 vehicle seconds per vehicle. That two immediately adjacent half hour periods of time should show such strong differences in the mean delay per vehicle, while still having quite similar traffic volumes and amounts of "green" per vehicle (2.98 seconds

Table 7

Selected "before" and "after" data for the southbound approach of East Executive Avenue to its "T" intersection with E Street, N.W.

	"Before"	"After"
Number of Signal Cycles Observed.	70 c.	88 c.
Total Traffic Volume Observed on this approach.	556 v.	697 v.
Approach Traffic Volume Per Signal Cycle Observed.	7.94 v./c.	7.92 v./c.
Number of Vehicles Which Experienced Zero Delay on this approach.	449 v.	505 v.
Percentage of Vehicles on this approach Which Experienced Zero Delay.	80.8%	72.5%
Total Delay to All Observed Vehicles on this approach.	3,917.6	8,049.1 v.s.
Mean Delay Per Vehicle for All Observed Vehicles	7.05 v.s./v.	11.55 v.s./v.
Mean Delay Per Delayed Vehicle.	36.61 v.s./v.	41.92 v.s./v.
Sum of DASG for All Vehicles on this approach.	368.5 v.s.	864.0 v.s.
Mean DASG Per Vehicle for All Vehicles on this approach.	0.66 v.s./v.	1.24 v.s./v.
Length of Green Signal Indication for Studied Movement Per 80 second signal cycle.	26.0 s.	26.0 s.

Table 7 (continued)

	"Before"	"After"
Signal's Green Time Per Vehicle on this approach	3.27 s./v.	3.28 s./v.
Number of Signal Violations Observed.	8	9
Percentage of Approach Vehicles Which Violated Signal	1.44%	1.29%
Mean DASG for Cars Turning Left, By Queue Position		
Queue Position One	2.19 v.s./v.	2.31 v.s./v.
Queue Position Two	4.12 v.s./v.	5.38 v.s./v.

per vehicle in reel 3 vs. 3.22 seconds per vehicle in reel 4) seems to suggest that the signal operation at the studied location was not the only cause of the variation in delays, either between conditions, or between different film reels of the same condition. The difference between these two reels, and much of the difference between the "before" and "after" conditions appears to have been related to the proportion of approach vehicles that were in the platoon of "through band" vehicles. Most southbound vehicles approaching this intersection were grouped into platoons moving in the "through band" of progression so that they reached the studied intersection when its signal was green for them. This grouping of the approaching vehicles into the "through band" took place at several signalized intersections upstream. To the extent that the proportion of vehicles entering these intersections by turning from cross streets (rather than passing straight through) changed, the proportion of vehicles that were in the "through band" changed. If the proportion of vehicles in the "through band" fell, a higher percentage of vehicles came up to the stuided intersection when its signal was red, and thus had to wait. In addition, if the queues of stopped vehicles waiting when the signal turned green grew sufficiently, those queues would not have cleared out by the time the platoon traveling in the "through band" arrived, and the platoon vehicles were also delayed. Changes in mean queue length also affected the sum of DASG for all vehicles on the approach, and the Mean DASG for them, since the further back in queue a vehicle was, the longer was its delay after start of green. Queue length is not believed to seriously affect the Delay After Start of Green for a particular queue position, but only for the total of all approach traffic, since (for a given approach volume) longer queues put a higher percentage of the vehicles further back where their delays are longer. Put another way, the mean delay of a queue position two vehicle may not be seriously affected by whether there is one vehicle or ten waiting behind it. However, for a given number of vehicles passing through an intersection in a given length of time and number of signal cycles, whether the mean queue length is three vehicles or twelve can make a great difference in both the total delay and the sum of the delays after start of green (and of course in the per vehicle means of both those values) on an intersection approach. The above described effects of changes in the proportion of the approaching traffic that is in the "through band" appear to have been the predominant cause of the difference between the delays observed in reels three and four of the "before" films at this location. Reel three (11:25 through 11:55 A.M. on May 14, 1974) had only 70% of its vehicles clear the intersection with no delays, while reel four (11:56 A.M. through 12:26 P.M.) had 87% of its vehicles undelayed. The primary cause of this difference appears to have been a difference in the proportion of vehicles in the "through band", which in turn appears to have resulted largely from random variations in traffic at upstream signalized intersections. That there were such substantial short term fluctuations in traffic flows and delays at intersections where there were no changes in the traffic controls is considered a significant finding of this study. It should be noted that the difference in the percentage of vehicles in the "through band" between Reels three and four of the "before" film was 17% (70% vs 87%) while the difference in the mean delay per vehicle was over two and one half times the smaller value (11.60 seconds per vehicle for reel three vs 4.26 seconds per vehicle for reel four). Thus, relatively small numerical differences in the percentage of the approach traffic which is in the "through band" were associated with very major changes in the total delay to traffic. It was not possible to determine what proportion of the increase in delays between the "before" and "after" conditions at this location was due to the change in the signal displays to the "all arrow" configuration, and what proportion was due to such a change in the proportion of "through band" vehicles. However, examination of the arrival and delay data for the individual vehicles in the "before" and "after" conditions strongly suggests that differences in the proportions of approach vehicles in the "through bands" on the two filming dates were responsible for a very substantial part of the difference in the delays "before" and "after". It is suspected that such a difference in the proportion of "through band" vehicles resulted from changes in the proportion of the approach traffic that turned onto East Executive Avenue at the nearest intersections to the north. Reels three and four of the "before" film demonstrate that quite small numerical changes in the proportion of "through band" vehicles could have produced the observed difference in the delays "before" and "after". It is emphasized that there was no change in the signal progression settings along East Executive Avenue between the "before" and "after" filming dates.

Whatever the cause of the increase in the (total) delay and the delay after start of green on a per vehicle basis at this location, the increase in the mean DASG for queue position two vehicles must be attributed th the change in the signal displays to the "all arrow" type. As there was no showing of any change in safety (either in frequency of violations or in accidents), and there was an increase in the mean DASG for queue position two, the change to an "all arrow" display was not beneficial. How seriously negative the results of that change are considered depends upon the extent to which responsibility for the increase in delays is assigned th the signal display change, and the extent to which it is assigned to random fluctuations in upstream traffic behavior.

4. Experimental Location on an Intersection Approach Which Has an Exclusive Lane for Turning Movements.

The experimental location for this part of the study is the intersection of New York Avenue with Bladensburg Road, N.E. This location is on a primary arterial route near the eastern border of the District of Columbia in an area with tourist services and industrial and warehousing land uses. Figure 27 shows the location. Figure 28 shows its traffic signal operations in the "before" and "after" conditions. The site was assigned location reference number 11 for film scoring and computer data analysis purposes.

The traffic movement of interest is a left turn from westbound New York Avenue onto south-westbound Bladensburg Road. The change of direction of a turning vehicle is approximately 60 degrees. This location has been channelized to provide an exclusive left turn slot separated by raised islands from both the opposing traffic and from through vehicles continuing westbound. Two turning lanes are provided to meet the high turning demand. The westbound to south-westbound left turn is signal controlled with a lagging protected turn and a "prohibited then protected" operation. The turn is prohibited during the interval when both eastbound and westbound through traffic flow. Then the opposing (eastbound) through traffic is stopped and the left turn has a protected movement, while the westbound through movement continues. The turn is controlled by dual far side signals post mounted on the islands of the channelization for a similar left turn channelization for eastbound New York Avenue traffic. The traffic signals are operated by a three dial, fixed time, controller.

In the "before" condition, the signal display controlling

Figure 27

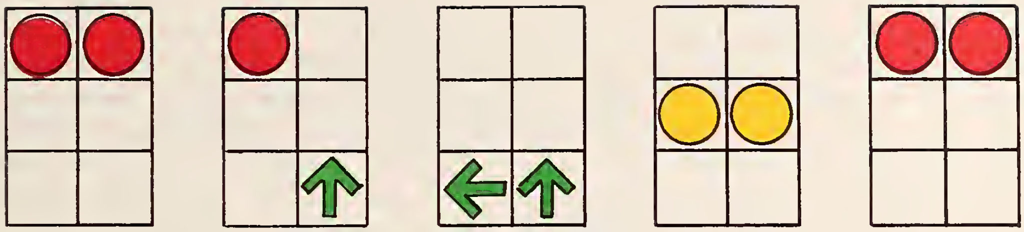
Views of the westbound approach of New York Avenue to its intersection with Bladensburg Road, N.E. (location 11).

Figure 27 (continued)

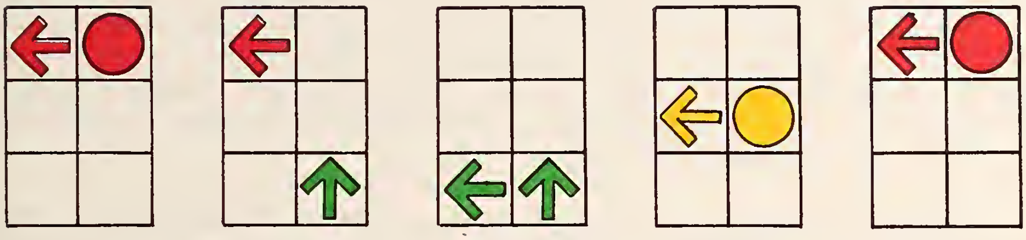
The signal in the "before" condition.

The signal in the "after" condition.

Figure 27 (Continued)



Signal displays in the "before" condition.



Signal displays in the "after" condition.

Figure 28

Signal operations on westbound New York Avenue at Bladensburg Road, N. E. in the "before" and "after" conditions.

the studied left turns by westbound traffic cycled through: a red ball; a green left arrow; a yellow ball; and back to the red ball indication. In the "after" (all arrow display) condition, the signal display for the left turns cycled through: a red left arrow; a green left arrow; a yellow left arrow; and back to the red left arrow. In both the "before" and the "after" condition, the display controlling westbound through traffic cycled through: a red ball; a green through arrow; a yellow ball; and back to a red ball indication. All signal lenses were 12 inch in both the "before" and "after" conditions. Since the only signal modifications required were a change in the red and yellow lenses of the two affected signal heads, the cost of the signal modifications was only $85.00.

Selected data for the "before" and "after" conditions is presented in Table 8. The time lapse films of traffic operations in the "before" and "after" conditions, from which the data in Table 8 was developed, were made between 9:50 and 11:35 A.M. on normal weekdays.

Initial review of the data in Table 8 indicates that the change from the "before" condition with its red and yellow ball signal indications, to the "after" configuration with its all arrow turn signal display, was associated with a substantial improvement in traffic operations. Total delays were cut in half and violations dropped by more than 60%. That signal observance would be much better with the relatively new red and yellow arrow displays, than it was with the completely conventional red and yellow ball (circular) signal displays which have been in very widespread use nationwide for generations, was a surprising and contra-intuitive result. Yet statistical tests showed the difference between the frequencies of violations "before" and "after" was too great to be reasonably explained by chance. (The Z value was + 2.36.)

In an effort to find an explanation for this unexpected result, detailed studies were made of the films of the study location and of the resulting data. By observation of the changes of the traffic signals shown on the film, and comparison with the timing data for those fixed time signals, it was possible to determine that the cameras had been operating properly, and that there had not been a variation in the camera's filming rate that had distorted the results. This meant that the large differences in delays and violations "before" and "after" had actually taken place. The data for the individual reels was then examined. Selected data by reel for this study location in the "before" condition is presented in Table 9.

Table 8

Selected "before" and "after" data on left turning traffic in the westbound approach of New York Avenue to its intersection with Bladensburg Road, N.E.

	"Before"	"After"
Number of Signal Cycles observed.	66 c.	67 c.
Total Traffic Volume Observed making studied turn.	369 v.	267 v.
Turning Traffic Volume Per Signal Cycle Observed.	5.59 v./c.	3.99 v./c.
Number of Turning Vehicles Which Experience Zero Delay	32 v.	37 v.
Percentage of Turning Traffic Volume Which Experience Zero Delay	8.7%	13.9%
Total Delay to All Observed Turning Vehicles.	21,029.0 v.s.	10,026.1 v.s.
Mean Delay Per Vehicle for All Observed Turning Vehicles	57.0 v.s./v.	37.6 v.s./v.
Mean Delay Per Delayed Turning Vehicle.	62.4 v.s./v.	43.6 v.s./v.
Sum of DASG for All Vehicles Observed making turn.	2,271.1 v.s.	1,414.9 v.s.
Mean DASG for All Vehicles Observed making turn.	6.15 v.s./v.	5.30 v.s./v.

Table 8 (continued)

	"Before"	"After"
Length of Green Signal Indication for Studied Movement per 80 second signal cycle.	7.2 s.	7.2 s.
Signal's Green Time Per Turning Vehicle.	1.29 s./v.	1.81 s./v.
Number of Signal Violations Observed.	25 v.	7 v.
Percentage of Turning Vehicles Which Violated Signal.	6.78%	2.62%
Mean DASG for Turning Cars by Queue Position:		
Queue Position One;	3.68 v.s./v.	4.07 v.s./v.
Queue Position Two;	6.25 v.s./v.	6.45 v.s./v.

Table 9

Selected data on traffic operations of left turning traffic in the westbound approach of New York Avenue to its intersection with Bladensburg Road, N. E. on July 19, 1974 ("before" condition).

	Reel Two	Reel Three	Reel Four
Time of Filming	9:51-10:21 A.M.	10:29-10:59 A.M.	11:01-11:31 A.M.
Total Turning Traffic Volume	79 v.	114 v.	176 v.
Total Delay to All Observed Vehicles	3,229.0 v.s.	4,087.4 v.s.	13,712.6 v.s.
Number of Signal Violations	1 v.	1 v.	23 v.
Number of Vehicles Which Experienced Zero Delay	13	16	3
Percentage of Vehicles Which Experience Zero Delay	16.5%	14.0%	1.7%

Examination of the data in Table 9 shows that traffic conditions varied greatly between these three reels of film, which cover one and a half hours in the middle of a normal day. Traffic volumes per half hour doubled between reels two and four, while delays increased by a factor of four. The largest change was in the violation rates. A statistical test showed that the violation rate for reel four was different from that for the combination of reels two and three by an amount that was far too large to be due to chance. (The Z value was 4.59 which shows statistical confidence at above the 99.99% level.) Almost all of the violations in reel four were of the "stretching the yellow" type in which vehicles continued to enter the intersection for the first few seconds after their yellow signal changed to red. The film shows that the combination of a short green interval and heavy demand created the situation where the capacity was not adequate to the demand and where drivers would not clear the intersection on the first cycle if they obeyed the signal. Rather than wait an extra cycle it appeared that many motorists chose to enter the intersection on the yellow, and even red, ball signal indications. It is believed that the phenomenon reflects an unwillingness by some motorists to wait an additional signal cycle before clearing, and not any lack of understanding of the conventional signal display. At least in this case, violation rates appear to have been more related to congestion and delay levels, than to the signal display. Since most of the reported failures of red arrow displays have also been under high congestion levels this effect may have been present there as well, and the relatively high violation rates reported for those cases may reflect more an unwillingness to accept delays than a lack of understanding of the red arrow displays. It should also be noted that the films of the "after" condition, taken within a month of the "before" films, did not show a similarly large fluctuation within the same time period. The volumes for "after" reels two, three and four were 99,81 and 87 respectively. The difference between the volumes in reel four of the "before" and the "after" films was 89 vehicles or 102% of the smaller volume. There was no evident explanation of these volume differences except simple random fluctuation. The above suggests that the combination of fixed time signal equipment, and the short green times (relative to the cycle length) when signal operations with many intervals are used for multi-phase operations, may lead to substantial delays, inefficiencies and perhaps violation rates due to the degree of short term variation in traffic demand (volume) experienced in normal traffic. Reference (17) appears relevant to this point.

When the violation rate for the combination of "before" reels two and three was compared to the violation rate for the "after" reels, a statistical test showed the violations rate in the "after" condition (2.62%) was not worse than the violation rate for the combination of reels two and three "before" (1.04%) by an amount that was so large that it could not reasonably be explained by chance.

Statistical tests showed that the clearing times of queue position one vehicles (as measured by the Delay After Start of Green or DASG) did not differ between the two approach turning lanes by an amount that was too large to be reasonably explained by chance. This was so for both the "before" period (whose Z value for the difference between the two lanes was 0.815), and the "after" period (whose Z value for the difference between the two lanes was 1.389) with the lane on the inside of the curve having slightly lower values. When the clearing (DASG) times of queue position one vehicles in both lanes were compared "before" and "after", a statistically significant difference was found (the Z value was - 2.028), with the "after" (arrow) values worse. There was some evidence that the effect of the signal display change on clearing (DASG) times was more pronounced in the lane on the outside of the left turn (the lane next to the westbound through movement) than it was in the lane on the inside of the turn. No statistically significant difference was found between the DASG times of queue position two vehicles "before" and "after". The Z value for that test was - 0.586.

5. <u>The Experimental Location Where Turning Movements Are "Protected" from Conflicting Movements by Other Indications or by the Signal Sequence</u>.

The experimental location for this part of the study was the intersection of Pennsylvania Avenue with 6th Street, N.W. This intersection of two arterial streets is in downtown Washington, D.C., in an area with office building and museum land uses. The location was given location reference number 01 for identification purposes during the scoring of the time-lapse films and the computer analysis of the resulting data.

The traffic movement of interest at this location is a left turn from eastbound Pennsylvania Avenue onto northbound 6th Street. A painted median with an exclusive left turn slot type channelization is provided. This left turn slot provides a fourth lane for the eastbound approach. The left turn is prohibited during the first portion of the eastbound through movement, and is then protected during the remainder of the eastbound through movement. A post mounted far side signal in the median serves as the primary control for the left turn, as well as being the supplemental signal for the through movement. A secondary left-turn signal is post mounted on the north east corner of the intersection. A far-side post mounted signal on the south-east corner serves as the primary signal for through movements and also serves as the indication for right turns (eastbound to southbound) and pedestrians. The location is shown in Figure 29. The signal operations for the eastbound approach in the "before" and "after" conditions are shown in Figure 30.

During the "before" condition the median mounted primary signal for the left turn had a single four light head with all eight inch lenses. The signal display sequence for this signal was: red ball; green through arrow displayed alone; green through arrow plus green left arrow; yellow ball; and then back to the red ball. The supplemental signal for the turn, mounted on the northeast corner, had three eight inch lenses; a red ball, a green left arrow and a yellow ball.

During the "after" condition, the median mounted signal was changed to a pair of side by side, three light heads with all 12 inch lenses. The left head was the primary signal for the left turn, while the right head was the supplemental signal for the through movement. The signal sequence for this pair of heads was: red left arrow plus red ball; red left arrow plus green through arrow; green left arrow plus green through arrow; yellow left arrow plus yellow ball; and then back to the red left arrow plus red ball. The supplemental turn signal on the northwest corner was changed to a three light, all 12 inch lens head, with red left arrow, green left arrow, and yellow left arrow indications. No signs to explain the arrow indications were provided.

It was initially proposed that the clearance interval for the through movement, in the median mounted signal, should be a yellow through arrow rather than a yellow ball. However this have required going to a four light head to control the through movement, so as to allow a yellow ball indication for use during

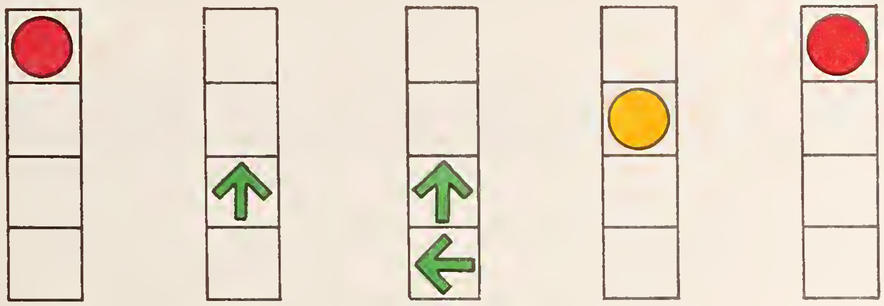
Figure 29

Views of the eastbound approach of Pennsylvania Avenue to 6th Street, N. W. (location # 01).

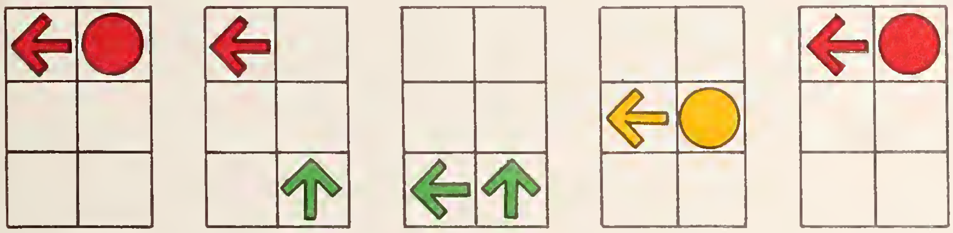
The signal in the "before" condition.

The signal in the "after" condition.

Figure 29 (Continued)



Signal displays in the "before" condition.



Signal displays in the "after" condition.

Figure 30

Traffic signal displays for the eastbound approach of Pennsylvania Avenue to 6th Street, N. W. in the "before" and "after" conditions.

flasher operations. (A flashing yellow arrow is not authorized in the M.U.T.C.D.) The increased cost and complexity of such a display were not felt warranted.

A point of interest about the arrow displays at this intersection (in both the "before" and the "after" conditions) is that through traffic saw a green through arrow indication in the median mounted signal head, but a green ball indication in the signal head on the far right corner (southeast corner). Use of a green ball indication on the right side of this intersection was necessary to allow for right turns which yield, in the normal manner, to pedestrians moving between the southeast and southwest corners. Had the display on the right side of this intersection been made to coincide with that on the median (that is, had through green arrows been used for both) then it would have been necessary to either: (a) prohibit the right turn from eastbound to southbound at this location; or else (b) separate the pedestrian movement from the right turn with separate intervals being provided for each, and with the consequent substantial loss of green time for both pedestrians and vehicles. As no significant pedestrian-turning vehicle conflict was evident, and as prohibiting or exclusive phasing the turn seemed otherwise unnecessary, it was decided that continued use of the ball green on the right corner was the best choice.

During both the "before" and "after" conditions, a second signal head was present on the northeast corner. This head was mounted to the north (left when looking east) of the supplemental signal for the eastbound to northbound left turn. The second signal head controlled eastbound pedestrian movements in the north crosswalk, and was louvered so its displays would not be visible to turning vehicles. This head used all eight inch lenses in conventional red, green and yellow ball displays.

The signal modifications were made on June 1, 1974 at a cost of $645.00. The "before" films of traffic behavior were taken on April 11, 1974 from 12:06 to 2:12 P.M. The "after" films were taken July 18, 1974 from 12:20 to 2:31 P.M. Analysis of those films yielded the data on "before" and "after" conditions which are presented in Table 10.

Statistical analysis of the "before" and "after" data showed that the changes in the frequency of signal violations, and the mean delay per delayed vehicle were both so small that they could very easily be explained by random fluctuation. The Z values for those changes were 0.081 and 0.299, respectively. The changes in the DASG times for queue position one and two

Table 10

Selected "before" and "after" data on traffic in left turn lane of eastbound approach of Pennsylvania Avenue to 6th Street, N.W.

	"Before"	"After"
Number of Signal Cycles Observed.	92 c.	74 c.
Total Traffic Volume Observed in studied lane.	.313 v.	231 v.
Traffic Volume in lane Per Signal Cycle Observed.	3.37 v./c.	3.12 v./c.
Number of Vehicles in lane Which Experienced Zero Delay	58 v.	63 v.
Percentage of Vehicles in this lane Which Experienced Zero Delay	18.5%	27.3%
Total Delay to All Observed Vehicles in this lane.	7,017.0 v.s.	4,737.3
Mean Delay Per Vehicle for All Observed Vehicles.	22.4 v.s./v.	20.5 v.s./v.
Mean Delay per Delayed Vehicle.	27.5 v.s./v.	28.2 v.s./v.

Table 10 (continued)

	"Before"	"After"
Sum of DASG for All Vehicles in this lane.	1,819.4 v.s.	1,174.7 v.s.
Mean DASG for All Observed vehicles.	5.81 v.s./v.	5.09 v.s./v.
Length of Green Signal Indication for Studied Movement per 80 second signal cycle.	10.4 s.	10.4 s.
Signal's Green Time per Vehicle for studied left turn.	3.06 s./v.	3.33 s./v.
Number of Signal Violations Observed.	14 v.	10 v.
Percentage of Turning Lane Vehicles which Violated Signal.	4.47%	4.33%
Mean DASG for Turning Cars By Queue Position:		
Queue Position One;	3.81 v.s./v.	4.17 v.s./v.
Queue Position Two.	6.48 v.s./v.	7.00 v.s./v.

vehicles were both suspiciously large, but were not so large that it was possible to say with as much as 95% confidence that the differences were not due to random fluctuation. The Z values for the changes in clearing (DASG) times for queue positions one and two were -1.646 and -1.717. Accident experience was compared for the June, 1973 through March, 1974 "before" period, and the June, 1974 through March, 1975 period. There were a total of three reported accidents which involved vehicles making the studied movement in the "before period, and none in the "after" period. The change was not so large that it could not have happened by chance.

It was noted that the westbound flow on Pennsylvania Avenue into this intersection was quite heavy, being on the order of 17,800 vehicles per day in three lanes. The fact that the opposing flow was heavy, with relatively few gaps which would permit illegal left turns by eastbound vehicles during the through only portion of the signal cycle, may have contributed to the lack of difference between traffic behavior in the "before" and "after" conditions. It has been noted at another intersection which was not included in this study that, when an individual signal cycle did not happen to have a substantial opposing through movement, the frequency of illegal left turns on a through only green arrow (displayed alone) was quite high.

There was no evidence, in either the "before" or the "after" condition, that the use of an arrow display in the median mounted signal, while a ball display was used in the far right corner mounted signal, created any operational problems or motorist confusion whatever. The width of the eastbound approach (a loading lane, three through lanes, and a left turn lane) may have contributed to this success.

6. The Experimental Location Where All the Movements on the Approach Do Not Begin or End at the Same Time and Where the Indications for the Turning Movements Will Also Be Visible to Traffic With Other Allowable Movements.

The experimental location for this part of the study was the intersection of Pennsylvania Avenue with 13th Street, N.W. This intersection of two arterial streets is in downtown Washington, D.C. in an area with office building land uses. It was assigned location reference code number 03 for film scoring and computer data analysis purposes.

The traffic movement of interest at this study site was a right turn by westbound Pennsylvania Avenue traffic onto northbound 13th Street. In order to protect a substantial east-west pedestrian movement between the northeast and northwest corners of the intersection, the right turn is prohibited throughout the through movement. The pedestrians move with the through traffic. Then the through and pedestrian movements are stopped, and the right turns have a protected movement immediately following the end of the yellow clearance interval for the through phase. The southbound traffic on 13th Street gets its green indication during the same phase as the right turn off of westbound Pennsylvania Ave. Because of heavy through bus usage of the westbound curb lane, and the presence of a nearside bus stop, it was not possible to provide an exclusive lane for the westbound to northbound right turn. Thus, both through movements and right turns were permitted from the curb lane (described and coded as Lane #1). No left turns were permitted from this approach. The location is shown in Figure 31, and the signal operations on its westbound approach are shown in Figure 32.

During the "before" condition, the movements were controlled by a single four light signal head with all eight inch lenses, on a far side pole mounting on the northwest corner. The vehicular signal display sequence was: red ball; green through arrow alone; yellow ball; red ball plus green right arrow; red ball plus yellow ball; and then back to the red ball alone. A supplemental indication was provided for through traffic by a far side pole mounted signal in the median.

During the "after" condition the westbound movements were controlled by a pair of three light, 12 inch lens, signal heads in a far side pole mounting on the northwest corner. All indications for the through movement were shown in the left signal head of the pair, and all indications for the right turn were shown in the right signal head. The vehicular signal display sequence was: red ball plus red right arrow; green through arrow plus red right arrow; yellow ball plus red right arrow; red ball plus green right arrow; red ball plus yellow right arrow; and then back to red ball plus red right arrow. No explanatory signing was provided. As in the "before" condition, supplemental indications were provided for the through movement by a post mounted, far side signal in the median.

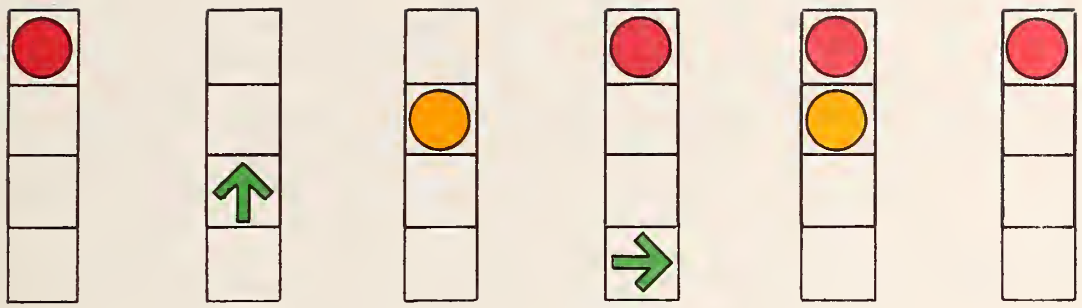
Figure 31

Views of the westbound approach of Pennsylvania Avenue to 13th Street, N. W. (location # 03).

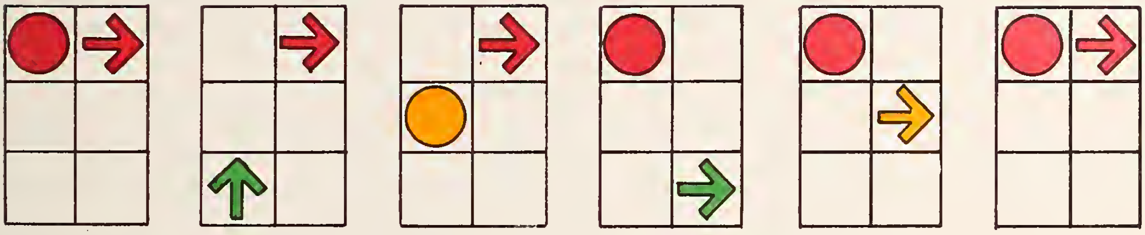
The signal in the "before" condition.

The signal in the "after" condition.

Figure 31 (Continued)



Signal displays in the "before" condition.



Signal displays in the "after" condition.

Figure 32

Traffic signal displays for the westbound approach of Pennsylvania Avenue to 13th Street, N. W. in the "before" and after conditions.

The signal was operated by a three dial, fixed time signal controller. No changes in the timing of the phases or intervals was made between the "before" and "after" conditions. The modifications to the signal display were made on June 5, 1974 at a cost of $330.00. The "before" time-lapse films of traffic behavior were made on April 30, 1974 from 12:02 to 1:35 P.M. The "after" films were made on June 18, 1974 from 12:25 to 1:59 P.M. Selected data for the "before" and "after" conditions is presented in Table 11. Observations were made of all vehicles in the westbound curb lane (lane #1) whether they turned right or went through, and of all vehicles which turned from any other lane.

Statistical analysis of the "before" and "after" data shown that the reductions both in the total frequency of signal violations of all types, and in the frequency of those violations which involved right turns while the signal indicated that only through movements were permitted, were both too large to be reasonably explained by chance. The Z values for these two changes were 3.397 and 3.011 respectively. This means that total violations, and turns on the through indication, were both substantially reduced by the change to the red arrow display. The change in the percentage of turning vehicles which experienced zero delay was not so large that it could not reasonably be believed to have happened by chance. The Z value for this change was 1.342 which indicates that this large a change could be expected by chance slightly less often than one time in five. The changes in the DASG times for cars in queue positions one and two were both small enough to be explained by chance, as shown by their Z values of 0.028 and -1.129 respectively. However, the change in the mean delay per delayed vehicle was larger than could be explained by chance (the Z value was 2.744) which proved that the mean delay, to vehicles that had to stop was longer in the "after" condition with its all arrow signal display. There were six reported accidents involving this traffic movement in the June, 1973 through March, 1974 "before" period, compared to two in the June 1974 through March, 1975 "after" period. This improvement was not so large that it could not have been caused by chance fluctuation.

It is therefore shown that the change from the "before" to the "after" display produced a proven improvement in signal observance (that is, it gave a proven decrease in violations), but did so at the cost of a proven increase in the delay to vehicles that had to stop at this signal. The most probable explanation of this result is that in the "before" condition, since more motorists violated the signal, their delays while

Table 11

Selected "before" and "after" data on right turning traffic and curb lane traffic on westbound approach of Pennsylvania Avenue to 13th Street, N.W.

	"Before"	"After"
Number of Signal Cycles Observed.	54 c.	68 c.
Total Traffic Volume Observed.	171 v.	305 v.
Traffic Volume Per Signal Cycle Observed.	3.17 v./c.	4.49 v./c.
Number of Vehicles Which Experienced Zero Delay.	27 v.	35 v.
Percentage of Observed Traffic Which Experienced Zero Delay.	15.8%	11.5%
Total Delay to All Observed Vehicles.	3,973.3 v.s.	8,533.4 v.s.
Mean Delay Per Vehicle for All Observed Vehicles	23.2 v.s./v.	28.0 v.s./v.
Mean Delay Per Delayed Vehicle.	27.6 v.s./v.	31.6 v.s./v.
Sum of DASG for All Observed Vehicles.	704.4 v.s.	1,733.7 v.s.

Table 11 (continued)

	"Before"	"After"
Mean DASG for All Observed Vehicles	4.1 v.s./v.	5.7 v.s./v.
Length of Green Signal Indication for Turn Per 80 second cycle.	18.4 s.	18.4 s.
Total Volume of Right Turning Traffic Observed.	152 v.	282 v.
Volume of Right Turning Traffic in curb lnae.	140 v.	267 v.
Percentage of Turning Traffic in curb lane	92%	95%
Turn Signal's Green Time Per Turning Vehicle.	6.54 s./v.	4.44 s./v.
Total Number of Signal Violations Observed.	36 v.	30 v.
Percentage of Total Observed Volume Which Violated Signal.	21.1%	9.8%
Number of Violations which involved Right Turns made against a Through Only Signal Indication	24 v.	19 v.
Proportion of Right Turns Made on Through Only Signal Indication.	15.8%	6.7%
Mean DASG for Right Turning Cars By Queue Position:		
Queu Position One;	1.66 v.s./v.	1.68 v.s./v.
Queue Position Two.	4.58 v.s./v.	5.07 v.s./v.

waiting for the signal were reduced. This hypothesis is based on the precept that motorists who run signals are not delayed by them (or at least are not delayed as long as they would have been if they had waited for their green). No effort was made to estimate what delays the violators would have suffered if they had obeyed the signal.

During both the "before" and the "after" conditions it was observed that there were fairly frequent blockages of the right turn movement while its green signal was displayed. These blockages were caused by: (a) through vehicles being at the head of the queue and stopping; (since the signal for through movements was red) and (b) vehicles loading in the curb lane (Lane #1). This is believed to be the primary cause for the turns from the second lane out from the curb. Had it been possible to make the curb lane an exclusive right turn lane the first, but not the second, cause of delays would have been avoided.

In both the "before" and "after" conditions a significant operational problem was noticed with pedestrians starting to make north-south movements in the east crosswalk as soon as the westbound through movement received its red signal indication. This illegal pedestrian action created a direct and substantial conflict with the right turn movement which received its green signal at this time. In the "before" condition 18 vehicles or 10.5% of the observed volume were delayed by such illegal pedestrian movements. In the "after" condition 35 vehicles or 11.5% of the observed turning volume were similarly delayed. It appeared that a significant proportion of the pedestrians waiting to make the north-south crossing were basing their decision on when to start their movement on the stoppage of the conflicting through movement, and not on the indications of the pedestrian signals. The problem with conflicting illegal pedestrian movements may be accentuated at this location by the fact that the signal for southbound vehicular flow goes green when the westbound through movement gets its red, although the pedestrian signal continues to show "Don't Walk". Thus, some pedestrians may have based their decisions on the vehicular, rather than the pedestrian, signal indication. Random observations at another location, where the through movement ended before the right turn (that is, where a "hot" right turn continued after the end of the through movement) showed a similar problem with pedestrians starting their movement when the conflicting through movement ends. Reference (18) reports that elderly pedestrians often base their judgements of when it is safe to cross the street on the movements of traffic, rather than on the indications of the traffic signals. In view of these observations, it is recommended that considerable caution be exercised in the use of signal phasings that include a right turn that starts immediately after the through movement from the same approach stops; as well as with signal cycles which provide for a right turn which continues while the through movement is cut off. Locations where such signal phasings are employed might benefit from a careful observation of their pedestrian behavior to detect possible hazards. It should be noted that, at the Pennsylvania Avenue and 13th Street study location, the presence of pedestrian signals did not eliminate the problem with conflicting illegal pedestrian movements. The pedestrian problem appears to be related to: (a) the signal cycle used at this particular study location; (b) basic patterns of on what basis the "go or no-go" decision is made by a significant proportion of the pedestrians; and perhaps to (c) pedestrian volume and delay levels which may encourage violations by the more agile pedestrians. It must be emphasized that the problem with the conflicting illegal pedestrian movements existed in both the "before" and the "after" conditions, and that it does not detract in any way from the success of the red arrow signal display in reducing vehicular signal violations.

7. A Further Analysis of the Signal Violations Data for the Experimental Locations in Washington, D. C.

Some of the reels of mid-day time-lapse film were randomly selected for a further study of signal violations. The selected reels contained information on 1,860 vehicles in the "before" condition, and 2,437 vehicles in the "after" condition, as they moved through five of the six experimental locations in Washington, D. C. (The location that was not included was the intersection of New York Avenue and 13th Street, N. W. where the change in signal operations was in effect only during the peak hours.) Data on the vehicles shown in these randomly selected films was analyzed to determine the frequencies of violations by vehicles of different types. The results of this analysis are presented in Table 12.

One of these reels of film (reel number three of the "after" films of the intersection of Pennsylvania Avenue and 13th Street) showed a light colored sedan, believed to be an unmarked police car on an emergency run, which made a right turn from the fourth lane from the right curb (the median lane) while the signal was yellow for the through movement and red for the right turn.

Table 12

Signal observance "before" and "after" by a random subsample of the mid-day vehicle population at experimental locations in Washington, D. C., including data on signal observance by type of vehicle.

	"Before" condition			"After" condition		
		Violations			Violations	
Type of Vehicle	Total Volume	Number	Percent	Total Volume	Number	Percent
Car or Light Truck	1,725	73	4.2	2,290	70	3.1
Single Unit Truck	53	2	3.8	61	1	1.6
Semi-Trailer	3	0	0	4	0	0
Bus	53	2	3.8	62	2	3.2
Construction Equipment	0	0	0	1	0	0
Car or Light Truck Pulling a Trailer	1	0	0	0	0	0
Motorcycle or Motorscooter	20	0	0	11	0	0
Bicycle	5	3	60	7	4	57
Emergency Vehicle on Emergency Run	0	0	0	1	1	100
Total for this Condition	1,860	80	4.3	2,437	78	3.2

If this vehicle was an authorized vehicle on an emergency run, then its right turn against the red right arrow was not a violation of the law.

A statistical analysis of the "before" and "after" violations experience shown in these randomly selected films showed that the improvement in signal observence (the reduction in signal violations) for this sample of five intersections of various types was just at the border of statistical significance. For the comparison of all "before" vehicles against all "after" vehicles the Z value was 1.8991 which indicates confidence at above the 93% level, but not to the 95% level, that the improvement was "real" (that is, too large to be due to chance). If the vehicle believed to be a police car on an emergency run was eliminated from the sample, then the Z value for the "before" vs "after" comparison rose to 1.9733 which shows slightly more than 95% confidence that the improvmeent was "real".

Comparison of the frequency of violations for the various types (classifications) of vehicles is interesting. While the sample sizes were very small, the results suggest that efforts to improve the signal observance of bicyclists are warranted.

8. <u>A Further Analysis of the Data on Clearing (DASG) Times By Queue Position for the Experimental Locations in Wash., D.C.</u>

Table 13 is a summary of the data on clearing times (delay after start of green, abbreviated DASG) for the experimental locations in Washington, D.C. in the "before" and "after" conditions. In order to test for any general trends, the DASG data for the various locations was grouped and statistical tests were made to determine whether or not the mean values of DASG had changed between the "before" and the "after" conditions by an amount that was too large to be reasonaly explained by chance. Separate tests were made for queue position one, and queue position two cars. For each of those queue positions two separate groupings were investigated. On grouping involved all locations where the signal phasing had been kept the same. This excluded the F Street at 10th Street, N.W. location. No "real" (statistically significant) change was found for this grouping in either queue position one or two. The Z values for these tests were -0.390 and -0.821 respectively. The second grouping was the total of all study locations, including both approaches to the F and 10th location. Once again, no statistically significant change was found in the DASG values for either queue position one or two. The Z values for this test were 1.794 and 1.377.

Table 13

Summary of data on DASG (clearing times) "before" and "after" at experimental locations in Washington, D. C.

	Mean DASG for Queue Position One			Mean DASG for Queue Position Two		
	"Before"	"After"	Statistically significant ?	"Before"	"After"	Statistically Significant ?
F at 10th Street, N.W.						
eastbound approach	4.93	4.21	yes	8.49	7.31	yes
westbound approach through movement	4.77	4.46	no	7.81	8.02	no
left turn	9.06	3.25	*	16.31	6.00	*
New York Ave. at 13th Street, N. W.	Low sample size prevented development of meaningful values.					
East Executive Ave. at E Street, N. W.	2.19	2.31	no	4.12	5.38	yes
New York Ave. at Bladensburg Rd., N.E.	3.68	4.07	yes	6.25	6.45	no
Pennsylvania Ave. at 6th Street, N.W.	3.81	4.17	no	6.48	7.00	no
Pennsylvania Ave. at 13th Street, N.W.	1.66	1.68	no	4.58	5.07	no

Note: * indicates that small sample size precluded completely reliable statistical test.

It can therefore be concluded that the change to the red arrow type signal display was not associated with any general overall trend of change in the clearing times of all types of intersections, although real changes in clearing times (DASG) did occur for some of the specific locations.

The substantial differences between the DASG times for the different locations should be noted. These differences indicate that clearing (DASG) times can not be expected to be the same under widely differing operating conditions. The low values for the Pennsylvania Avenue at 13th Street location are believed due to the fact that the yellow indication at the end of the through movement alerts motorists familiar with the location to the fact that the green indication for the turn is about to be displayed.

9. A Further Analysis of the Accident Data for the Experimental Locations, and for Matched Control Locations, in D. C.

The accident data for the experimental locations, and for matched control locations, within Washington, D.C. was reviewed. The time periods used in the comparison of "before" and "after" accident experience were calender matched (e.g. the June, 1973 through March, 1974 period was compared to the June, 1974 through March, 1975 period) to avoid distortions due to seasonal fluctuations in accident experience. The accident experience "before" and "after" at the various experimental locations was then added, as was the accident experience at the matched control locations. For the experimental locations the total "before" accident experience was 38 accidents, and the "after" total was 19 accidents. For the matched control locations the "before" total was 33 accidents and the "after" total was 22. Because of the large influence of the New York and Bladensburg intersection and its control on the totals, and because operational changes at that location rendered the change there not necessarily due only to the change from ball to arrow signal indications, it was felt best to eliminate that one location from the comparison. With the New York and Bladensburg site, and its matched control location, eliminated from the totals, the "before" and "after" accident experience total for the experimental locations were 12 and 3 accidents respectively. For the control locations the respective totals were 9 and 6. Using a raw Chi Square test the reduction at the experimental locations would be statistically significant. If however allowance was made for the 1/3rd decline in accident experience at the control locations, then the "expected" experience in the "after" period if the change of the signal displays had not been made would have been 8 accidents.

The difference between this "expected" 8 accidents, and the 3 that actually took place after the arrow signal displays were installed was suspiciously large, but was not statistically significant at the 95% level of confidence. That means that we can suspect, but cannot prove, that the change to the arrow displays improved safety. This large an improvement might be expected by chance roughly one time in ten. Comparisons across a time period of several years might be required to prove conclusively whether or not there was a difference in safety. The fact that, even when the experience at several sites was grouped, no difference in safety was proved, suggests that, if there was a difference in safety between the conventional and arrow displays, it was not of major proportions. Obviously however, real improvements, even if minor, are to be desired. Examination of the accident experience data from the various experimental locations suggests the possibility that arrow displays may be more beneficial in some applications than others.

E. The Experimental Locations in Montgomery County, Maryland.

Two experimental sites in a suburban area, approximately 12 miles northwest of the center of Washington, D.C. were also studied, through the courtesy of the Division of Traffic Engineering, Department of Transportation, of Montgomery County, Maryland. Both sites were "T" intersections of collector streets with an arterial. At both sites the traffic movement studied was a signalized left turn off of the arterial onto the collector. One of the study sites had post mounted left turn signals in the median. The other had its left turn signal mounted overhead. Thus, these two locations provide a comparison of post mounted vs. overhead mounted left turn signals in a suburban area.

1. A Suburban Site With Post Mounted Left Turn Signals in the Median.

The study site was the intersection of Montrose Road with Jefferson Street. Montrose Road was an east-west primary arterial route. At this location it had two lanes in each direction for through traffic, plus an exclusive left turn lane for eastbound traffic desiring to turn north onto Jefferson Street. Montrose Road had a raised median on both sides of the intersection but no access control. Jefferson Street had four lanes undivided, and ran from this "T" intersection northward, providing high type collector service to apartments and to the back of a shopping center. The location is shown in Figure 33. This site was assigned location reference number 21 for film scoring and data analysis purposes.

Figure 33

Views of the eastbound approach of Montrose Road to Jefferson Street (location 21)

The signal in the "before" condition.

The signal in the "after" condition.

Figure 33 (continued)

The volume of the studied left turn was substantial. Traffic through this intersection was signal controlled with separate phases for: (a) westbound throughs and right turns, plus eastbound throughs (with the eastbound to northbound left prohibited); (b) eastbound throughs and left turns (with all westbound stopped) plus right turns only from southbound Jefferson; and (c) both lefts and rights from southbound Jefferson, with all Montrose traffic stopped. This signal was operated by a fully actuated controller with skip phase capability so that it could adapt to the heavy fluctuations in demand by skipping an uncalled phase.

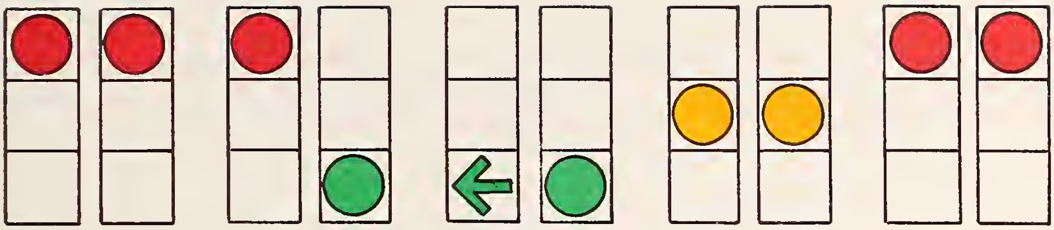
The left turn of interest was controlled by two signal heads. Both were pole mounted in the median, one on the near side of the intersection and the other on the far side. In the "before" portion of the study, the signal display controlling the left turn cycled through: a red ball; a green left arrow; a yellow ball; and back to a red ball. In the "after" condition the left turn cycled through: a red left arrow; a green left arrow; a yellow left arrow; and then back to the red left arrow. These signal operations, in the "before" and "after" conditions, are shown in Figure 34.

In the "after" condition "No Left Turn on (red arrow symbol)" signs were mounted immediately below both the near and far side median mounted left turn signals. These signs may be seen in several of the views of the location presented in Figure 33.

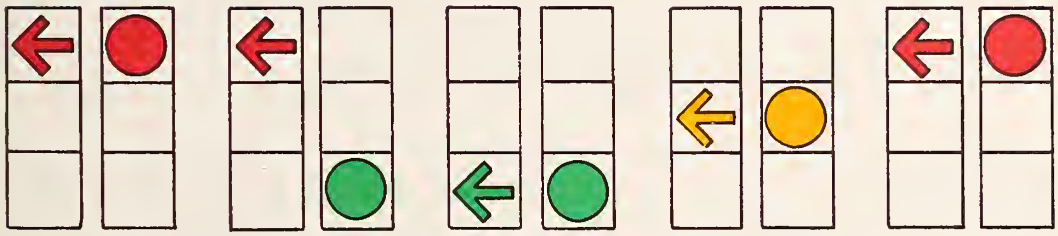
Selected data on "before" and "after" conditions is presented in Table 14. The "before" films from which this data was taken were made on May 13, 1974; the signal modifications were made on or about May 31, 1974; and the "after" films were made June 14, 1974.

The frequency of violations was low in both the "before" and the "after" condition, and while the "after" condition was better, a statistical test showed that the difference could be due to chance. The Z value for this test was 1.090. The changes in the clearing times (DASG) for queue positions one and two were also small enough to be explained by chance random fluctuation. The Z values for queue positions one and two were -1.258 and 1.043 respectively.

It will be noted that, due to normal daily and seasonal fluctuations, traffic volumes were significantly heavier in the



Signal displays in the "before" condition.



Signal displays in the "after" condition.

Figure 34

Traffic signal operations on the eastbound approach of Montrose Road to Jefferson Street in the "before" and "after" conditions.

Table 14

Selected "before" and "after" data on traffic in the left turn lane of the eastbound approach of Montrose Road to Jefferson Street, in Montgomery County, Maryland (location 21).

	"Before"	"After"
Total Traffic Volume Observed in this lane.	531 v.	925 v.
Number of Vehicles Which Experienced Zero Delay.	221 v.	371 v.
Percentage of Vehicles in this lane Which Experience Zero Delay.	41.6%	40.1%
Total Delay to All Observed Vehicles in this lane.	6,560 v.s.	13,750 v.s.
Mean Delay Per Vehicle for All Observed Vehicles.	12.4 v.s./v.	14.9 v.s./v.
Mean Delay Per Delayed Vehicle.	21.2 v.s./v.	24.8 v.s./v.
Sum of DASG for All Vehicles in this lane.	2,660 v.s.	5,670 v.s.
Total Number of Signal Violations Observed.	2	1
Percentage of Vehicles in lane Which Violated Signal.	0.4%	0.1%
Mean DASG for Cars By Queue Position:		
Queue Position One;	3.7 v.s./v.	3.9 v.s./v.
Queue Position Two.	6.5 v.s./v.	6.3 v.s./v.

"After" condition than in the "before" condition. Since the DASG times were similar for both conditions, it appears reasonable to assign the increase in delays in the "after" condition to increased congestion and longer queues at the signal resulting from the random volume fluctuation, and not to attribute the increase in delays to the introduction of the red turn arrow displays. Thus, it is reasonable to conclude that the change from the "before" to the "after" turn signal display had no real effect on traffic delays.

A study of traffic accident experience for six month periods "before" and "after" did not show any real (statistically significant at the 95% level) change in safety. There was one accident involving the studied movement in the "before" period, and none in the "after" period.

2. A Suburban Site With an Overhead Mounted Left Turn Signal

The study site was the intersection of Montrose Road with Tildenwood Drive. This intersection was approximately 3/4 mile west of the other suburban site. At this location Montrose Road had two lanes for through traffic in each direction, and a painted median which narrowed on the east side of the intersection to provide an exclusive turning lane for the westbound to southbound left turn. This left turn was the movement of interest. The location is shown in Figure 35. The site was assigned location reference number 23 for film scoring and data analysis purposes.

Traffic through this intersection was controlled by span-wire mounted signals operated by a fully actuated controller. The signal operation was three phase with: (a) Montrose westbound through traffic and the westbound to southbound left turn flowing, while eastbound Montrose was stopped and right turns by northbound Tildenwood's vehicles were permitted; (b) through traffic on Montrose flowing in both directions, while the lefts from westbound Montrose and all movements from northbound Tildenwood were prohibited; and (c) lefts and rights from northbound Tildenwood moving while all traffic on Montrose was stopped. The signal controller had the capability to skip any uncalled phase.

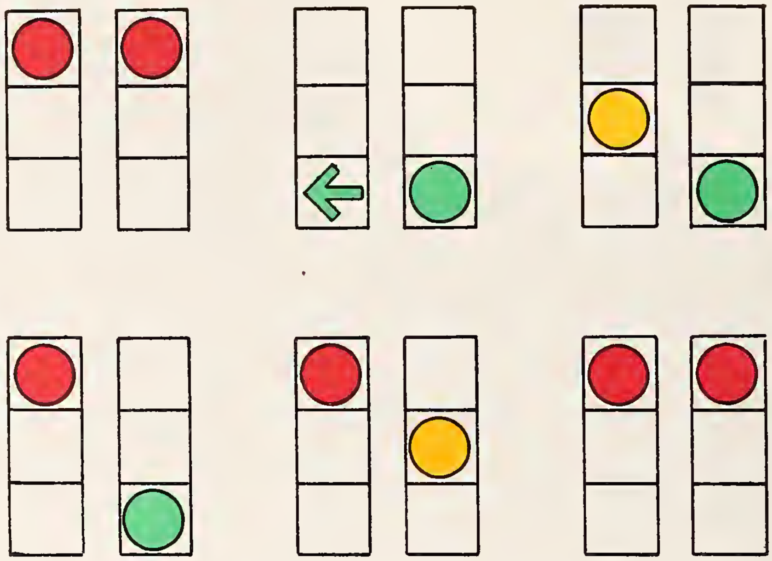
Figure 35

Views of the westbound approach of Montrose Road to Tildenwood Drive (location 23)

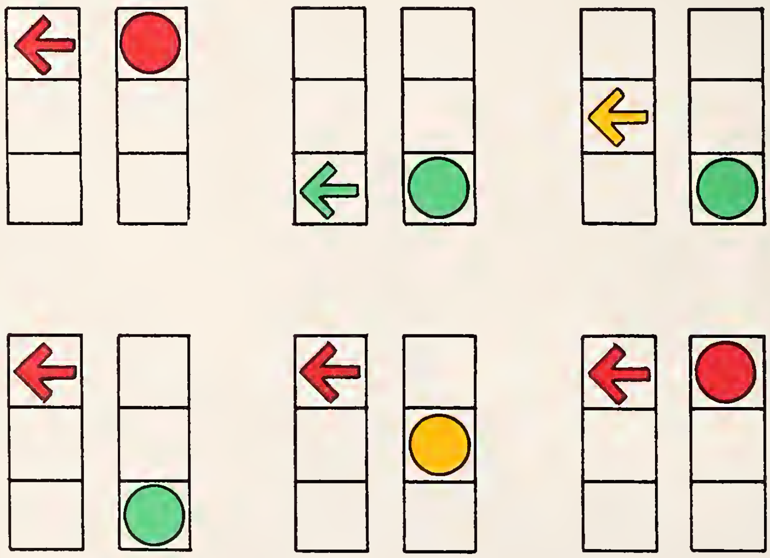
The signals in the "before" condition.

The signals in the "after" condition.

Figure 35 (continued)



Signal displays in the "before" condition.



Signal displays in the "after" condition.

Figure 36

Traffic signal displays on the westbound approach of Montrose Road to Tildenwood Drive in the "before" and "after" conditions.

Table 15

Selected "before" and "after" data on traffic in the left turn lane of the westbound approach of Montrose Road to Tildenwood Drive, in Montgomery County, Maryland (location 23).

	"Before"	"After"
Total Traffic Volume Observed in this lane.	48 v.	43 v.
Number of Vehicles in lane Which Experienced Zero Delay.	8 v.	3 v.
Total Delay to All Observed Vehicles in this lane.	975 v.s.	1,270 v.s.
Mean Delay Per Vehicle for All Vehicles in this lane.	20.3 v.s./v.	29.5 v.s./v.
Mean Delay Per Delayed Vehicle.	24.4 v.s./v.	35.2 v.s./v.
Sum of DASG for All Vehicles in this lane.	140 v.s.	170 v.s.
Total Number of Signal Violations	0	0
Percentage of Vehicles in lane Which Violated Signal	0	0
Mean DASG for Cars in lane By Queue Position:		
Queue Position One;	3.0 v.s./v.	3.3. v.s./v.
Queue Position two.	5.1 v.s./v.	5.4 v.s./v.

In the "before" condition, the signal display for left turning traffic cycled through: a red ball; a green left arrow; a yellow ball; and then back to the red ball. In the "after" condition the left turn signal display cycled through: a red left arrow; a green left arrow; a yellow left arrow; and then back to the red left arrow. In the "after" period a "No Left On (red arrow symbol)" sign was hung from the spanwire just to the right (north) of the left turn signal head. Figure 36 illustrates the "before" and "after" signal operations for the studied approach.

"Before" films of this location were made on May 13, 1974. The signal modifications were made on or about May 31, 1974. The "after" films were made on June 13, 1974. Data developed from those films is presented in Table 15. No "real" (statistically significant at 95%) changes were found between the "before" and "after" conditions in either the violation rates or the DASG times of queue position one vehicles. The sample size was too small for a meaningful test on queue position two vehicles but, there again, no real change was evident. Study of the accident experience at this location during six month periods "before" and "after" showed no accidents in the "before" period and two (both rear end) in the "after" condition. This difference in accident experience can be explained by random chance. Study of Table 15 shows that there were longer delays (both total and after start of green) in the "after" condition.

3. <u>Comparison of the Post Mounted and the Overhead Mounted Suburban Sites.</u>

The left turn signals at both locations were visible to drivers desiring to travel straight through the intersection. There has been concern within the traffic engineering profession over the possibility of monentary confusion of through motorists who, on seeing a yellow or red ball display in a turn signal, might believe the signal applied to them and brake unnecessarily, thus creating the potential for rear end collisions. Such confusion may be most likely at night and/or at times when only a single through indication is visible (e.g. when one of the green dual indications has burned out). The adoption of the three color left arrow display at these two suburban locations was designed to minimize the potential for such confusion. With the limited period for which accident data was available for these two locations it was not possible to prove that the change in the signal displays resulted in any change in safety.

Comparison of the clearing times (DASG) of queue position one vehicles between these two locations showed that there were real differences and that the mean DASG times were shorter for the site with the post mounted signal in the median (Montrose and Jefferson) than they were for the site with the overhead mounted turn signal (Montrose and Tildenwood). The differences in mean delay after start of green were too large to be due to chance in both the "before" and the "after" condition. The Z values were 2.953 and 2.234 respectively for the two conditions.

Variations between locations in approach width, intersection geometrics, sight distances, right-of-way width available, visual clutter, etc. make it unwise to reach any general conclusions as to the relative merits of median mounted vs overhead mounted turn control signals. It does appear however that clearing times (DASG), and hence starting delays, will be shorter at locations with post mounted signals in the median. Locations where any lane is an optional through or turn lane, and where the through and turn movements are phased separately with a protected then prohibited type operation, appear to be seriously inferior to single movement lanes regardless of the type of signal head mounting. In cases where median mounted left turn signals are not feasible, this study should particularly NOT be taken as encouraging use of right corner mounted left turn signals, rather than overhead (mast arm or spanwire) mounted signals. Engineering judgement suggests great caution in the use of right corner post mounted left turn signals on multiple lane approaches. Such right corner mounted left turn signals may have the potential to encourage left turns from other than the left lane, and the resulting potential for same-direction sideswipe accidents.

CHAPTER VII. NET ECONOMIC BENEFITS ACCRUING FROM USE OF ARROW INDICATIONS

A. General

The members of the National Advisory Committee on Uniform Traffic Control Devices were of the opinion that turn arrows (red, yellow and green) used in lieu of, or to supplement, conventional circular indications in traffic signals may be beneficial to traffic operations in certain types of locations.

A principal objective of this study was the determination of the net economic benefits (if any) derived from use of arrow indications. Webster's (19) definition of "benefit" as:

"anything contributing to an improvmeent in condition"

was accepted for this case. Improvement in conditions, as applied to traffic flow, was interpreted as: reduction of travel time, energy dissipation and/or traffic accidents. These factors have been universally accepted as measures of improvement in traffic conditions. They are readily adaptable to a common base of "cost". Other factors may be considered, such as better understanding of control devices, reduction of unauthorized movements, etc., but these are not readily convertible to a common base for comparison. They are treated elsewhere in this report.

Benefits are measured by the differential in cost, prior to, and subsequent to, the changes. Decremental costs (decreases in costs) are a "positive benefit". Incremental costs (increases in costs) are a "negative benefit". The "net benefit" is the algebraic sum of all decremental and incremental costs.

B. Elements of Cost

The net benefit is the net difference in costs between the "before" and the "after" conditions. The component costs included in the calculation of the net benefit in this study were:

1. Stopping Cost - This is the cost per vehicle to stop from the mean speed of traffic on the approach to an intersection, and then to accelerate back up to that mean speed.

2. Idling Cost - This is the cost of motor fuel, wear, lubricants, etc. used while a stopped vehicle was waiting for the green indication.

3. Occupant Time Cost - This is the cost of the time of all vehicle occupants for the time between when an arriving vehicle stopped in queue, and when it cleared the intersection.

4. Accident Cost - This is the cost of accidents for a given period of time in the "before" and "after" conditions.

5. Cost of Control Change - This is the total cost to make the change in the traffic controls. This cost applies only to the "after" condition.

C. Unit Values for Those Costs

Initial data for the unit values for the Stopping Cost, the Idling Cost, and the Occupant Time Cost have been taken from the book Economic Analysis for Highways by Robley Winfrey (20). Mr. Winfrey is a recognized authority in highway and traffic economics. His book was written after over 40 years of practice in this field. His tables, providing cost factors on vehicles in traffic flow, were compiled from data of his own collection, as well as from many of his colleagues. The book was printed in 1969. But much of the cost data are from studies made in the early 1960's. To compensate for the changes over the years, a yearly increase of 6 percent has been applied for a period of 12 years.

Mr. Winfrey's cost tables provide data for all classes and types of vehicles. Continuing traffic studies, as well as samples taken in this study, indicate little or no change in the magnitude and composition of traffic before and after the changes were made in the traffic controls. The magnitude of the net benefit is to be measured by the differential in cost before and after the changes were made in the controls. This and the large preponderance of passenger cars and light trucks (of the passenger car performance class) justify treating all traffic as one class, namely the 4,000 pound passenger car, as reported in the Winfrey tables, and updated as described above.

1. Stopping Cost

Unit costs to stop a vehicle from varying mean speeds and then return to that speed were taken from Table A-8 (page 688) of the Winfrey tables. Updated to 1974 the values are given in Table 16 below.

Table 16

Excess cost for a 4-kip passenger car above continuing at selected initial speeds, to stop and the return to that initial speed.

Initial Speed (mph)	Projected 1974 Cost ($) per vehicle
20 mph	$0.010
25 mph	$0.014
30 mph	$0.019
40 mph	$0.032

2. Idling Cost

The value for the idling cost for a 4,000 pound car was developed from Winfrey's Table A-41 (page 723). When updated to 1974 it is $0.23 per vehicle hour.

3. Occupant Time Cost

Occupant time costs for travel time were found by Winfrey (page 269) to be within a range from $1.00 to $4.00 per passenger hour. Vehicle occupancy studies made by the D.C. Department of Transportation) recorded an average of 1.38 persons per vehicle. By taking an average of Mr. Winfreys values, allowing for 1.38 persons per vehicle, and up-dating to 1974, a unit cost for occupant time of $6.90 per vehicle hour of delay, from stopping in queue to clearing the intersection, has been arrived at.

4. Accident Cost

Representative costs for accidents of various types have been developed from the 1966 report of the Washington Area Motor Vehicle Accident Cost Study (21). This study was jointly sponsored by the U. S. Bureau of Public Roads, the District of Columbia Government, the Maryland State Roads Commission, and the Virginia Department of Highways. The accident cost data presented in the study report are circa 1964. Those values have been increased by six percent a year for 10 years to allow for inflation. The updated values are given in Figure 37. Traffic accident experience at the experimental locations was compiled from individual accident reports prepared by the Metropolitan Police Department of the District of Columbia and the Montgomery County, Maryland Police Department. Accidents analyzed and recorded herein are only those which occurred in the movement of concern at the experimental and control locations. The unit costs for the appropriate type of accident were applied to each reported accident, and then the total accident costs were calculated for the "before" and "after" periods. Total accident costs "before" and "after", and the statistical analysis of any differences in accident costs are presented in Tables 17 through 24. Differences in accident frequency at the locations were discussed in Chapter VI.

5. Cost of Control Change

The costs to install the turn arrows at the experimental locations was taken from work orders and invoices issued during the conduct of the study. The total costs of each control change are shown in Table 25.

D. Cost Effectiveness

The "before" and "after" costs, and their sums, for each of the six experimental locations in Washington, D.C. are recorded herein Tables 26 through 31. The sum of the "after" costs at each location includes the cost of its control change.

A location where the sum of the "after" costs was lower than the sum of the "before" costs had an improvement in net costs. Such an improvement was called "a positive cost benefit". Positive cost cost benefits were found at two of the D.C. experimental locations. The location types where such improvements were found were:

1. An intersection approach having an exclusive lane for turns (see Table 29).

2. An intersection approach where movements are "protected" from conflicting movements by other indications and/or by the signal sequence (see Table 30).

One other type of location may be worthy of consideration from a cost benefit standpoint, based on traffic cost. This is a location "where certain movements are prohibited" (see Table 27). Overall cost in the "after" period was some 10 percent higher than in the "before" period. These costs include an accident cost of $700 in the "before" period with no accident cost in the "after" period, and a cost of the change from circular signal indications to arrow indications of $1,500 in the "after" period. Analysis of traffic costs only indicated "after" costs to be on the order of 20 percent less than "before" costs. If, then, control change cost and accident costs were neglected from consideration, it might be said that a cost benefit resulted from the change to arrow indications. Other factors may have a greater bearing in evaluating this case. Further analysis of traffic costs revealed some 40 percent saving in overall travel time and idling time costs. But there were considerably more stopped vehicles in the "after" period than in the "before" period; actually over 40 percent increase.

Other factors (including delay after start of green and the frequency of violations of the signal indications) brought out in Chapter VI should be taken into account in making a final determination as to the efficacy of red, yellow and green turn arrow indications in each of the six types of location allowed in the MUTCD.

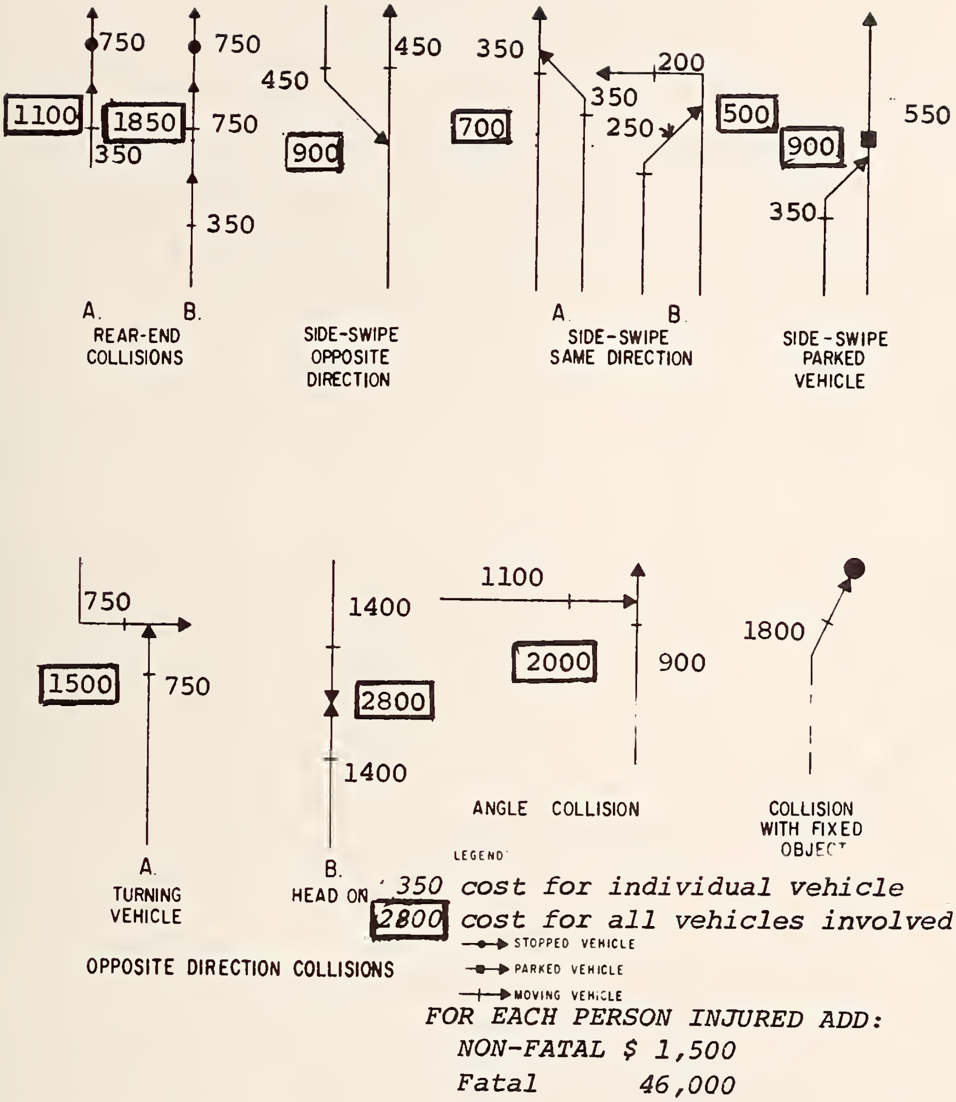


Figure 37

Representative costs for accidents of various types and severities, updated to 1974.

Table 17

"Before" and "after" accident experience and costs for an approach intersecting a one-way street.

Experimental Location & Movement of Concern	F Street at 10th Street, N. W. All eastbound plus the westbound to southbound left turn.					
Accident Experience	Before Period:			After Period:		
Type of Collision	Number	Persons Injured	Cost	Number	Persons Injured	Cost
Fixed Object						
Head On						
Rear End 2 cars Over 2 ( )						
Side Swipe: Opp Direction Same Dir Rt Same Dir Lt Parked Veh						
Turning Vehicle						
Right Angle	2	-	$ 4,000	1	-	$ 2,000
Totals	2	-	$ 4,000	1	-	$ 2,000

Remarks:

In the 212 day time period some 433,000 vehicles made the movements of concern through this intersection. Accident probability = 0.0000045.

Conclusion: Change of signal indications is of no significance regarding accident expectancy.

Control Location & Movement of Concern	G Street at 10th Street, N. W. Movements same as for experimental location.					
Fixed Object						
Head On						
Rear End 2 cars Over 2 ( )						
Side Swipe Opp Direction Same Dir Rt Same Dir Lt Parked Veh						
Turning Vehicle						
Right Angle						
Totals						

NO ACCIDENTS REPORTED IN TIME FRAME AND DIRECTIONS OF STUDY

Table 18

"Before" and "after" accident experience and costs for an intersection approach where certain traffic movements are prohibited.

Experimental Location & Movement of Concern	New York Avenue at 13th Street, N. W. East bound to north bound from 7:00 AM to 10:00 AM & from 4:00 to 7:00 PM on week days Mondays through Fridays only.					
Accident Experience	Before Period: September, 1973 thru March, 1974			After Period: September, 1974 thru March, 1975		
Type of Collision	Number	Persons Injured	Cost	Number	Persons Injured	Cost
Fixed Object						
Head On						
Rear End 2 cars Over 2 ( )						
Side Swipe:						
Opp Direction						
Same Dir Rt	1	-	$700			
Same Dir Lt						
Parked Veh						
Turning Vehicle						
Right Angle						
Totals	1	-	$700			

NO ACCIDENTS REPORTED IN TIME FRAME AND DIRECTIONS OF STUDY

Remarks:

Time period 212 days. Vehicles involved in movement of concern = 300,000. Accident probability = 0.0000033.

Conclusion: Change of the signal indications was of no significance regarding accident expectancy.

Table 18 (continued)

Control Location & Movement of Concern	H Street at 13th Street, N. W. Same movements an times as for experimental location					
Fixed Object						
Head On				1	-	$2,800
Rear End 2 cars	1	-	$1,100			
Over 2 ( )						
Side Swipe						
Opp Direction						
Same Dir Rt	2	-	1,400	1	-	700
Same Dir Lt						
Parked Veh						
Turning Vehicle						
Right Angle						
Totals	3	-	$2,500	2	-	$3,500
	Average Cost (μ)		$ 833.			$1,750
	Std Deviation (σ)		231			1,484

Remarks:

Hypothesis: $U_b = U_a$ and there is no real difference between mean accident costs "before" and "after".

Test: Student t at 95% = 2.35

$$\sigma = \sqrt{\frac{3(231)^2 + 2(1484)^2}{3 + 2}} = 955; \qquad t = \frac{833 - 1750}{955\sqrt{1/3 + 1/2}} = -1.05$$

Hypothesis cannot be disproved.

Table 19

"Before" and "after" accident experience and costs for an intersection approach where certain movements are physically impossible.

Experimental Location & Movement of Concern	East Executive Avenue at E Street, N. W. South bound on East Executive to east bound on E Street.					
Accident Experience	Before Period: June, 1973 thru March, 1974			After Period: June, 1974 thru March, 1975		
Type of Collision	Number	Persons Injured	Cost	Number	Persons Injured	Cost
Fixed Object						
Head On						
Rear End 2 cars						
Over 2 ( )						
Side Swipe:						
Opp Direction						
Same Dir Rt						
Same Dir Lt						
Parked Veh						
Turning Vehicle						
Right Angle						
Totals						

NO ACCIDENTS REPORTED IN TIME FRAME AND DIRECTIONS OF STUDY

Control Location & Movement of Concern	19th Street at Constitution Avenue, N. W. South bound to east bound.					
Fixed Object						
Head On						
Rear End 2 cars						
Over 2 ( )						
Side Swipe						
Opp Direction						
Same Dir Rt						
Same Dir Lt						
Parked Veh						
Turning Vehicle						
Right Angle						
Totals						

NO ACCIDENTS REPORTED IN TIME FRAME AND DIRECTIONS OF STUDY

Table 20

"Before" and "after" accident experience and costs for intersection approaches which had an exclusive lane for turns.

Experimental Location & Movement of Concern	New York Avenue at Bladensburg Road, N. E. West bound to south bound					
Accident Experience	Before Period: September, 1972 thru August, 1973			After Period: September, 1973 thru August, 1974		
Type of Collision	Number	Persons Injured	Cost	Number	Persons Injured	Cost
Fixed Object	2	3	$ 8,100	2	1	$ 5,100
Head On	1	-	2,800	1	-	2,800
Rear End 2 cars	14	4	21,400	8	3	13,300
Over 2 ( )	4	6	16,400	3	3	10,050
Side Swipe:						
Opp Direction						
Same Dir Rt	2	-	1,400	2	2	5,200
Same Dir Lt						
Parked Veh						
Turning Vehicle						
Right Angle	3	2	9,000			
Totals	26	15	$59,100	16	9	$36,450
		Average cost (μ)	2,273			2,278
		Std Deviation (σ)	1,703			1,063

Remarks:

Hypothesis: $U_b = U_a$ and there is no real difference between mean accident costs "before" and "after".

Test: Student t at 95% = 1.68

$$\sigma = \sqrt{\frac{26(1703)^2 + 16(1063)^2}{26 + 16 - 2}} = 1529; \quad t = \frac{2273 - 2278}{1529\sqrt{1/26 + 1/16}} = -0.01$$

Hypothesis cannot be disproved.

Control Location & Movement of Concern	New York Avenue at Bladensburg Road, N. E. East bound to north bound					
Fixed Object	1	-	$ 1,800	3	2	$ 8,400
Head On	4	3	15,700	1	-	2,800
Rear End 2 cars	6	2	9,600	2	2	5,200
Over 2 ( )	4	4	14,150	4	3	13,400
Side Swipe						
Opp Direction						
Same Dir Rt	7	1	6,400	4	1	4,300
Same Dir Lt						
Parked Veh						
Turning Vehicle						
Right Angle	2	--	4,000	2	-	4,000
Totals	24	10	$51,650	16	8	$38,100
	Average Cost (μ)		2,152			2,381
	Std Deviation (σ)		1,791			1,102

Remarks:

Hypothesis: $U_b = U_a$ and there is no real difference between mean accident costs "before" and "after".

Test: Student t at 95% = 1.68

$$\sigma = \sqrt{\frac{24(1791)^2 + 16(1102)^2}{24 + 16 - 2}} = 1593; \quad t = \frac{2152 - 2381}{1593\sqrt{1/24 + 1/16}} = -0.45$$

Hypothesis cannot be disproved.

Table 21

"Before" and "after" accident experience and costs for intersection approaches where traffic movements are "protected" from conflicting movements by other signal indications and/or by the signal sequence.

Experimental Location & Movement of Concern	Pennsylvania Avenue at 6th Street, N. W. East bound to north bound					
Accident Experience	Before Period: June, 1973 thru March, 1974			After Period: June, 1974 thru March, 1975		
Type of Collision	Number	Persons Injured	Cost	Number	Persons Injured	Cost
Fixed Object	1	-	$1,800			
Head On						
Rear End 2 cars Over 2 ( )						
Side Swipe:						
Opp Direction						
Same Dir Rt	2	--	1,400			
Same Dir Lt						
Parked Veh						
Turning Vehicle						
Right Angle						
Totals	3	-	$3,200			

NO ACCIDENTS REPORTED IN TIME FRAME AND DIRECTIONS OF STUDY

Remarks:

Time period 304 days. Vehicles involved in movement of concern = 714,400. Accident probability = 0.0000042.

Conclusion: Change of the signal indications was of no significance regarding accident expectancy.

Table 21 (continued)

Control Location & Movement of Concern	Pennsylvania Avenue at 11th Street, N. W. East bound to north bound					
Fixed Object						
Head On						
Rear End 2 cars	1	-	$1,100			
Over 2 ( )	1	1	3,350			
Side Swipe						
Opp Direction						
Same Dir Rt	1	-	700	1	-	$ 700
Same Dir Lt						
Parked Veh						
Turning Vehicle						
Right Angle				1	-	2,000
Totals	3	1	$5,150	2	-	$2,700
	Average Cost (μ)		1,717			1,350
	Std Deviation (σ)		1,429			919

Remarks:

Hypothesis: $U_b = U_a$ and there is no real difference between mean accident costs "before" and "after".

Test: Student t at 95% = 2.35

$$\sigma = \sqrt{\frac{3(1429)^2 + 2(919)^2}{3+2}} = 1250; \qquad t = \frac{1429 - 919}{1250\sqrt{1/3 + 1/2}} = 0.45$$

Hypothesis cannot be disproved.

Table 22

"Before" and "after" accident experience and costs for an intersection approach where all the traffic movements do not begin and/or end at the same time, and where the signal indications for turning movements will also be visible to traffic with other allowable movements.

Type of Location	Where all the movements in the approach do not begin or end at the same time & where indications for turning movements will also be visible to traffic with other allowable movements					
Experimental Location & Movement of Concern	Pennsylvania Avenue at 13th Street, N. W. West bound to north bound					
Accident Experience	Before Period: June, 1973 thru March, 1974			After Period: June, 1974 thru March, 1975		
Type of Collision	Number	Persons Injured	Cost	Number	Persons Injured	Cost
Fixed Object				1	-	$1,800
Head On						
Rear End 2 cars Over 2 ( )						
Side Swipe: Opp Direction Same Dir Rt Same Dir Lt Parked Veh	4	-	$2,800	1	-	700
Turning Vehicle						
Right Angle	2	-	4,000			
Totals	6	-	$6,800	2	-	$2,500

Remarks: *Average cost* (μ) 1,133   1,250
Std Deviation (σ) 671   778

Hypothesis: $U_b = U_a$ and there is no real difference between mean cost "before" and "after".

Test: Student t at 95% = 1.94

$$\sigma = \sqrt{\frac{6(671)^2 + 2(778)^2}{6+2}} = 699 \qquad t = \frac{1133 - 1250}{699\sqrt{1/6 + 1/2}} = -0.20$$

Hypothesis cannot be disproved.

Control Location & Movement of Concern	Pennsylvania Avenue at 11th Street, N. W. West bound to north bound.					
Fixed Object				1	-	$1,800
Head On						
Rear End 2 cars Over 2 ( )	1	1	$3,350			
Side Swipe Opp Direction						
Same Dir Rt	1	-	700	1	-	700
Same Dir Lt						
Parked Veh						
Turning Vehicle						
Right Angle	1	-	2,000			
Totals	3	1	$6,050	2	-	$2,500
	Average Cost (μ)		2,017			1,250
	Std Deviation (σ)		1,325			778

Remarks:

Hypothesis: $U_b = U_a$ and there is no real difference between mean accident costs "before" and "after".

Test: Student t at 95% = 2.35

$$\sigma = \sqrt{\frac{3(1325)^2 + 2(778)^2}{3+2}} = 1138; \qquad t = \frac{2017 - 1250}{1138\sqrt{1/3 + 1/2}} = 0.74$$

Hypothesis cannot be disproved.

Table 23

"Before" and "after" accident experience and costs for a suburban intersection with post mounted traffic signals.

Experimental Location & Movement of Concern	Montrose Road at E. Jefferson Street, Montgomery County, Maryland. East on Montrose Road to north on Jefferson Street					
Accident Experience	Before Period: 29 November, 1973 to 29 May, 1974			After Period: 29 May, 1974 to 29 Npvember, 1974		
Type of Collision	Number	Persons Injured	Cost	Number	Persons Injured	Cost
Fixed Object						
Head On						
Rear End 2 cars Over 2 ( )	1	1	$3,350			
Side Swipe: Opp Direction Same Dir Rt Same Dir Lt Parked Veh						
Turning Vehicle						
Right Angle						
Totals	1	1	$3,350			

NO ACCIDENTS REPORTED IN TIME FRAME AND DIRECTIONS OF STUDY

Difference between "before" and "after" accident experience can not be shown to be other than the result of chance variation. No difference in hazard level can be proved to exist.

Table 24

"Before" and "after" accident experience and costs for a suburban intersection with span wire mounted traffic signals.

Experimental Location & Movement of Concern	Montrose Road at Tildenwood Drive, Montgomery County, Maryland West on Montrose Road to south on Tildenwood Drive					
Accident Experience	Before Period: 29 November, 1973 to 29 May, 1974			After Period: 29 May, 1974 to 29 November, 1974		
Type of Collision	Number	Persons Injured	Cost	Number	Persons Injured	Cost
Fixed Object	NO ACCIDENTS REPORTED IN TIME FRAME AND DIRECTIONS OF STUDY					
Head On						
Rear End 2 cars Over 2 ( )				2	1	$3,700
Side Swipe: Opp Direction						
Same Dir Rt						
Same Dir Lt						
Parked Veh						
Turning Vehicle						
Right Angle						
Totals				2	1	$3,700

Difference between "before" and "after" experience can not be shown to be other than the result of chance variation. No difference in hazard level can be proved to exist.

Table 25

Signal modifications to add turn control arrow indications to traffic signals at experimental locations in Wash., D.C.

Location	Modification	Cost
F Street at 10th Street, N.W.	Remove four signal heads with three 8" lenses each. Install two 5-light and two 6-light signals, all with 12" lenses. Install new and larger controller and controller base. Add conduit and cable.	$3,230
New York Ave. at 13th Street, N.W.	Remove two 3 light, all 8 inch lens, signals. Install two 5 light "house type" signals with all 12 inch lenses. Add conduit and cable.	$1,500
East Executive Avenue at E Street, N.W.	Remove one 4 light, 8 inch lens, signal (one head not in use). Install one 4 light 12 inch lens signal. Make special provision for flashing operation.	$ 305
New York Avenue at Bladensburg Road, N.E.	Change 12 inch circular red and yellow lenses in two signal heads to 12 inch red and yellow arrows.	$ 85
Pennsylvania Ave. at 6th Street, N.W.	Remove one 3 light, and one 4 light, 8 inch lens signal. Install three 3 light 12 inch lens signals.	$ 645
Pennsylvania Ave. at 13th Street, N.W.	Remove one 4 light, 8 inch lens, signal. Install two 3 light, 12 inch lens, signals.	$330

Table 26

Analysis of travel costs "before" and "after" change in signal operations on F Street at 10th Street, N.W.

Type of location:	Intersection approaches of a two-way street intersecting a one-way street.
Movement controlled:	Change in control of left turn from westbound F street altered control of all eastbound and westbound F Street traffic.
Traffic affected:	All traffic on F Street.

Magnitude of traffic flow:	Annual Average Daily Traffic (AADT)	Yearly flow
Total in street:	15,100	5,512,000
Affected traffic:	15,100	5,512,000

Vehicle occupancy - 1.38

Mean traffic speed on intersection approach - 20 mph.

Traffic properties determined from study sampling	Before change Sample	Before change Expanded	After change Sample	After change Expanded
Vehicles involved:				
Total number	1,395	5,512,000	953	5,512,000
Not delayed	226	893,000	219	1,267,000
Stopped in queue	1,169	4,619,000	734	4,245,000
Travel time to clear facility after:	Vehicle Seconds	Vehicle Hours	Vehicle Seconds	Vehicle Hours
Arrival in queue	49,441	54,265	38,123	61,249
Go indication	13,340	14,642	6,018	9,673
Idling time	36,101	39,623	32,105	51,576

Travel costs in $		Before	After
Stopping cost	@ $ 0.010 /v.	46,200	42,500
Idling cost	@ $ 0.23 /v.h.	9,100	11,900
Occupant cost	@ $ 6.90 /v.h.	374,400	422,600
Accident cost		4,000	2,000
Subtotal		$ 433,700	$ 479,000
Cost of control change		-	3,230
Total cost involved		$ 433,700	$ 482,230

Net difference: Negative cost benefit of $ 48,530

Table 27

Analysis of travel costs "before" and "after" change in signal operations on New York Avenue at 13th Street, N.W.

Type of location: An intersection approach where certain movements are prohibited.

Movement controlled: Eastbound traffic on New York Ave. is prohibited from making a left turn during the AM & PM peak periods of traffic flow.

Traffic affected: Eastbound traffic desiring to turn northbound from 7:00 - 9:30 AM and 4:00 - 6:30 PM on Mondays through Fridays.

Magnitude of traffic flow:	Annual Average Daily Traffic (AADT)	Yearly flow
Total in street:	14,700	5,365,500
Affected traffic:	450	164,300

Vehicle occupancy - 1.38

Mean traffic speed on intersection approach - 30 mph.

Traffic properties determined from study sampling.	Before change Sample	Before change Expanded	After change Sample	After change Expanded
Vehicles involved:				
Total number	45	164,300	83	164,300
Not delayed	37	135,100	62	122,700
Stopped in queue	8	29,200	21	41,600
Travel time to clear facility after:	Vehicle Seconds	Vehicle Hours	Vehicle Seconds	Vehicle Hours
Arrival in queue	254	258	290	160
Go indication	27	28	151	84
Idling time	227	230	139	76

Travel costs in $	Before	After
Stopping cost @ $ 0.019 /v.	550	790
Idling cost @ $ 0.23 /v.h.	50	20
Occupant cost @ $ 6.90 /v.h.	1,780	1,100
Accident cost	700	none
Subtotal	3,080	1,910
Cost of control change	-	1,500
Total costs involved	3,080	3,410

Net difference: Negative cost benefit of $ 330

Table 28

Analysis of travel costs "before" and "after" change in signal operations on East Executive Ave. at E St., N.W.

Type of location: A location where certain movements are physically impossible.

Movement controlled: Left turn from southbound East Executive onto eastbound E St.

Traffic affected: All southbound traffic on East Executive at this point.

Magnitude of traffic flow:	Annual Average Daily Traffic (AADT)	Yearly flow
Total in street	17,500	6,387,500
Affected traffic	6,670	2,434,600

Vehicle occupancy - 1.38

Mean traffic speed on intersection approach - 25 mph.

Traffic properties determined from study sampling	Before change Sample	Before change Expanded	After change Sample	After change Expanded
Vehicles involved				
Total number	556	2,434,600	697	2,434,600
Not delayed	449	1,966,100	505	1,764,000
Stopped in queue	107	468,500	192	670,600
Travel time to clear facility after:	Vehicle Seconds	Vehicle Hours	Vehicle Seconds	Vehicle Hours
Arrival in queue	3,936	4,787	8,031	7,792
Go indication	369	449	862	837
Idling time	3,567	4,338	7,169	6,955

Travel costs in $		Before	After
Stopping cost	@ $ 0.014 /v.	6,500	9,400
Idling cost	@ $ 0.23 /v.h.	1,000	1,600
Occupant cost	@ $ 6.90 /v.h.	33,000	53,800
Accident cost		none	none
Subtotal		$ 40,500	$ 63,200
Cost of control change		-	305
Total costs involved		$ 40,500	$ 63,505

Net difference: Negative cost benefit of $ 23,005.

Table 29

Analysis of travel costs "before" and "after" change in signal operations on New York Ave. at Bladensburg Rd. N.E.

Type of location:	An intersection approach having an exclusive lane for turns.
Movement controlled:	Left turn from westbound New York onto southbound Bladensburg
Traffic affected:	Two lanes of traffic in left turn slot channelization physically separated from both east and westbound through movements.

Magnitude of traffic flow:	Annual Average Daily Traffic (AADT)	Yearly flow
Total in street	58,600	21,389,000
Affected traffic	3,750	1,368,800

Vehicle occupancy - 1.38 persons per vehicle

Mean traffic speed on approach - 40 mph.

Traffic properties determined from study sampling	Before change Sample	Before change Expanded	After change Sample	After change Expanded
Vehicles involved				
Total number	370	1,368,800	267	1,368,800
Not delayed	32	118,400	37	189,700
Stopped in queue	338	1,250,400	230	1,179,100
Travel time to clear facility after:	Vehicle Seconds	Vehicle Hours	Vehicle Seconds	Vehicle Hours
Arrival	21,334	21,933	10,026	14,278
Go indication	2,310	2,374	1,415	2,016
Idling time	19,024		8,611	12,262

Travel costs in $	Before	After
Stopping cost @ $ 0.032 v.	40,000	37,700
Idling cost @ $ 0.23 v.h.	4,500	2,800
Occupant cost @ $ 6.90 v.h.	151,300	98,500
Accident cost	59,100	36,500
Subtotal	$ 254,900	$ 175,500
Cost of control change	-	85
Total costs involved	$ 254,900	$ 175,585

Net difference: Positive cost benefit of $ 79,315

Table 30

Analysis of travel costs "before" and "after" change in signal operations on Pennsylvania Ave. at 6th St., N.W.

Type of location:	Location where movements are protected from conflicting movements by other indications and/or by the signal sequence.
Movement controlled:	Left turn from eastbound Pennsylvania to northbound 6th.
Traffic affected:	One lane of traffic in painted left turn slot channelization.

Magnitude of traffic flow:	Annual Average Daily Traffic (AADT)	Yearly flow
Total in street	33,000	12,045,000
Affected traffic	2,200	803,000

Vehicle occupancy - 1.38 persons per vehicle

Mean traffic speed on approach - 25 mph.

Traffic properties determined from study sampling	Before change Sample	Before change Expanded	After change Sample	After change Expanded
Vehicles involved				
Total number	313	803,000	231	803,000
Not delayed	58	148,800	63	219,000
Stopped in queue	255	654,200	168	584,000
Travel time to clear facility after:	Vehicle Seconds	Vehicle Hours	Vehicle Seconds	Vehicle Hours
Arrival	6,925	4,935	4,737	4,574
Go indication	1,820	1,297	1,175	1,134
Idling time	5,105	3,638	3,562	3,440

Travel costs in $		Before	After
Stopping cost	@ $ 0.014 v.	9,200	8,200
Idling cost	@ $ 0.23 v.h.	800	800
Occupant cost	@ $ 6.90 v.h.	34,100	31,600
Accident cost		3,200	none
Subtotal		$ 47,300	$ 40,600
Cost of control change		-	645
Total costs involved		$ 47,300	$ 41,245

Net difference: Positive cost benefit of $ 6,055

Table 31

Analysis of travel costs "before" and "after" change in signal operations on Pennsylvenia Ave. at 13th St. N.W.

Type of location:	Location where all movements in the approach do not begin and/or at the same time, & where indications for turning movements will also be visible to traffic with other allowable movements.
Movement controlled:	Right turn from westbound on Pennsylvania to north bound on 13th.
Traffic affected:	Two lanes of traffic, nearest the curb, westbound on Pennsylvania Avenue.

Magnitude of traffic flow:	Annual Average Daily Traffic (AADT)	Yearly flow
Total in street	38,100	13,906,500
Affected traffic	11,400	4,161,000

Vehicle occupancy - 1.38 persons per vehicle

Mean traffic speed on approach - 25 mph.

Traffic properties determined from study sampling	Before change Sample	Before change Expanded	After change Sample	After change Expanded
Vehicles involved				
Total number	171	4,161,000	305	4,161,000
Not delayed	27	657,000	35	477,500
Stopped in queue	144	3,504,000	270	3,683,500
Travel time to clear facility after:	Vehicle Seconds	Vehicle Hours	Vehicle Seconds	Vehicle Hours
Arrival	3,981	26,909	8,537	32,352
Go indication	706	4,772	1,734	6,571
Idling time	3,275	22,137	6,803	25,781

Travel Costs in $	Before	After
Stopping cost @ $0.014	49,000	51,600
Idling cost @ $0.23 v.h.	5,100	5,900
Occupant cost @ $6.90 v.h.	185,700	223,200
Accident cost	6,800	2,500
Subtotal	246,600	225,700
Cost of control change	-	330
Total Costs involved	$ 246,600	$ 283,530

Net difference: Negative cost benefit of $ 36,930

CHAPTER VIII. USERS MANUAL

A. Introduction

Red, yellow and green steady (that is non-flashing) arrow indications have been found useful in certain applications. Guidelines for their use are presented in Chapter IX. The need for, and desireability of, using steady arrow indications in a signal operation is directly related to both: (1) the signal phasing used at the location; and (2) its physical and operational characteristics. It will be useful to consider these two aspects of the location separately while deciding whether, and if so how, to use arrows in a given traffic signal display.

B. Signal Phasing Considerations

For the purposes of this discussion the various possible signal phasings will be grouped into three basic types. These will be referred to as: (1) "normal"; (2) "protected-permitted"; and (3) "protected-prohibited". They are defined and discussed below.

1. "Normal" Signal Phasings

With a "normal" type phasing all vehicular movements from any given approach to the intersection move at the same time. No movement is started, or cut off, before any other movement from the same approach. Most frequently two opposing approaches (e.g. north and south) will get their green indications at the same time, and left turns from either approach will be made under the normal right-of-way rule that turning traffic yields to through vehicles and pedestrians. Special cases of a "normal" phasing might include provision of an exclusive pedestrian phase, and/or allowing traffic to enter the intersection from only one approach at a time, so there was no opposing flow.

On approaches from which only a single traffic movement is permitted, green arrow indications have sometimes been used in "normal" signal phasings to emphasize the fact that only one traffic movement is allowed. In such applications the green arrows have replaced green circular (ball) indications. For example, at a "T" intersection where the continuing street (the top of the "T") is one-way, the display for the street that ends (the stalk of the "T") has sometimes included a green arrow pointing downstream on the one-way, instead of a green ball indication. For a second example, at intersections where both left and right turns are prohibited, a green through arrow is sometimes used (instead of a green ball) to emphasize the fact that turns are prohibited, and that only the through movement is allowed. This study has shown that a substantial proportion of the motoring public does not understand that turns are prohibited on a through green arrow (displayed alone). A green through arrow should not be relied upon to carry the message that turns are prohibited. Positive signing of the prohibition is required.

This study found no benefits to be gained by using red and/or yellow turn arrows with any "normal" type signal phasing.

2. "Protected-Permitted" Signal Phasings

With a "protected-permitted" type operation, one or more vehicular movements are protected from traffic conflicts during one portion of the signal cycle, and are permitted during another portion of the cycle subject to the normal right-of-way rules. For example, the north approach to an intersection might be given its green before the south approach so as to expedite north to east left turns; and then those left turns could continue to be permitted (subject to the standard "turning traffic must yield to opposing through traffic" right-of-way rule) after the south approach also gets its green (both north and south approaches having their green at the same time during some part of the signal cycle). This would be a "protected-permitted" operation since the left turn is protected from conflicts during one portion of the signal cycle, and is permitted (subject to the normal right-of-way rules) during another portion of that cycle. Whether the "protected" portion of the cycle preceeds or follows the "permitted" portion is immaterial to the classification of the type of signal operation.

Green turn arrows are customarily used, in conjunction with green circular (ball) indications, to indicate "protected-permitted" signal phasings. Both the green ball and the green turn arrow are displayed together during the interval in which the turn is protected. The green ball is displayed alone during the interval when the turn is permitted subject to the normal right-of way rules.

Yellow turn arrows may be used to indicate the clearance interval at the end of the "protected" interval if it is to be followed by a "permitted" interval.

That is, a yellow turn arrow can indicate the clearance interval at the end of a "leading green". In such a signal operation, the signal indications would change from: red ball; to green ball plus green left arrow; to green ball plus yellow left arrow; to green ball alone; to yellow ball; and then back to the red ball. In this operation the yellow arrow warns turning traffic of the impending change in right-of-way assignment (of the impending end of its priority over the opposing through movement). In doing so it fulfills the requirement of Section 4B - 15 of the MUTCD (on page 228) that "(a) clearance interval shall be provided between the termination of a green arrow indication and the showing of a green indication to any conflicting traffic movement."

This study found no benefit to be gained from use of red turn arrows with any "protected-permitted" type signal operation.

3. "Protected-Prohibited" Signal Phasings

With a "protected-prohibited" type operation, a vehicular movement is permitted and provided with protection from conflicts during one portion of the signal cycle, but is prohibited during another portion of the cycle while traffic from the same approach is permitted to make some other movement. For example, if the northbound through and left turn movements both start together, but the left turn is cut off before the through movement is (to permit the southbound through to flow simultaneously with the northbound through) then the operation is "protected-prohibited". The left turn has been protected from conflicts during part of the cycle, and then prohibited while other movements from its approach were moving. For a second example, left turns might be permitted simultaneously from the northbound and southbound approaches with all through traffic movements held. Then the left turns could be stopped, and both the northbound and southbound through movements flowed. Whether the "protected" interval preceeds or follows the interval when the movement is "prohibited" (while other traffic from the same approach flows) is irrelevant to the classification of the type of signal operation.

Red, yellow and green turn arrows were found to offer worthwhile benefits in certain applications with "protected-prohibited" signal phasings. Guidelines for such uses are set forth in Chapter IX. The recommended steps for implementing the use of arrows are set forth in Section C of this chapter.

Selection between the above described three basic types of signal operation, and of the details of the specific phasing chosen, is a matter of engineering judgement. No generally accepted warrants for the selection of one or the other of the three basic types, for use at any given location, have come to light. It was not the purpose of this study to develop such warrants. In general it may be said that the "normal" type operation places the greatest reliance on the driver's understanding of, and compliance with, the normal right-of-way rules. This gives the "normal" type operation the greatest flexibility in meeting changing demands. The "protected-prohibited" type operation obtains (if the signals are obeyed) full protection from conflicts for its protected movements, but only at the cost of a loss of flexibility to meet changing traffic demands and an increase in the number of signal intervals required. As the number of signal intervals used in a cycle rises, so does the proportion of the cycle devoted to clearance intervals. This reduces the available total green time per cycle.

Observations made during this study tend to suggest that, when traffic congestion reaches levels that require motorists to wait more than one complete signal cycle before clearing an intersection, their observance of traffic signals declines seriously. An increased tendency develops for some drivers to "stretch the yellow" by entering the intersection on the very end of the clearance interval or even on the first several seconds of their red indication. This tendency was observed with conventional circular (ball) yellow and red indications, as well as with yellow and red arrow indications. If this point is reached with a "protected-prohibited" signal phasing, then the intended protection from conflicts may be destroyed by the violations, while traffic handling capacity may be well below what could have been obtained with a less restrictive phasing. Further, such a "protected-prohibited" operation, with its higher number of signal intervals, will be inherently less able to deal successfully with the normal short term fluctuations in traffic volumes without undue delays. It may be that there is an inherent trade-off between freedom and efficiency of movement on the one hand, and of high levels of protection of the various movements from conflicts on the other. If this is so, the choice of the appropriate phasing may be, to some extent, a political decision. Additional research on the relative merits and disadvantages of the various potential phasings for common traffic situations appears to be strongly warranted.

During the course of this study a significant problem was noted with pedestrian behavior when one specific type of split-phase signal operation was used. A significant proportion of pedestrians appear to use the stoppage of through traffic over the crosswalk they wish to use as their indication that it is safe to cross. This is so even when pedestrian signals are present. In view of this, a split-phase signal operation that gives pedestrians this (false) visual clue that they can cross, while at the same time continuing or starting a vehicular movement that conflicts with the pedestrian crossing, can create the illusion of safety but the reality of substantial hazard to pedestrians. It is recommended that such split-phase operations be avoided.

Only after the optimum signal phasing for present conditions at the site in question has been selected, should consideration be given to the appropriateness of arrow vs. circular indications to control the various movements, and to development of the final operational plans.

C. Considerations for Use of Turn Arrow Displays in Traffic Signals

If it is determined that it will be desireable to adopt a signal operation in which turn arrows can be fruitfully employed, then it is recommended that the first consideration be given to obtaining proper operation of the proposed green turn arrow. After this is achieved, the yellow and red arrow operations should follow naturally.

1. Use of Green Arrow Signal Indications

Proper green arrow installations are the subject of a number of significant provisions of the Manual on Uniform Traffic Control Devices, 1971 edition. Some of these provisions, and their implications for traffic signal installations including turn arrow indications, are discussed in the following paragraphs.

Section 4B - 5 (1.b.) of the MUTCD (page 217) states that the meaning of a green arrow signal indication is that traffic may "...enter the intersection only (emphasis added) to make the movement indicated by such arrow, or such other movement as is permitted by other indications shown at the same time." Both the questionnaire and the observations of traffic behavior in this project have shown that a significant proportion of the motoring public do not understand this limitation, and that they will make turns (especially right turns) when confronted with a signal showing only a through green arrow. Thus, a green through arrow alone should not be considered a sufficient display to prevent turns.

Section 4B - 6 (4) of the MUTCD states, in the second paragraph dealing with "steady arrow indications", subsection "e", (page 219) "(a) steady green arrow indication shall be used only when there would be no conflict with other vehicles or with pedestrians crossing in conformance with the walk indication." (emphasis added) However, Section 4B - 5 (l.c.) of the MUTCD states (page 217) "(u)nless otherwise directed by a pedestrian signal, pedestrians facing any (emphasis added) green indication, except when the sole (emphasis added) green indication is a turn arrow, may proceed across the roadway within any marked or unmarked crosswalk". These provisions appear to allow a conflict between pedestrians and turning vehicles at intersections without pedestrian signals, but which have green turn arrow displays. For example, if a north-south street has a green left turn arrow which is displayed simultaneously with a through indication (either a green ball or a green through arrow) during one interval of the signal cycle (e.g. a leading protected left turn), then Section 4B - 5 (l.c.) appears to permit a legal pedestrian crossing in the west crosswalk at the same time the green left arrow is indicating a protected left turn across that crosswalk by northbound to westbound traffic - an obvious pedestrian-vehicle conflict - as long as there are no pedestrian signals. A turn on a green turn arrow is protected from a pedestrian conflict if a pedestrian signal is in place and operating. However, a turn on a green turn arrow is not protected from pedestrian conflict, and turning vehicles are required to yield to pedestrians, if no pedestrian signal is in operation, and the through vehicular movement from the turning vehicles approach is also flowing. Since this appears a rather fine distinction for drivers to make in urban traffic, and could well be a source of confusion, it is strongly recommended that pedestrian signals be used at all locations where green turn arrow signal indications are provided.

According to the interpretation of the MUTCD used in this study, Section 4B - 6 (4)'s prohibition of vehicular conflicts on a green arrow indication means that: if a through movement in one direction receives a through green arrow indication, then the opposing movement may not receive a green ball indication at any time while the through arrow is displayed. For example, if the northbound flow received a through green arrow indication, then the southbound flow could not be simultaneously shown a green ball (although it could be simultaneously shown a green through arrow). Showing the southbound a green ball would permit southbound to eastbound left turns across the northbound through movement proceeding on its green arrow. Even though such left turns are burdened by the normal right-of-way rule that left turns must yield to opposing through traffic, there is still some chance of conflict. If the above interpretation of the MUTCD is accepted, then it follows that, if one approach has a through arrow display, the opposing approach must also have such arrow displays.

When left turns from an approach are prohibited during part of the signal cycle, and a through green arrow indication is shown to that approach (with or without a red left arrow) , significant problems can occur in handling the right turns from that approach and the pedestrian movements in the crosswalk on that approach's right. To carry the previous example further, if north and southbound movements have green through arrows, then provision must be made for both the southbound to westbound right turn, and the north-south pedestrian movement in the west crosswalk. One way to handle this is to go to an exclusive pedestrian phase. This would prohibit pedestrian movement north-south while the northbound and southbound vehicles were moving, and would give a right turn free of conflicts with legal pedestrian movements. Such a signal operation is likely to increase pedestrian delays, and to also reduce the proportion of the signal cycle available for vehicular movements. A second approach would be to make an additional split in the phasing and to have both: (a) an interval for north-south pedestrian movements while the right turn was prohibited; and (b) an interval for the right turn while pedestrians were prohibited from being in the crosswalk. In view of pedestrian crossing time requirements for wide streets this could lead to long signal cycle lengths, as well as to increased delays to both pedestrians and right turning vehicles. A third approach would be to simply prohibit either the right turn, or the pedestrian movement in the west crosswalk. At several locations in this study where the approach was multi-lane a fourth approach to dealing with the problem of handling right turns and pedestrians at a location with a through arrow was tried, and found successful. This approach involved using: (a) a through green arrow plus red left arrow display on the left side of the approach to show the left turn prohibition; and (b) a green ball display on the far right corner of the intersection to show that both through and right turn movements were permitted, but that the right turn was not protected from a pedestrian conflict (that the right turn was burdened by the normal right-of-way rule that turning vehicles must yield to pedestrians). Installations with median mounted through arrows and right side mounted green ball displays were used very successfully in this study at both the New York and Bladensburg, and the Pennsylvania at 6th experimental sites. These installations are shown in Figure 38. Yet a fifth possible approach to preventing a left turn without creating problems for right crosswalk pedestrians and the right turn would be to use a green ball plus red left arrow display. This display is prohibited by Section 4B - 6 (5.e.) of the MUTCD (page 220). However, such a display was tested in the Questionnarie used in the

Figure 38

Intersections using green ball displays on right side of through approach, and green through arrows on left side of through approach, with turn arrows to control left turn lanes.

Public Understanding portion of this research study. Question 13 of the questionnaire shows such a display. With absolutely no experience with such a display, and with no educational effort whatsoever, 89.9 % of the respondents understood that it meant that left turns were prohibited. In view of this finding the green ball plus red left arrow display may well offer promise. Horizontal separation of the signal head with the red arrow, from the signal head with the green ball, should further act to eliminate confusion. How such a display might look is shown in Figure 39.

It is most strongly recommended that a through green arrow not be used alone to indicate that a turn is prohibited. Despite years of use of such green through arrow displays, their prohibition on turns is not adequately understood by the motoring public. Through green arrow displays should always be supplemented by a red turn arrow, by a blankout sign showing when the turn is prohibited, or by conspicuous fixed signing.

2. Use of Yellow and Red Turn Arrow Indications

With the need established for a split-phase signal operation; with it established that yellow and red turn arrows can be beneficial in that signal operation; and with the proper application of the green arrow developed; the correct and effective use of the yellow and red turn arrow indications should be a straightforward matter. The applicable sections of the MUTCD should be consulted. These specifically include Sections 4B - 5, 4B -6, and 4B - 9. Note that red through arrows are not authorized. A red arrow may be used "only in a separate signal face which also contains steady yellow and green signal indications". (Section 4B - 6 (4. second paragraph) In this study that was interpreted as prohibiting use of a red turn arrow burning continuously throughout all intervals of a signal cycle, in order to indicate a peak hour turn prohibition. This was why no red arrow was included in the display at the New York Avenue at 13th Street, N. W. experimental location.

D. Miscellaneous Operational Matters

The visibility from a distance of an arrow display is less than that of an equal size circular (ball) lens illuminated by the same lamp, and yellow arrows have significantly better visibility from a distance than do red or green arrows. This is the reason for the MUTCD requirement (Section 4B - 8 (5)) for using 12 inch lenses with all arrow displays. Shifting from eight (8) inch ball displays to 12 inch arrow displays for the turn signals increases the

Figure 39

How a red left turn arrow plus green circular (ball) lens signal display would look. The signal assembly comprises a signal head with red, yellow and green left turn arrows to control the left turn, horizontally separated from a head with conventional circular lenses to control through and right turn movements.

size of the signal head. If the height of the upper signal head mounting remains the same, then 12 inch lens heads will hang lower than the 8 inch lens heads they replace. This may produce vertical clearance problems. A shift to taller signal poles and/or relocation of pole bases may be required to restore necessary clearances.

Since there may be some objection to the aesthetics of a signal installation that mixes 8 inch and 12 inch lenses, it may be found desireable to provide 12 inch lenses for all displays in any one mounting.

In a previous study (7) it was found that horizontal separation of turn signal heads from the head with the through indications was significantly beneficial to motorist understanding of the signal. Such a separation is shown in Figure 40.

Provision is required for flashing operation of the signal. Since flashing operation of red and yellow arrow displays is not presently generally authorized in the MUTCD, it may be necessary in some cases to install a fourth light with a ball lens in the signal head, just to provide for flashing operation in emergency or late night situations.

It is strongly recommended that all arrow turn signal displays be provided with explanatory signing. In signing turn arrows it is recommended that word messages, rather than mixed word and symbolic messages be used. It was found at night that under low levels of illumination the color red tends to "fade down" to black and make a symbolic red arrow appear to be a black arrow. The same effect appears, to a somewhat different extent, with symbolic green arrows. These effects can destroy the meaning of signs using symbolic arrows to explain the meaning of turn arrows in signals. The effect can be seen in Figure 41, a black and white photograph of a "No Left Turn On (symbolic red arrow)" sign. Note that, with the color gone, the sign appears to read "No left Turn On Arrow". While the effect is not accute, it does appear to make use of word message signing (e.g. "Right Turn On Green Arrow Only" superior to mixed word and symbol signing.

At locations where traffic is halted on one approach before it is halted on the opposite approach (locations with a "lagging green") there is a potential for an accident hazard to vehicles turning left. The hazard results from the tendency of drivers waiting to turn left from the approach whose movement is shut off first, to try to make left turns at the end of their movement in the mistaken belief that opposing traffic is also being stopped. The driver waiting to turn left and seeing his movements clearance interval display may, naturally but incorrectly, decide that the opposing flow is also being stopped and try to make the turn,

Figure 40

Horizontal separation of the turn signal head from the head with the indications for through traffic.

Figure 41

Black and white photograph of sign using symbolic colored arrow showing loss of meaning of such a sign when color is lost. Such loss of color is typical when colors "fade down" to black under low levels of illumination at night.

thus creating a collision hazard with opposing through vehicles which approach unabated. This hazard can be avoided by either: (1) prohibiting the opposing left turn in any case where there is a lagging through movement; or (2) adopting a "protected-prohibited" signal phasing for the opposing left turn, with the end of its left turn well separated in time from the end of its through movement. Three color arrow displays can be an effective way to provide such positive signal control of the left turn.

CHAPTER IX. GUIDELINES FOR USE OF TRI-COLOR (RED, YELLOW AND GREEN) ARROW INDICATIONS IN TRAFFIC SIGNALS

A. General

Sections 4C-1 through 4C-12 of the Manual on Uniform Traffic Control Devices (1) specify warrants which should be met for installing traffic control signals, or for continuing the use of signals already in place. These warrants may be applied generally but appear to have been drafted primarily for circular signal head lenses. Findings of this study show that, in some instances, traffic flow can be improved by substituting three lenses with tri-color (red, yellow and green) arrows for the "standard" circular lenses in traffic signals. Guidelines for such installations follow.

B. Advance Engineering Data Required

In addition to the traffic studies set forth in Section 4C-1 of the MUTCD, the investigation of traffic conditions and physical characteristics of the location which precedes the installation of tri-color arrow signal indications desirably should include:

1. Any existing and/or proposed turning restrictions or regulations for each approach during each period of the day.

2. The volume of each traffic movement, during representative A.M. peak, P.M. peak, and off-peak conditions, from each lane of each approach.

3. In the case of an existing traffic signal where installation of tri-color arrow indications is being considered to supplement or replace the pre-existing indications, complete information on the existing signal timing should be obtained. For signals with fixed-time controllers this informaiton should include the cycle length, the length of each interval, and the traffic movements on each interval, for all periods of the day.

4. The existing and proposed displays of the signal to all approaches during flashing operation.

5. The frequency of violations of existing controls, for each movement, from each approach, during the same periods as the turning volume counts in paragraph (2) above.

The following data are also desirable for a more precise understanding of the operation of the intersection and may be obtained, for each lane of each approach, during the periods specified in paragraph (2) above.

1. Travel times per vehicle from arrival to clearing (crossing the Stop Line or some other point of reference at the enterence to the intersection).

2. Amount of waiting time for stopped vehicles.

3. Start-up time to clear by queue position.

4. For each observed signal cycle, the amount of green (Go) time remaining after the last vehicle in queue has cleared, or the number of vehicles remaining in queue after the end of the green (Go) time.

C. Guidelines for Use of Red, Yellow and Green Arrows

The findings of this study indicate that the quality of traffic flow may be improved by installation of tri-color (red, yellow and green) arrow indications in traffic control signals under the conditions set forth in the following guidelines. Tri color (red, yellow and green) arrow indications may be installed in traffic signals at locations which meet one, or more, of the following conditions. In addition the traffic signal installation should meet at least one of the warrants set forth in Section 4C-1 through 4C-12 of the Manual on Uniform Traffic Control Devices (MUTCD). It is presumed that the signal and all related traffic control devices and markings are installed according to the standards set forth in the MUTCD.

Condition No. 1 - Where all the traffic movements on an approach do not begin and/or end at the same time, and where the indications for the turning movement(s) will also be visible to traffic with other allowable movements. To comply with this condition all movements to be controlled by arrow indications must be protected from conflicting vehicular and pedestrain movements.

Patterns of traffic movement are generally complex at intersections of this type. Multiple phasing of signals is required to produce this condition. It is often impractical to shield all of the signal faces from operators of vehicles who are not concerned with that indication's traffic movement. This frequently leads to confusion and an inordinate number of violations of signal controls and improper movements. Substitution of arrow indications for conventional indications may alleviate operator confusion and reduce violations. At one studied location, such a signal change reduced the violations rate to less than one-half the previous figure.

Condition No. 2 - On an intersection approach which has an exclusive lane for turning movements and where said turning movement is protected from vehicular and pedestrian conflicts.

The value of special lanes for high volume turning movements has long been recognized by engineers charged with expediting traffic flow. Turning lanes are installed only after a careful appraisal by engineers that turning volumes in the direction for which the special lanes are provided are of sufficient magnitude to justify the costs of the lanes. Generally, traffic signals are justified at urban intersections, at grade, where special turn lanes have been found needed. In many cases special phasing of the signal controller may also be required to permit turns being made without interference or conflict between movements of traffic or pedestrians.

It can be said, then that: When findings of engineering studies indicate a need for one or more special turn lanes for an approach to an intersection at grade, the use of red, yellow and green arrow indications in the signal controlling the movement is justified, so long as said arrow indications fully comply with all appropriate provisions of the MUTCD regarding avoidance of conflicts and other matters.

Condition No. 3 -Where there is a high frequency of turns made in violation of a through green arrow.

Turning when a traffic signal displays only a through green arrow is a violation. This was found not to be understood and/or respected by a significant portion of the motoring public. Public understanding and compliance was found to be markedly improve when a through green arrow was supplemented by a tri-color turn arrow display. The principal objective of a traffic signal is to tell the operator of a vehicle how he may proceed without requiring him to make a judgement as to whether it will be safe or expedient for him to do so. Arrow indications, placed in accord with the specifications enunciated in the MUTCD, reduce driver uncertainties.

Condition No. 4 -Where turning movements are protected from conflicting vehicular and pedestrian movements by other indications and/or by the signal sequence.

While such locations may most commonly met either, or both, conditions No. 1 and No. 2, in some cases it may be determined, as a matter of engineering judgement, that the use of tri-color arrows will be beneficial even in locations where an exclusive turn lane is not provided, and where all movements from an approach start and end at the same time. One such case might involve a protected turning movement being made at the same time as the through movement, with a green turn arrow being used in conjunction with a green circular indication to emphasize that the turn was protected and thus to expedite that turning movement. In such a case the decision as to whether or not a full tri-color arrow display would be used would be a matter of engineering judgement.

The foregoing guidelines are intended to apply to installations of tri-color arrows. They should not necessarily be used to restrict the use of green only, or green plus yellow, arrow indications. Such one and two color arrow displays may have broader application than tri-color arrow displays. Green turn arrows are frequently used in conjunction with green circular indications to indicate the "protected" interval in a "protected then permitted" turning movement control. Yellow turn arrows are often used to indicate the clearance interval for leading turns. In such uses they emphasize the end of the protected turning movement without confusing through motorists. Installation of both green turn arrow indications, and green plus yellow turn arrow installations should be made in accord with the MUTCD and good engineering judgement.

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