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Bulletin 271

Increasing Traffic Capacity Of Arterial Streets

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Increasing Traffic Capacity Of Arterial Streets

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Increasing the Traffic-Carrying Capability of Urban Arterial Streets*

JACK BERMAN and ARTHUR A. CARTER, JR., Highway Research Engineers, Division of Traffic Operations, Bureau of Public Roads

● TRAFFIC CONGESTION on many major urban arterial routes has reached intolerable proportions. Construction of the urban freeways contemplated in current highway programs will provide substantial relief to cities, but arterial streets must remain the urban transportation system's bulwark for providing traffic distribution services. Presently the urban arterials are overtaxed in their ability to provide traffic service for through traffic as well as to provide land-use services along the facility itself. These two services clash and in practically every major city the freeways that are being planned and built have as one of their major considerations the need to separate those two service functions.

Highway administrators and engineers recognize that the tremendous cost, taking of land, and other difficulties involved in urban freeway construction preclude their adoption as a wholesale solution to this problem. Proposed circumferential freeway routes will also provide relief to the urban areas of today and tomorrow, but they, too, can only slightly ease the impact of the work trip rushes imposed on major urban arterial routes. It is obvious that the major arterial street systems must be used to the maximum capacity and efficiency so that the standards of our cities' economic life may be advanced.

It is well known that many urban arterial streets could operate more efficiently and safely if all presently known methods of increasing their carrying capacity could be applied. Recognizing an important and timely need, the Bureau of Public Roads, in December 1958, undertook a pilot study, with the cooperation of the District of Columbia Department of Highways and Traffic, for the purpose of demonstrating theoretically the effectiveness of these various known methods of increasing traffic capacity, when used in combination.

As a convenient "test track," Wisconsin Avenue in the District of Columbia was selected, and the pilot study has thus become known as the Wisconsin Avenue Study.

The basic objective of the Wisconsin Avenue Study was to estimate how great an increase in the traffic-carrying capability of an existing urban arterial street could be developed within existing right-of-way limits, if all known traffic control techniques could be adopted and if major construction were carried out.

This research study was not intended to develop entirely new techniques of traffic operations, but rather was intended to predict the level of increased capacities that can be obtained by using existing tools now available.

It was not within the scope of this study to evaluate the changes in the composition of the city inself or, more specifically, of the neighborhoods through which the study street passes, that might be invoked to produce an efficient transportation system. That area of study properly belongs within the framework of the over-all transportation planners. The nature of the city's plan, whether organic or other, must ultimately be decided by the citizens themselves. Of course, it is recognized that changes in land use, changes in zoning, and introduction of residential land uses mixed with commercial development, would tend to change trip lengths as well as characteristics of traffic flow. Such an area of study encompasses radical changes in land values and land patterns which are associated with the economic and sociological responsibilities

* This is a summary report of a comprehensive study. The full report will be published by the Bureau of Public Roads probably late in 1960.

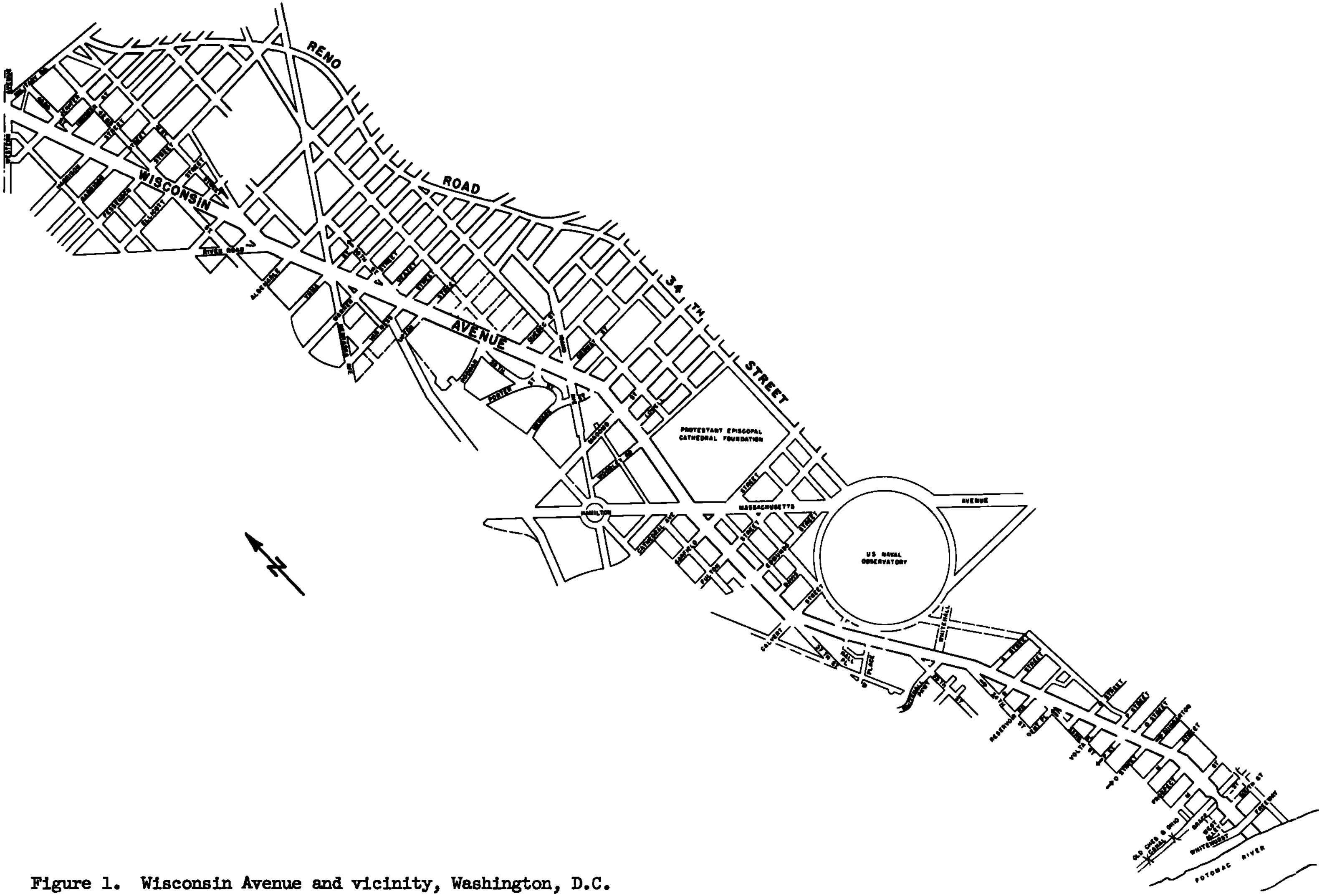

Figure 1. Wisconsin Avenue and vicinity, Washington, D.C.

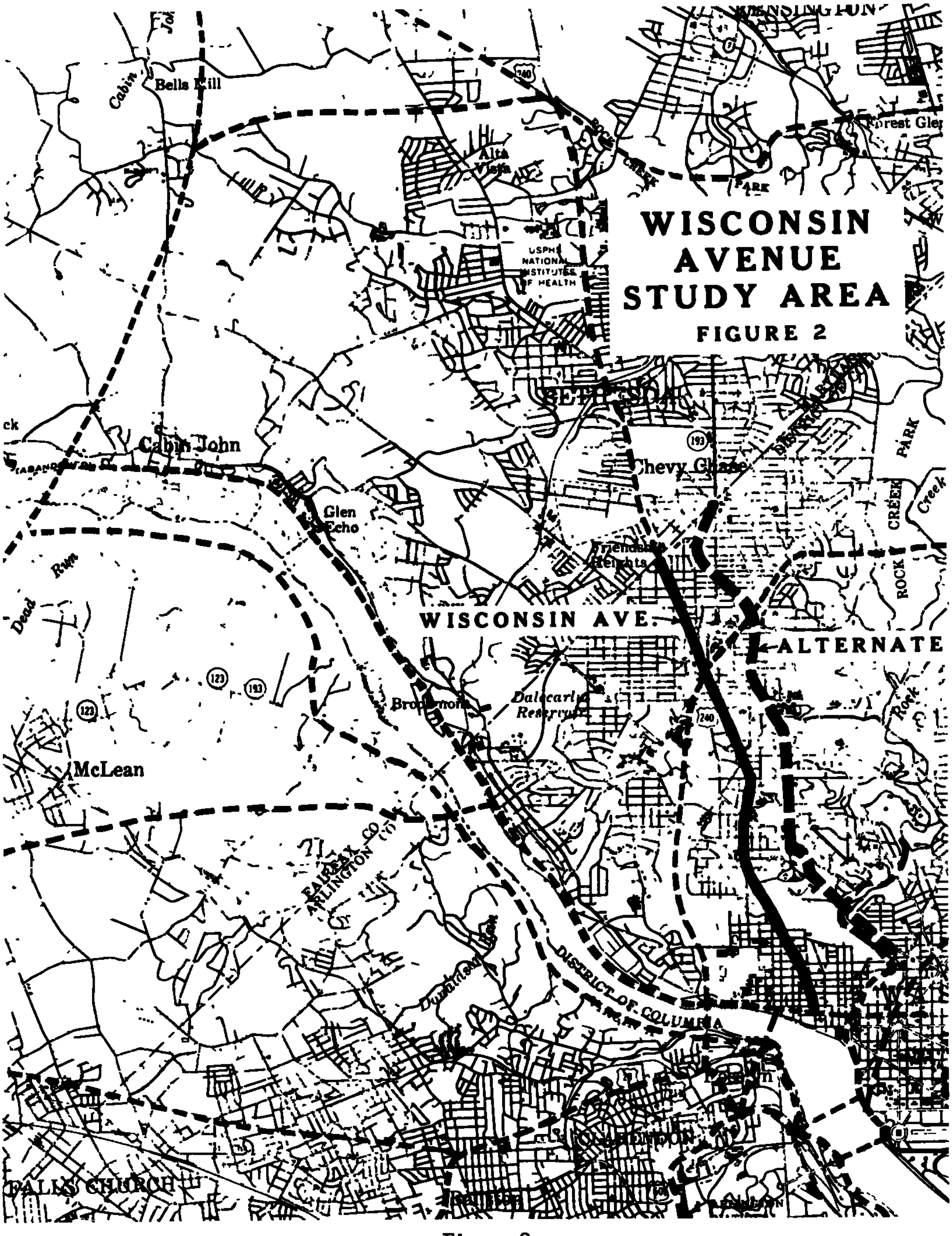

Figure 2.

of the community. Although it is recognized that traffic volumes are a direct function of these over-all planning considerations, the purpose of this study was to treat the existing disease with existing medicines rather than to develop new antibiotics.

It should be stressed that this study was limited to consideration of improvements possible without destruction of or damage to any fronting buildings, except in very special cases. That is, all potential improvements would have to fit within existing building lines, with adequate provision for sidewalks.

The study recognized that as pressure increases to push the capacity levels of our existing streets to greater and greater heights, a real danger exists that these highly developed major arterial routes will no longer adequately serve the adjacent land. It was the hypothesis that these two services can and must be maintained in balance on an arterial such as Wisconsin Avenue. This involved the use of the best-known traffic operation techniques, which provide a traffic stream having minimum friction while at the same time providing conditions conducive to patronage of the adjacent land services.

Wisconsin Avenue is the central artery in what is known as the Wisconsin Avenue corridor in northwest Washington, D.C. Figures 1 and 2 show the geographical location of the study route as well as its adjacent alternate route. The study section, from K Street at the Potomac River north to the D.C. boundary at Western Avenue, is about 4½ mi long. The southern end in Georgetown is of variable width, ranging from 35 to 56 ft. The remaining 3-mi section from Calvert Street to Western Avenue is generally 60 ft wide. The street contains many, though by no means all, of the traffic problems associated with urban arterial routes. On it throughout its length, at the time of the field study, was a streetcar operation, complete with center-of-street loading platforms along most of its length. There exist various grades ranging up to 7 percent, and curvature as high as 10 degrees.

The street traverses several commercial strip areas including Georgetown, a commercial section having many of the characteristics of a downtown area. In fact, Wisconsin Avenue, in its length in the District of Columbia from the Potomac River to Western Avenue, falls into eight very general land subdivisions. Within each of these groupings will be found a mixture of several land uses and a variation in the intensity of use. For example, in one study control section, multistory building units are located on one side of the street, and on the other side, single family dwelling units are present. Figures 3 through 6 show current conditions along the street.

While there has been considerable discussion concerning the desirability of developing a fully controlled access freeway to serve the travel desires in this area, this research study is not in any way related to that problem. Wisconsin Avenue could be "Any Street, U.S.A." It was selected for study because it offered a convenient "test track." This pilot study, therefore, while necessarily geographically related to Wisconsin Avenue, should be interpreted as national in scope.

The magnitude of the Wisconsin Avenue problem is comparable, relatively speaking, to the magnitude of the problems in most of our cities regardless of size. Basic

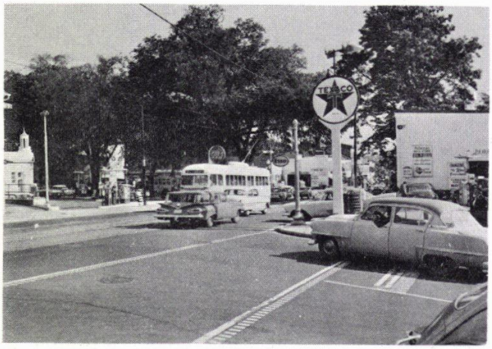

Figure 3. Looking south on Wisconsin Avenue at the "dog-leg" Q Street intersection. The street is 45 ft wide here, but narrows to 35 ft just to the north.

Figure 4. Looking south on Wisconsin Avenue at the intersection with 37th Street (right) and Calvert Street. At this curve, the street narrows, southbound, from 60 ft to 55 ft.

Figure 5. Looking north on Wisconsin Avenue at Upton Street, showing congestion ahead at the Van Ness intersection and a conflict at one of the four driveways now present on the west side of the street in this area.

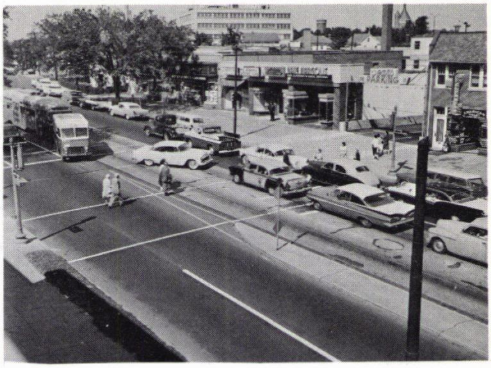

Figure 6. Looking north on Wisconsin Avenue north of Albemarle Street, showing turbulence due to pedestrians, turning vehicles, double parking, and streetcars in this major department store neighborhood.

arterial traffic operations problems exist regardless of the population groups within which these major arterials are located. Fortunately, cures for many of these problems, or at least effective remedies, fall within the purview of improved traffic operation techniques.

A variety of data-gathering procedures were employed on this study. First, all available existing data regarding current conditions on the study street were reviewed. Most of this material was in the files of the D. C. Department of Highways and Traffic, but other sources were also used. Material obtained included data on traffic volumes, traffic accidents, signal system features, existing lighting, and right-of-way locations, as well as historical background material.

Then, field crews conducted a variety of actual field studies. Two of these studies involved use of a test car traveling in the traffic flow. In one case, the car was equipped with a digital "Traffic Impedance Analyzer" which recorded vehicle speed, travel distance, and time. Frictional events occurring during the trip also could be entered in coded form by an observer. In the other case, the driver's tension level was continuously recorded by means of a galvanic skin resistance recorder.

The remaining field studies were conducted manually. Included were a series of intersection capacity studies, special studies of traffic interference at problem locations, parking regulation and usage investigations, studies of speed distributions, studies of vehicle occupancy, state-of-registration checks, and accumulation of physical feature and land-use data.

A special study was also made of police power and planning controls which relate to this problem, to determine whether or not suggested street improvements could be legally implemented.

SUMMARY OF FINDINGS

Through study of several efficiently operating urban streets, combined with other available criteria for free-flow and interrupted-flow volumes, capacity curves were developed showing traffic volumes which are considered attainable on a typical urban arterial, given any width. These curves (Fig. 7) make allowances for bus transit operations, and for continued service to intersecting streets and to businesses along the street, including some turning movements. Therefore, in either direction of travel, the curb and the extreme left lanes would carry considerably less traffic than do the remaining lanes; 1,000 vehicles per hour of green signal per 10 ft of width in the curb and left lanes as compared to 1,750 in the lanes between them. Attainment of these volumes would require efficient traffic control techniques and a smooth street surface free of streetcar tracks.

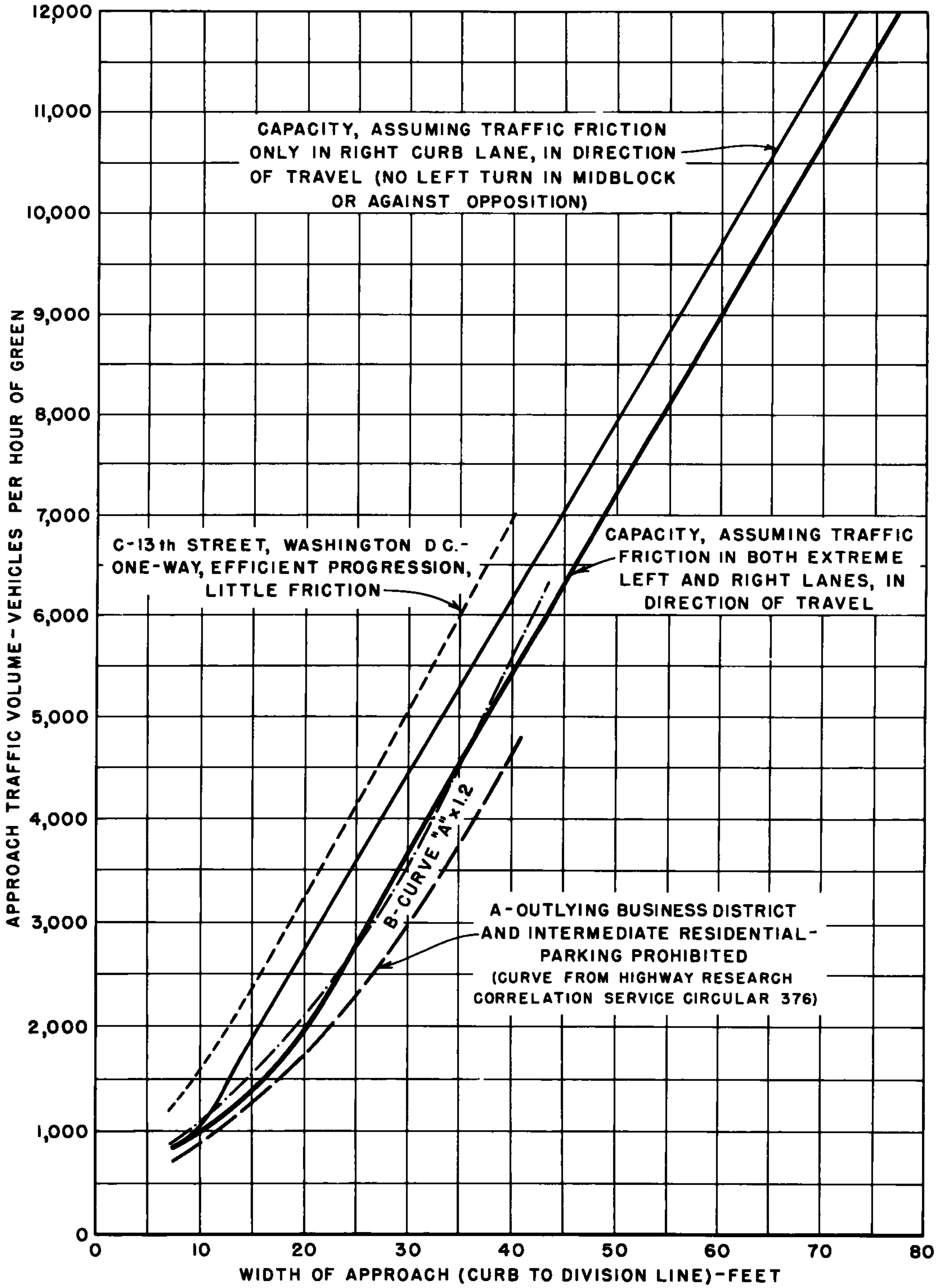

Figure 7. Intersection approach capacities of efficiently-operated two-way urban arterial streets (with progressive signalization, no parking and separate left-turn lanes in addition to width shown where opposing traffic is significant).

The steps that would be required to develop these increased volumes on the street have been classified into three phases in order of increasing complexity and expense. In the first phase, these volumes per lane may not be attained, inasmuch as resurfacing is not considered until Phase 2. They would be attainable in the remaining phases.

Phase 1

In the first phase, the suggested steps do not involve general widening, channelization, and other physical improvements. Rather, they develop more efficient use of the presently available street width at relatively little cost and without appreciable construction.

At present, very few of the intersections are operating at capacity. However, traffic flow friction throughout the street, in midblock as well as at intersections, creates turbulence for all vehicles using the street. This turbulence may cause many drivers to avoid using the street at all. The several frictional factors creating turbulence at the time of the study can be grouped into a few basic categories. These include streetcars and their loading platforms; streetcar tracks; U-turns; turning movements into and out of side streets, parking areas, and driveways; parking and parking turnover; and absence of lane markings. Because these factors produce irregular travel times, efficient signal progression cannot be established and as a result the signals themselves become a serious frictional factor.

Removal of streetcars, along with the platforms, in January 1960, is expected to result in increasing the street's traffic-carrying capability by 25 to 30 percent. However, this step is of localized interest only because streetcars remain in so few cities. In this study, removal of the unused rails is not contemplated until resurfacing is considered in Phase 2.

Other important steps will be described briefly in the suggested order of adoption.

1. Encourage drivers to signal all turns well in advance.
2. Adopt "spot" turning movement controls to alleviate special current problems at several intersections.
3. Change parking regulations. Eliminate curb parking at all times on the sections of the street narrower than 50 ft. Elsewhere, remove parking progressively as necessary. First, "spot" removal of parking at critical points may suffice. Next, complete removal of parking during the rush hours in the heavy flow direction may become necessary. Later, total elimination of parking on both sides during peak periods may be required together with widespread off-peak restrictions. Finally, may come total removal of parking at all times except at night. It is believed that reasonably adequate substitute parking is available except in the area where the narrow street width requires immediate elimination of parking. Here, development of off-street parking facilities is badly needed.

   Prohibit double parking, and parking close to driveways and intersections, on the intersecting streets as well as on the study street itself.
4. Establish a few pedestrian controls.
5. Install lane markings on the existing street, to make full use of the pavement between the curbs and the remaining streetcar rails, and to guide motorists in using the center car track area on the wider part of the street in one of two possible ways, either as a two-way operation or as a reversible-flow segment.
6. Enforce prohibition of U-turns where necessary.
7. Prohibit left turns into and out of minor intersections where they are few in number yet interfere with through traffic.
8. Control turning movements in midblock into driveways and parking areas, though they need not be eliminated except in special cases. The problem here appears to be concerned more with smoothing the internal operations of the facilities served, to eliminate backups into the street, than with changes on the street itself. Where many driveways presently are located close together, serving adjacent facilities, consolidation of access points is suggested.

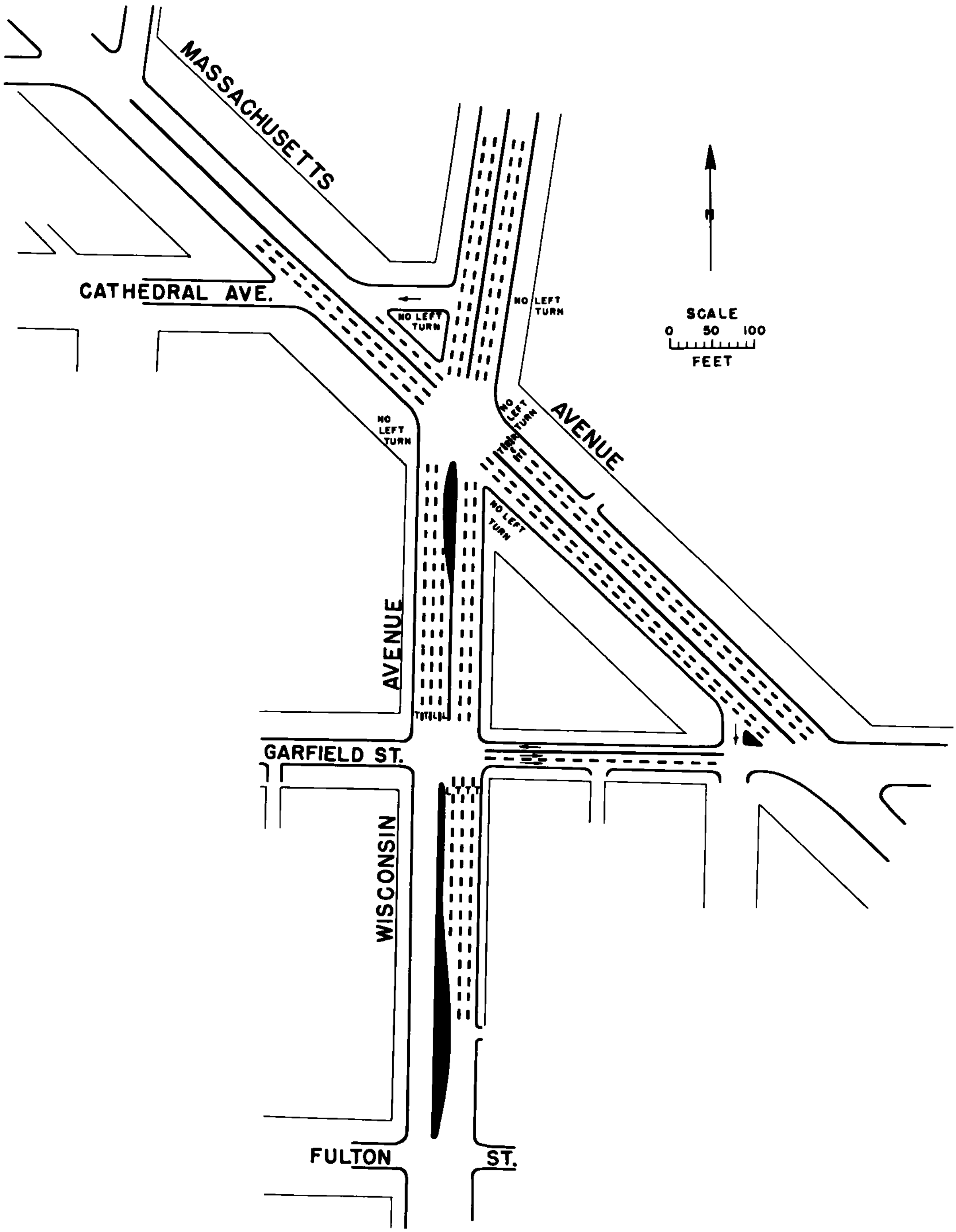

Figure 8. Proposed improvements (Massachusetts Ave.-Garfield St.).

9. Re-time the existing traffic signals to establish the best possible progression, once the foregoing steps have established a more orderly and predictable flow.

10. Make certain intersecting streets one way, particularly where a "Y" intersection is involved.

With all of the foregoing improvements, it is expected that the narrow section in lower Georgetown can accommodate about 900 vehicles per hour in one direction, not far above current peak volumes in this section. A reversible, 3 lane-2 lane, operation of the 56-ft wide section (that between 34th and Calvert Streets) can carry about 1,600 vehicles per hour in the heavy-flow direction.

The main 60-ft wide portion of the street (that from Calvert Street to Western Avenue) might handle an estimated 1,600 vehicles per hour in the heavy direction under balanced flow operation as compared with about 1,150 vehicles per hour currently. If the entire center area now occupied by the car tracks were operated reversibly, then about 1,950 might be accommodated.

Phase 2

The next series of improvements to the study street, grouped into study Phase 2, involves moderate expenditures and some construction. In this phase, it is suggested that signalization be upgraded, that improvements to specific intersections be made to permit them to handle the loads which the now smoothly operating midblock sections can accommodate, that resurfacing be accomplished, and that associated improvements be made. Briefly, the steps contemplated are as follows:

1. Widen the narrow 35-ft and 40-ft sections in lower Georgetown to 44 ft.
2. Install a modern, flexible progressive signal system.
3. Channelize several major at-grade intersections. In most cases, some widening would be involved. (On the study street, the intersections included are those at Q Street, Reservoir Road, Calvert Street, Garfield Street, Massachusetts Avenue, Upton Street, Van Ness Street, Tenley Circle, River Road, and Western Avenue.) Figure 8 shows typical proposed improvements.
4. Resurface the entire street within the existing curb lines.
5. Mark the street for five lanes, for reversible lane operations (3-2), except on the 44-ft section where only four lanes can be provided.
6. Provide bus bays at bus stops.
7. Install a modern lighting system.

With these improvements, the capacity of the improved 44-ft section in lower Georgetown should be about 1,150 vehicles per hour in the heavy direction, and that of the 56-ft segment about 2,100 vehicles per hour. The capacity of the 60-ft street sections, including major intersections, should approach 2,600 vehicles per hour in the heavy-flow direction.

Phase 3

Further improvements to increase capacity involve major expenditures and construction. Grade separations at major intersections, and widening throughout, are required. In practice, these improvements may not function efficiently unless corresponding improvements are made on a few connecting streets to prevent their overloading.

At this stage, few generalized recommendations are possible, because each improvement must be designed to fit specific conditions. For example, for the study street the following improvements are suggested:

1. Reconstruct the Q Street intersection to reduce the "dog-leg." In this one case land taking will be required.
2. Construct a grade separation at Massachusetts and Wisconsin Avenues. Three different designs have been considered in the study. The three are independent, not successive steps of progressive stage construction. One separates only the southbound Wisconsin-to-eastbound Massachusetts left turns, all other flows being at grade. The second design depresses Massachusetts Avenue under Wisconsin Avenue, but leaves the previously mentioned left turns at grade. The ultimate design (Figs. 9 and 10) separates all three of these flows.

At this location, improvement of the intersecting street, Massachusetts Avenue, east of Wisconsin Avenue will very likely be necessary if any one of the suggested grade separations is to operate efficiently.

3. Widen the street within the existing right-of-way lines, with allowance for adequate sidewalks.

a. South of Massachusetts Avenue, varying amounts of widening are possible and necessary. In Georgetown, restricted right-of-way limits widening to possibly 48 ft at most points and only 44 at some. From 34th Street to Calvert Street, a median is not considered feasible, but widening from the present 56 ft to 60 ft could be

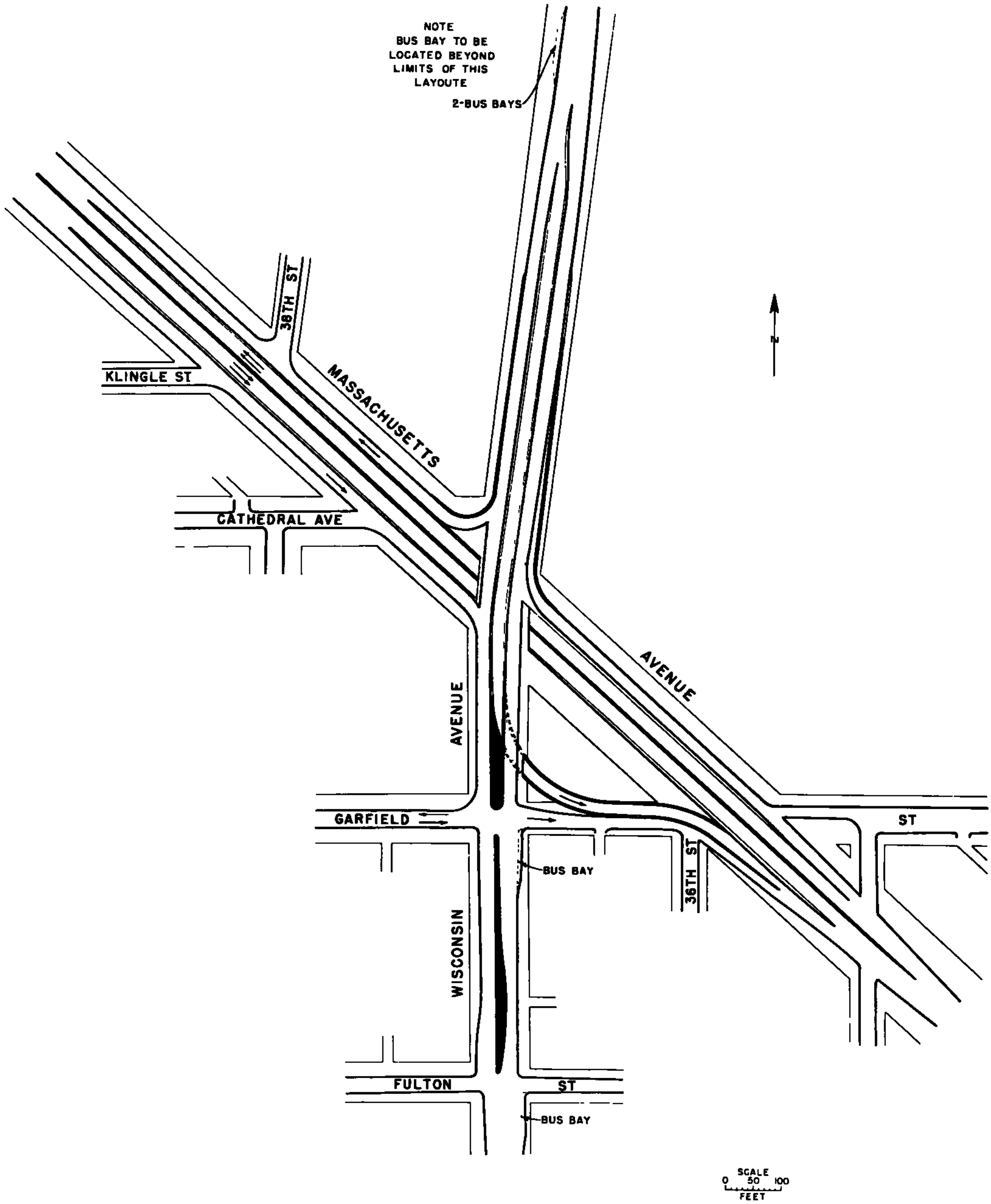

Figure 9. Proposed improvements: full grade separation of all movements (Massachusetts Avenue—Garfield Street).

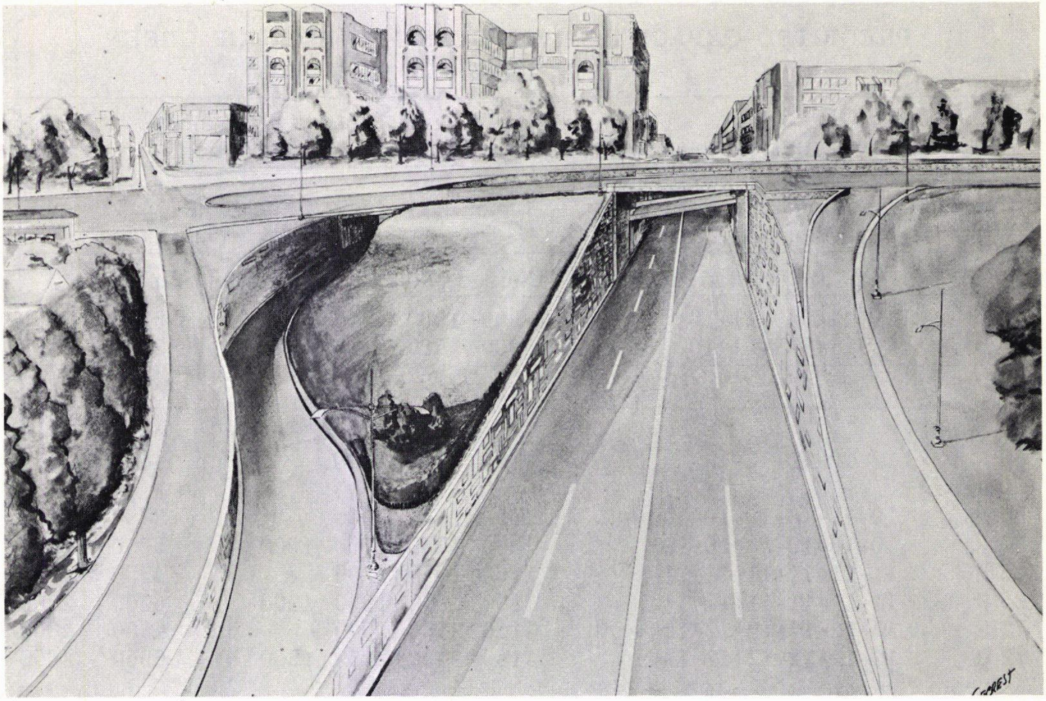

Figure 10. Ultimate design of Wisconsin Avenue at Massachusetts Avenue.

accomplished. Between Calvert Street and the Massachusetts Avenue interchange, the current 60-ft street could be widened to at least 76 ft within available right-of-way limits, with allowance for sidewalks, to provide six 12-ft lanes and, if desirable, a 4-ft median. Widening of the adjacent sections of some intersecting streets might also be needed.

b. North of Massachusetts Avenue, 120 ft of right-of-way generally are available. Four lanes in the heavy direction are needed during peak periods. Either a 4-4 balanced lane operation of eight 11-ft lanes, or a 4-3 reversible operation of seven 12-ft lanes, would be adequate to equal the capacity of controlling major intersections, the latter plan being somewhat superior from a heavy-flow volume standpoint. Appropriate modification of bus bays and of already-widened major intersections is necessary.

TABLE 1

	Traffic Volumes						
	Current Peak Hour-	Phase 1 Peak Hour		Phase 2 Peak Hour		Phase 3 Peak Hour	
Location	VPH in Heavy Direction (avg)	VPH in Heavy Direction	Percent Increase Above Current	VPH in Heavy Direction	Percent Increase Above Current	VPH in Heavy Direction	Percent Increase Above Current
Lower Georgetown	600	900	50	1,150	92	1,200 to 1,300	100-117
Upper Georgetown	1,000	1,300 to 1,600	30-60	2,100	110	2,400	140
North of Mass. Ave.	1,150	1,600 to 1,950	39-70	2,600	126	3,600	213

TABLE 2

PREDICTED CAPACITIES, VEHICLES PER HOUR OF GREEN (NO PARKING)

Curb-to-Curb Width	Width Distrib. into Lanes (Vertical Line Represents Division Line Between Directions of Travel)	Volume Distrib. by Lanes—Heavy Flow Direction: Curb Lane 1	Lane 2	Lane 3	Lane 4	Lane 5	Total, All Lanes	Volume, Opposing Direction—Total
(a) Car Tracks Present but Unused (No Platforms Remaining)								
60 ft	10-11-9+9-11-10	900	1500	800			3200	3200
60 ft	10-11-9-9+11-10	900	1500	1000	500		3900	1800
(b) No Car Tracks								
5 lanes								
60 ft	12-12-12+12-12	1150	2150	1500			4800	2650
6 lanes								
60 ft	10-10-10+10-10-10	1000	1750	1000			3750	3750
60 ft	10-10-10-10+10-10	1000	1750	1750	1000		5500	2000
66 ft	11-11-11+11-11-11	1100	1950	1200			4250	4250
66 ft	11-11-11-11+11-11	1100	1950	1950	1200		6200	2300
72 ft	12-12-12+12-12-12	1150	2150	1500			4800	4800
72 ft	12-12-12-12+12-12	1150	2150	2150	1500		6950	2650
7 lanes								
70 ft	10-10-10-10+10-10-10	1000	1750	1750	1000		5500	3750
70 ft	10-10-10-10-10+10-10	1000	1750	1750	1750	1000	7250	2000
77 ft	11-11-11-11+11-11-11	1100	1950	1950	1200		6200	4250
77 ft	11-11-11-11-11+11-11	1100	1950	1950	1950	1200	8150	2300
84 ft	12-12-12-12+12-12-12	1150	2150	2150	1500		6950	4800
84 ft	12-12-12-12-12+12-12	1150	2150	2150	2150	1500	9100	2650
8 lanes								
80 ft	10-10-10-10+10-10-10-10	1000	1750	1750	1000		5500	5500
80 ft	10-10-10-10-10+10-10-10	1000	1750	1750	1750	1000	7250	3750
88 ft	11-11-11-11+11-11-11-11	1100	1950	1950	1200		6200	6200
88 ft	11-11-11-11-11+11-11-11	1100	1950	1950	1950	1200	8150	4250
96 ft	12-12-12-12+12-12-12-12	1150	2150	2150	1500		6950	6950
96 ft	12-12-12-12-12+12-12-12	1150	2150	2150	2150	1500	9100	4800

Note: At any level, provision of a continuous midblock nontraversable median, together with separate L. T. lanes outside the continuous through lane limits, will increase capacity by 700 vphg. Width of median will be in addition to widths shown.

Median dividers are desirable, provided that their restriction of service to fronting businesses is found acceptable. If the medians are provided, or if pedestrian refuge islands are adopted to aid pedestrians in crossing the wide street, then the reversible plan will not be feasible. The preferred design is an 8-lane divided facility, composed of four 11-ft lanes in each direction plus a 4-ft median, with bus bays and with appropriate widening at important intersections to provide for a left-turn lane.

4. Although not critically needed, a grade separation at Tenley Circle would provide more flexible operation and lower travel times through this busy location, particularly helping Nebraska Avenue cross traffic.

It is estimated that, following Phase 3, the 44-ft street in lower Georgetown can accommodate 1,200 vehicles in the heavy direction, while 2,400 can be handled from 34th to Massachusetts on the 56- to 76-ft street. Assuming that the "ultimate" improvement is adopted at the Wisconsin-Massachusetts Avenue intersection, the 8-lane

TABLE 3

Location	Current Actual Average Speeds: Peak Period Heavy Dir.	Current Actual Average Speeds: Peak Period Light Dir.	Current Actual Average Speeds: Daytime Off-peak Period	Phase 1: Peak Period Heavy Dir.	Phase 1: Peak Period Light Dir.	Phase 1: Daytime Off-peak Period	Phase 2: Peak Period Heavy Dir.	Phase 2: Peak Period Light Dir.	Phase 2: Daytime Off-peak Period	Phase 3: Peak Period Heavy Dir.	Phase 3: Peak Period Light Dir.	Phase 3: Daytime Off-peak Period
				Estimated Future Average Speeds (Volumes at or Below Practical Capacity)								
Lower Georgetown (M-Reservoir)	14	14	13	18	18	16	23	21	22	25	21	22
Upper Georgetown (Reservoir-Massachusetts	19	20	19	24	22	22	30	25	25	30	25	25
North of Massachusetts Avenue (Massachusetts-Western)	20	22	21	25	23	23	30	25	26	30	25	26

divided facility north of Massachusetts Avenue can accommodate 3,600 vehicles per hour in the heavy direction. If this is expanded on the basis of a 60-40 traffic split between directions, assuming desirable achievement of 10 percent of the ADT in the peak hour, the equivalent ADT is 60,000, adequate for the predicted 1980 ADT of 58,000. If the current value of 7 percent of the ADT in the peak hour on Wisconsin Avenue is acceptable, then the equivalent ADT is higher, 86,000. Table 1 is a compilation of the traffic volumes developed in three phases of the study, while Table 2 gives the predicted capacities of the originally-60-ft-wide section for the various improvement levels considered.

Peak hour speeds in the heavy direction, after completion of all improvements considered in the three phases, are estimated to be 25 mph in Georgetown and 30 mph throughout the remainder of the street. Table 3 gives the current average speeds as well as speeds that could be provided by each of the several phases of improvements.

From a research standpoint, it would be both interesting and valuable to use the street as a test track, actually carrying out each of these improvements separately in the order suggested, and making detailed observations to determine the volume increase produced by each. From a practical standpoint, however, time probably would not permit such an incremental approach, even if research funds and manpower were continuously available. Traffic demand is increasing at too rapid a rate to permit a series of minor improvement steps, each necessarily followed by a familiarization period for traffic before useful observations could be recorded. More rapid adoption of improvements is desirable.

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Application of Police Power and Planning Controls to Arterial Streets

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● MILLIONS of dollars have been spent over the years in the development of urban arterial street systems. Unfortunately, the utility, safety, and traffic-carrying capability of these facilities generally deteriorate as the city grows up around them. The factors which contribute to this deterioration are internal (traffic on the street) and external (expansion and construction of residential, commercial, and other land uses near the arterial).

In addition to the general increase in volume of all traffic, urban growth aggravates the problems caused by different classes of traffic using the arterial for conflicting purposes. An arterial street is supposed to facilitate relatively long trips by through traffic at higher speeds than would be possible on a lesser city street. However, as nearby land develops, there is an increasing proportion of local traffic on the arterial. This traffic consists of mass transit and private vehicles bringing people to and from the abutting residences and businesses, the pedestrians, and delivery trucks servicing these roadside uses. Once the arterial is used for these local purposes, there is also the problem of automobiles and delivery trucks parked at the curb.

Probably the main external factor in arterial deterioration is the location of major traffic-generating uses immediately adjacent to the arterial without adequate access arrangements. Some of the examples which are all to familiar in every metropolitan area are (a) shopping centers with access along the entire frontage or with too many curb cuts; (b) closely spaced residential driveways; (c) inadequate loading facilities for businesses; (d) narrow commercial driveways which cause entering cars to back up traffic on the arterial; and (e) parking lots so located that pedestrians have to cross the arterial to get to their destination.

Thus the arterial, which was primarily meant to serve highway users, is used to provide land service to local needs as well. It is not surprising that in trying to serve these two conflicting functions the arterial does not serve either one very well. The through traffic and the local traffic interfere with each other and the result is an inefficient facility which does not adequately meet the needs of the highway users, the abutting landowners or, as a result, the taxpayers in general.

Wisconsin Avenue, in Washington, D.C., which was recently the object of intensive analysis by the Bureau of Public Roads, is a good example of an arterial which has suffered from being used for conflicting purposes. All the manifestations of deterioration mentioned above are present to some degree on this street.

The object of this paper is to explore ways in which police power regulations, access control provisions, and land use and planning controls can be used to help solve this arterial problem. Suggestions are made for applying these measures to the internal and external causes of deterioration in an effort to halt it, and to develop the maximum effectiveness of existing arterial streets such as Wisconsin Avenue.

The authors have indicated how each measure could be extended to its legal limits. However, it must be borne in mind that there are often practical limitations which might preclude adopting regulations even though they are legally justifiable. These practical limits are pointed out in the situations where they are most significant.

REGULATORY AND ACCESS CONTROL PROVISIONS

Developing Freeway Characteristics

The best way to accommodate the heavy traffic of the congested city arterial street would be to convert all arterials into high-capacity freeways. This, of course, is an economic impossibility. However, a look at the nature of the freeway can suggest methods of improving existing city streets.

The freeway, as defined by the American Association of State Highway Officials[1] has three chief characteristics in which it differs from a city street and which contribute to its high traffic-carrying capacity: (a) divided roadways, (b) controlled access, and (c) grade separated intersections. Although none of these freeway characteristics can be fully imposed on an existing city street without great cost, they all can be imposed to a lesser degree on many streets at little cost. The result of partial attainment of freeway standards would not, of course, be full freeway capacity, but it could be a substantial increase in the capacity of most arterial streets.

The inexpensive means of getting the benefit of the three freeway characteristics is the exercise of three police power regulatory measures. The proposed application of the three measures will be briefly presented, followed by a more detailed legal analysis of each measure.

Physically divided roadways eliminate friction between opposing lanes of traffic. Much of the benefit of a divided roadway, as far as an urban arterial is concerned, can be realized by merely prohibiting all left turns onto or off the arterial, except at certain designated places. This minimizing and localizing of interfering turns will allow the movements to be accommodated with as little interference as possible.

The control of private access is another important characteristic of the freeway in that it keeps abutting business from growing up and choking the highway. Along the existing arterial, future adjacent growth can be controlled and guided by zoning regulations, building regulations, driveway permit regulations, and other development control devices. The matter of existing driveways which interfere with the traffic flow is more difficult. In some instances such driveways can be closed if there is other access to the land. At any rate, the landowner can be required to construct driveway entrances which are adequate and which will minimize interference. In this manner, although the result is far short of full control of access, some of the more harmful features of free access roads can be controlled or eliminated and the capacity of the street can be preserved or increased.

The third outstanding factor in the freeway's high capacity is the lack of at-grade intersections. Constructing grade separations is very expensive, especially in built-up urban areas. The effect of at-grade intersections can be reduced, however, by reducing their number. This could be accomplished by closing the entrances to many cross streets and concentrating the cross traffic at more widely spaced, well-designed intersections. A less drastic variation of this would be to allow right turn movements at all cross streets, but to prohibit left turns and cross movements except at a relatively few intersections.

Inasmuch as these proposals are intended to be general and adaptable to any urban arterial, as well as to Wisconsin Avenue, the following analysis of each proposal covers the District of Columbia law and also the general law of the United States. This approach results in a broader development of the concept under consideration and suggests arguments for making such restrictions legal under the police power in jurisdictions where they are now held to be unauthorized by the police power.

The Wisconsin Avenue study is generally limited to those corrective measures which do not require a taking of land or compensable interference with abutters' rights of access. Therefore, use of the power of eminent domain is outside the scope of this report and the following analyses concern the application of control measures under the police power.

1/"A Policy on Geometric Design of Rural Highways." AASHO, p. 632.

Restricting Mid-Block Left Turns

Left turn movements into and out of the traffic stream are a well-recognized source of interference and congestion. If such movements are restricted to specified places, such as intersections, provision can be made to minimize the interference caused by them. There are two ways to prevent left turns between intersections. One is to make them impossible by constructing a barrier in the middle of the road. The other is to make them illegal without physically changing the roadway.

Preventing mid-block left turns does not deprive the abutting landowners of their right of access, but it does make such access more inconvenient and circuitous. For an adjacent business, such as a gas station or parking lot, this more inconvenient access may well mean a loss of business. Does the municipality have the power to impose such regulation? What are the rights of an abutting landowner where such a restriction is imposed?

Court decisions generally hold that prohibition of left turns into and out of private driveways, even where it causes considerable inconvenience or loss of business, is within the authority of a city. Such prohibition, because it promotes public safety and convenience, is a valid exercise of the police power and does not require compensation of affected abutters. Furthermore, it does not make any difference whether the left turns are eliminated by putting a barrier in the middle of the street or by simply forbidding the turns without physically changing the roadway. Some of the cases which developed the rule previously stated involved a law against crossing the centerline[2] which required a landowner to travel five miles to get to his land on the other side of the road, and construction of roadway dividing barriers which affected the business of a trailer court,[3] a truck repair shop[4] and a "truck stop" restaurant and gas station.[5]

There are no District of Columbia statutes or cases on the matter, but the rule that left turns may be prohibited in the public interest seems to have been applied universally by the courts which have tried the question, and it would almost certainly be applied here.

Inasmuch as this regulation is for the good of the community, many, if not all, property owners will agree to it willingly instead of taking the case to court. In the District of Columbia, left turns have been restricted in several instances without objection by the affected landowners. Peak hour left turns into three downtown parking garages and all left turns into and out of a busy driveway on an arterial outside of the downtown area have been prohibited with satisfactory results.

The Wisconsin Avenue Research Project turned up several instances where application of this regulation would be helpful. Left turns into and out of driveways serving gas stations, parking lots, restaurants, stores, and other businesses cause interference at several points along the arterial.

It is emphasized that this part of the study is concerned with the legal authority to make regulations. There may be practical reasons for not prohibiting left turns, such as the desire not to hurt local businessmen, but nevertheless the legal authority to do so does exist.

Closing Driveways

Roadside development has caused the deterioration of many highways. The situation became so bad that a radically new concept of highway engineering—control of access—was developed to combat this deterioration. It would be impractical to try to impose complete control of access on existing built-up city streets. However, some of the benefits of access control could be enjoyed by closing some of the more troublesome driveways along an arterial. Whether and under what conditions a city can close driveways involves the question of what legal rights of access a property owner has in an abutting highway.

2/ Jones Beach v. Moses, 268 N.Y. 362, 197 N.E. 313 (1935).
3/ Fort Smith v. Van Zandt, 197 Ark. 91, 122 S.W.2d 187 (1938).
4/ Holman v. State, 97 Cal. App.2d 237, 217 P.2d 448 (1950).
5/ Iowa v. Smith, 248 Ia. 869, 82 N.W.2d 755 (1957). For diagram and explanation, see HRB Bul. 189, p. 38.

The driveway closure device would be most applicable in situations where a piece of property, such as a gas station or parking lot, has access to both an arterial street and other streets. The effect of closing the arterial driveway would be less detrimental in such a case than in one where the property owner had no other access. The analysis of this proposal then revolves about the question of whether a city is authorized under the police power to close driveways on one street where there are driveways to the property from other streets.

A general statement of the law accepted by all courts is that an abutting owner has a right to construct a driveway to the public street,[6] but that this right is subject to reasonable regulation in the public interest. But the courts, while agreeing on the rule, disagree in its application. Some courts hold that cutting off all access to one abutting street, if it leaves reasonable access from the property to another street, is not necessarily a compensable taking, and may be allowable under the police power.[7] However, other courts applying the same rule hold that there is an absolute right of access to every abutting street, that the right to regulate does not include the right to prohibit, and that all driveways from one street to a piece of property cannot be closed under the police power, even if other access to the lot exists.[8]

The rule, that the closing of all existing access to one abutting street cannot be accomplished under the police power, has the advantage of drawing a sharp line beyond which the police power cannot be exercised. This rule may make things easier for the courts if the problem comes up for litigation, but it seems doubtful whether that advantage should be determinative when it is considered that it is gained at the expense of unnecessary restriction of the highway department in its function of providing an adequate system of roads for the use of the general public.

The other rule, that the closing of all access to one street is not necessarily a compensable taking, does not present any hard and fast line beyond which the police power cannot operate. The question to be decided would be whether the closure was reasonable. The factors to be weighed in making this decision would be the amount of access taken away, the amount of access remaining, the resultant loss to the property owner, and the resultant gain to the highway users and the general public. If the closing of all access to one street would not work an unreasonable hardship on the individual owner, it would be allowed. If on the other hand such closure would cause an unreasonable injury to the individual, compensation would be required. This element of flexibility, where the exercise of police power is limited, not by a set mechanical rule but by the equities of the situation, would promote increased highway effectiveness, while protecting the rights of abutting landowners.

In applying this approach to a particular problem, for instance a customer parking lot for a store, the highway department would have to make a detailed analysis of the situation. Traffic counts, interference counts, and other engineering techniques could be used to show clearly the amount of interference with through traffic which results from the use of the driveway to the lot. From this information the department can make an estimate of the benefit which will accrue to the public from the closing of this driveway.

Studies of possible alternate access arrangements would be made to determine which arrangement minimized the damage to the landowner. After this device had been used for some time, case studies could be developed which showed the actual effect of such driveway closure on various businesses. The department would then have an authoritative and objective estimate of the benefits and losses to be expected from

6/This does not refer to new construction which is designated as controlled access highway. Several States have held that no right of access arises in such a case. See HRB Bul. 189, p. 31.

7/San Antonio v. Pigeonhole Parking of Texas, 311 S.W.2d 218 (1958); Alexander v. Owatonna, 222 Minn. 312, 24 N.W.2d 244 (1946); Farmers-Kissinger Market v. Reading, 310 Pa. 493, 165 Atl. 398 (1933); Wood v. City of Richmond, 148 Va. 400, 138 S.E. 560 (1927); Socony v. Murdock, 165 Misc. 713, 1 N.Y.S.2d 574 (1937).

8/Brownlow v. O'Donoghue, 276 F. 636 (D.C. Cir. 1921); Newman v. Newport, 73 R.I. 385, 417, 57 A.2d 173, 181 (1948); Elder v. Newport, 73 R.I. 482, 57 A.2d 653 (1948).

closing the driveway. If the loss to the property owner is not unreasonable when compared with the resulting gain of the traveling public, this rule will allow closing of the driveway under the police power. When these estimates and comparisons are presented to a landowner, he might be convinced that the loss of one of his driveways would not unduly hurt him and that he should not object. However, if he does object to the extent of going to court, the facts which the court needs to reach a just conclusion have already been developed and organized. This procedure should lead to orderly settlement of these cases.

On Wisconsin Avenue there are several corner businesses, such as gas stations and parking lots, which have driveways to another street. The only D.C. case on closure of such driveways,[9] unfortunately, adopts the rule that compensation must be made when all access to one street is taken. But the case was decided in 1921 and urban transportation and highway law have changed greatly since then. In view of this, the courts might be prevailed upon to adopt the other rule (closure under the police power) if a detailed study clearly showed that such adoption would further the public interest without seriously injuring the private parties involved.

Of course, such closure is a rather drastic step, and it would be much better to control the use of driveways so that they will not develop into extreme points of interference and to remedy these trouble spots, if they do develop, by restricting only some of the turning movements or by redesign of the driveway. This police power device, however, does serve as a last resort which can be used to prevent an access point from choking the life out of a highway when the problem has deteriorated beyond the stage where lesser measures will help.

Barricading Cross Streets

The third method of increasing the efficiency of an arterial street is to restrict or prohibit conflicting vehicle movements at certain cross streets. Several alternate degrees of restriction were mentioned in the section on "Developing Freeway Characteristics." Each is treated in more detail here and also the question of legal authority for such restriction is considered.

One possibility is to barricade entrances to most of the side streets and force traffic to enter, leave, and cross the artery at fairly widely spaced intersections. This would eliminate all the minor intersection interference and the remaining street crossings could be designed to handle the traffic as efficiently as possible for an at-grade intersection.

On many arterials, traffic during the day is light enough so that vehicles entering and leaving cross streets do not cause much interference, but these same movements are very troublesome during rush hours. In this situation a better solution is to barricade the cross streets only during rush hours. This would best serve the needs of the arterial traffic when it is heaviest without interfering to any great degree with the local neighborhood traffic on the cross streets.

If complete barricading of the cross streets is not warranted on a particular arterial, even during rush hours, all left turns and cross-movements could be prohibited, while allowing right turns either onto or off the arterial. This regulation could be set up permanently, or just during rush hours. If it is to apply all day, a barrier island could be constructed on the arterial, through the intersection. Such island might be objectionable, however, especially if reversible flow is used on the arterial.

Probably no one of these variations would be universally applicable to a particular city or even to a particular arterial street. At different intersections different movements may be the cause of interference. For instance, at one intersection there might be plenty of room for right turns and the only interference is caused by left turns and crossing vehicles. Here only the troublesome movements would have to be prohibited. At another intersection on the same arterial right turns, either because of their number or the shape of the intersection, may cause congestion and here complete blocking of the entrance would be the appropriate regulation.

9/Brownlow v. O'Donoghue, supra, note 8.

A thorough search turned up no cases or statutes which concerned barricading one end of a street. There is, however, a considerable body of law dealing with the abandonment, vacation, or closing of streets, and principles which apply to barricading can be drawn from this law of vacation.

Vacation or abandonment of a portion of a street is a much greater interference with the rights of, or at least the convenience of, the abutting landowners and the traveling public than is the closing of one entrance to a street. If the street is merely blocked at one end, the abutters' access to the street is not disturbed as it would be by vacation. The other interested party, the highway user, is also hurt more by vacation than by barricading. If a street is vacated, it is no longer part of the highway system; if the road is only barricaded at one end, the road user can still traverse the street from one end to the other. Thus, it would seem that, because vacation is a more severe restriction than barricading, the power to vacate would include the power to barricade. To clear up any logical difficulty in inferring the power to barricade from the power to vacate, the barricading could be considered as vacation of a very short segment of the street.

Whether a highway can be vacated depends on considerations of its necessity or public utility. It is generally the law throughout the country that roads may be vacated[10] if they are useless, inconvenient, or burdensome.[11] If a cross street is hampering the heavy flow on an arterial while benefiting only the relatively few drivers who use it, the net effect of that street remaining open is burdensome and probably dangerous. This, under existing law, would give the city the right to vacate the street and, it follows from the reasoning developed in the preceding paragraph, also the right to barricade on end of the street.

The Commissioners of the District of Columbia are authorized by statute[12] to close a street or highway if that street becomes useless or unnecessary. This fits the general pattern of law developed in the foregoing, and it follows that the District of Columbiä also has the authority to barricade cross streets.

The part of the street in the same block as the barricade is effectively turned into a dead-end street or cul-de-sac, and the same rules of compensation to abutters are assumed to apply. There are many decisions to the effect that, unless an owner retains access in both directions at least to the next intersecting street, any decrease in value resulting from a cul-de-sac is "special" injury and requires compensation to the owner, even though reasonable access may be available in one direction.[13]

This is a controversial area, and there seems to be a trend toward the view that the mere creation of a cul-de-sac is not of itself sufficient to entitle an owner to compensation and that the real question is whether he still retains reasonable access to the general system of highways.[14]

The creation of a cul-de-sac and the creation of a one-way street have similar effects on the abutting property. The owners still have their old access to the street, but for some purposes their access to the general highway system will require some circuity of travel. There are a tremendous number of one-way streets in this country, but there are no cases in which property owners were compensated because the streets they abutted were made one-way. Inasmuch as the infringement on the enjoyment of

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10/A. T. & S. F. Ry. Co. v. Shawnee, 183 F. 85 (8th Cir. 1910); Lockwood v. City of Portland, 288 F. 480 (9th Cir. 1923).

11/68 A.L.R. 794.

12/District of Columbia Code 7-401.

13/Okla. Turnpike Authority v. Chandler, 316 P.2d 828 (1957); Coy v. Tulsa, 2 F. Supp. 411 (1933); Felton v. State Highway Board, 47 Ga. App. 615, 171 S.E. 198 (1933); Cartmell v. Maysville, 231 Ky. 666, 22 S.W.2d 102 (1929); Beals v. City of Los Angeles, 23 C.2d 381, 144 P.2d 839 (1943); Bachich v. City of Los Angeles, 23 C.2d 343, 144 P.2d 818 (1943); 93 ALR 639, 150 ALR 644, at 651.

14/Dept. of Highways v. Jackson, Ky., 302 S.W.2d 373 (1957); Spicer v. State, 8 Misc.2d 930, 169 N.Y.S.2d 128 (Ct. of Claims, 1957); Warren v. Iowa State Highway Comm., 93 N.W.2d 60 (1958); Handlan Buck Co. v. State Highway Comm. of Missouri, 315 S.W.2d 219 (1958). See also 93 ALR 639; Paper on compensability of interference with access by H.H. Krevor, Asst. General Counsel, BPR, Oct. 13, 1959.

private property rights is similar in both cases, and it is well established that no compensation is due for the establishment of one-way streets, it follows that no compensation should be paid merely because a landowner is placed on a cul-de-sac and that the second rule is the better one. This is supported by the fact that in the usual urban grid street pattern the creation of a cul-de-sac is almost no inconvenience to the abutting owners because there are plenty of alternate routes nearby.

Rush Hour Freeways

These three proposals, of course, will not all be useful in all situations. Differences in traffic patterns, physical characteristics of streets, legal authority, and the lengths to which civic authorities are willing to go to alleviate traffic problems require that different measures be applied to different arterials, and even to different parts of the same arterial. But by adapting and combining variations of these proposals, and of the principles which gave rise to the proposals, freeway characteristics can be developed to some extent in many existing arterials.

An example of such variation would be the institution of all three proposed regulations—left turn restriction, driveway closure, and street barricading—for the rush hours only. The resulting "rush hour freeway" would best provide traffic service to highway users when their needs were greatest without unduly sacrificing the arterial's other function of providing land service for local traffic and abutting owners. Of course such a rush hour freeway might not be adequate for an arterial which carried heavy traffic all day long. This illustrates that the applicability of these proposals depends on the local situation and that this situation should be carefully analyzed to determine which measures will do the most good.

PLANNING CONTROLS

There are a number of land use and planning control measures that can be used to increase the efficiency of arterial operation. The purpose of this section of the paper is to analyze legislation and other legal material pertinent to these measures in the District of Columbia and in other jurisdictions, and to develop legal tools which can be used to increase the traffic-carrying capability of arterial streets and highways.

Implicit in this analysis is the need to investigate many techniques and procedures that might not prove helpful in the situation at hand. Thus, subdivision regulations, conditional use of access permits, restrictive covenants, easements, development rights, and many of the regulations for the control of development did not, even after a thorough study and attempt to extend existing uses and procedures, seem to be of help in solving the problems encountered in the Wisconsin Avenue corridor. For this reason these measures are not discussed. However, it should be stressed that if this arterial went through undeveloped areas these measures would be of considerable use and help.

The land use control techniques that were found to be of use are considered and an attempt is made to develop ways to increase the effectiveness of Wisconsin Avenue as an arterial.

Zoning

Zoning, a government regulation of the uses of land and buildings according to districts or zones, has in the District of Columbia three purposes of special importance:

1. To lessen congestion in the streets;
2. To prevent undue concentration of population; and
3. To promote the general welfare.[15]

Zoning regulations should be responsive to transportation requirements. The development of a city and its street system are closely interrelated. Urban development, even with good zoning regulations, will be stifled by an inadequate

15/Zoning Act of June 20, 1938 (52 Stat. 797), as amended.

street system. On the other hand, haphazard development under an inadequate zoning ordinance will reduce the effectiveness of an otherwise adequate street system. Thus, zoning programs and street systems, if not coordinated, will each tend to reduce the effectiveness of the other. Zoning regulations formulated with transportation requirements in mind can help prevent the zoning and highway programs from working at cross-purposes, and thereby help the community reap the full benefits of both programs.

This section on zoning is primarily devoted to exploring and developing this relationship between zoning and the arterial system and to indicating ways in which zoning can be used to promote the degree of utilization of an existing arterial street. This analysis has been applied to these three general areas of zoning where significant improvement seems to be most possible: (a) provision of adequate parking for new structures; (b) achievement of better use of existing streets; and (c) development of a balance between land use and transportation.

Adequate Parking and Loading Zones for New Structures

Arterials are intended primarily for moving traffic, but unfortunately they must usually serve, as truck loading zones for adjacent businesses and as storage areas for passenger cars. Three important uses compete for curb space: loading, parking, and traffic movement, the latter both pedestrian and vehicular. Wisconsin Avenue is a striking example of an arterial where these conditions exist and where the traffic-carrying capability suffers drastically as a result. Hence, the recommendation is often made that parking and loading be moved to off-street locations in order to reserve street space for the movement of vehicles.

Such a regulation should be accompanied by an attempt to provide adequate off-street parking and loading areas. The extent to which zoning may provide the needed solution in the District of Columbia has been well documented by Lewis in a recent study.[16] Others have outlined these principles also and for a number of years have called for more extensive utilization of zoning powers in programs that seek to solve the parking problem.[17]

Recommendations usually encourage:

1. Development of adequate parking facilities for existing buildings of high residual value.
2. Provision for adequate parking for all new or substantially altered buildings.
3. Authorization (or prohibition) of the establishment of parking accommodations as a separate property use either in a parking district or zone, or in some other authorized district or zone.
4. Establishment of entire districts adjacent to commercial areas, dedicated to parking or to a combination of parking and residential uses.
5. Regulation of parking areas in commercial or industrial zones which abut residential property.
6. Adoption of transitional zones where parking uses are permitted in a residential zone along and within a specified distance from a commercial or industrial district.
7. Development of a program providing special incentives (a) for creation of off-street parking facilities to replace curb parking spaces, and (b) for disposing of obsolete structures with parking inadequacies that cannot be remedied.

Each of these could help solve a significant problem prevailing currently along the

16/ Lewis, Harold M., "A New Zoning Plan for the District of Columbia." Washington Zoning Revision Office, Washington, D.C. (1956).

17/ See generally: "Parking Requirements in Zoning Ordinances," HRB Bul. 99 (1955); "Parking Guide for Cities," U.S. Department of Commerce, Bureau of Public Roads (1956); "Parking- Legal, Financial, Administrative," Eno Foundation (1956); Mogren and Smith, "Zoning and Traffic," Eno Foundation (1952); "An Analysis of State Enabling Legislation of Special and Local Character Dealing with Automobile Parking Facilities," HRB Bul. 7 (1947); "Zoning for Parking Facilities," HRB Bul. 24 (1950); "Off-Street Parking: Legislative Trend and Administrative Agency," HRB Bul. 48 (1952).

Wisconsin Avenue arterial. Since even a partial solution of these problems would ease the parking situation along the corridor, adoption of the recommendations would tend to offset the disadvantages of removal of curb parking on the arterial.

The present District of Columbia zoning regulations permit action on most of the recommendations, although new legislation specifically responsive to arterial problems would enable adoption of even more effective measures. For example, recommendations 2 through 6 can be adopted to some extent without additional authority. On the other hand, broadened authority would permit more effective steps to accomplish objectives 2 through 6, and is necessary to accomplish objectives 1 and 7.

Taking the proposals item by item, accomplishing the first objective would require the amortization, as nonconforming uses, of existing buildings with insufficient parking spaces. New legislation specifically covering this course of action would make adopting it more feasible. The second recommendation is covered by sec. 7202[18] which provides that "on and after the effective date of these regulations all structures shall be provided with parking spaces" as specified in the section. Effectively administered, this provision should result in meeting the second objective. Authority to adopt proposals 3 and 4, although not as broad as might be desired, does exist. See, for example, sec. 3104[19] on the R-4 district, especially subsection 3104.44. Likewise the regulations cover recommendation number 5. The sixth can be accomplished at least to a limited degree by taking advantage of subsection 3101.48 and Article 74.[20] And finally, to achieve the important objective covered in recommendation 7, it would seem to be necessary to obtain new legislative authority setting up these programs in specific terms.

Generally, even though a more effective parking program could be adopted under broadened authority, the better approach might be to develop a plan of action going to the limit of existing authority. This action program could then, even while it is getting results, be evaluated and used along with other studies to determine the need for new legislation. Should such a need exist, the same studies would be of use in supplying the substantive know-how for drafting effective enabling legislation.

Achieving Better Use of Existing Streets

Removing curb parking from a traffic arterial is an obvious but very effective method of achieving better use of existing streets. It was treated separately because the important role of parking in urban transportation warrants special emphasis. The purpose of this section is to point out the weaknesses of a zoning ordinance as far as traffic needs are concerned and to evaluate the various proposals that have been made on how to use zoning to meet traffic needs. Some of these weaknesses and the benefits that will accrue to the arterial if they are overcome are discussed in the following.

A. Inadequate front yard setbacks in blocks terminating at key intersections of the major thoroughfare plan and lack of control over the build-up of structures on corner lots.

This condition is usually the result of a failure to coordinate zoning and the arterial street plan. With effective coordination, setback requirements can aid in meeting traffic needs by providing extra space for later enlargement of the intersection without excessive cost or building damages if the property must be condemned. In prescribing setbacks, space should be allowed both for street improvements and for replanting and landscaping as well. Also control over build-up of structures on corner lots can main-

18/ Zoning Regulation of the District of Columbia, effective May 12, 1958, adopted by the Zoning Commission under and by virtue of the authority conferred upon it by an Act of Congress, approved June 20, 1938, as amended. No attempt is made in this report to evaluate the requirements for parking spaces, done comprehensively in the Lewis zoning study, but instead it is recommended that an adequate parking program be devised and the ability of the zoning ordinance to support the program thereafter evaluated.

19/ Ibid.

20/ Ibid.

tain sight distances and otherwise limit the creation of hazardous conditions. And, finally, combination of control over build-up and adequate setback requirements permits efficient administration of curb opening and control of development programs.

B. Uncontrolled location and design of curb-cuts.

Zoning can supplement a curb-cut control procedure with the objective of reducing to a minimum openings detrimental to the safety and efficiency of the arterial. For example, large traffic generators should not be allowed to locate at key intersections.

C. "Strip commercial or business districts" running along the artery with a shallow depth, back from the road, of 100 to 200 ft.

This type of "strip zoning," evident on most major arterials, including Wisconsin Avenue, excludes the desirable shopping center cluster and encourages the undesirable "road towns."

In addition to adopting provisions to alleviate these conditions, there are many other positive steps that can be taken to make zoning work to meet traffic needs. For example, where new and remodeled buildings are required by zoning to provide off-street parking, the municipality through a public orientation program could sponsor a plan calling for a pooling of required parking stalls, thus permitting joint operation of a large parking lot or garage.

Use of Zoning to Equate Urban Land Uses and Transportation Facilities

Proper planning for the correction of defects in existing street systems requires an awareness, by those responsible for the planning, of the functional differences and relationships between streets and the zones they serve. That zoning and an arterial system are closely related is borne out by the ability of each to render the other more, or less, effective. For example, a basic purpose of zoning has been to promote control over population density. On the other hand, control over density is also basic to maintaining an adequate transportation system. Since density controls can be made unworkable by an inadequate arterial system, and an arterial system can be rendered ineffective by weak or nonexistent density controls, it is clear they are interdependent. Keeping these two components of the municipality's comprehensive plan in balance must be a prime objective of sound planning.

There are many facets to equating urban land uses and the transportation facilities that serve them, and an exhaustive analysis would not be wholly pertinent to this study of the Wisconsin Avenue arterial. However, two objectives of zoning, land use and density controls, are so closely related to achieving the highly desirable balance between zoning and transportation that they warrant special attention. The following observations on these two functions of zoning refer to conditions encountered during the Wisconsin Avenue research; however, to keep from limiting the analysis, specific examples are not used.

Stability of Land Use.—Planning must reflect changing conditions, and flexibility is an important attribute of any usable comprehensive plan. Since "total planning" must have these characteristics, it seems hardly necessary to point out that land use planning, an important component of comprehensive planning, must be capable of reflecting changing conditions. Nevertheless, planning efforts will fail unless, within certain limits, stability is also a goal of land use planning. A degree of stability is necessary, for example, to provide time for developing a street arterial system sufficient to serve the various zoning districts with efficient and convenient movement of people and goods. Once the system is developed, it can remain sufficient only so long as land use and other conditions are not allowed to change in such a way as to render the system ineffective.

No street or thoroughfare system will remain sufficient if competing demands for land use remain uncontrolled. The number and type of new buildings in congested areas must be controlled. Unfortunately, however, land use controls frequently permit too dense a grouping of large traffic generators, clearly causing traffic congestion. This grouping may occur outside the boundaries of the district where the congestion occurs, the congestion resulting from too much traffic passing through the district or neighborhood. Traffic congestion, in turn, is a major cause of deterioration and blight, thus calling for remedies more expensive by far than properly conceived and administered planning and zoning would have been in the first place. Nevertheless, the zoning ordinance and administration that takes this cause and effect relationship into account with an action program is rare indeed, and although the D. C. ordinance purports to do so, numerous neighborhoods congested with traffic border Wisconsin Avenue.

Density Controls.—A basic purpose of zoning and planning is to promote control over population density. Population density must be coordinated with available feeder roads and access roads to major thoroughfares and freeways in order to insure the continued efficient operation of the street and arterial system.

When large apartments are involved instead of single family residences, this relationship becomes even more significant. This is clearly the situation along Wisconsin Avenue where transportation problems have been worsened considerably by zoning large portions of the corridor for apartments.

In addition to controlling population density, it is important to control the density and location of large traffic generators both with respect to amount and to type of traffic generated. In fact, it appears correct to say that a zoning plan which does not have as a partial purpose the distribution of major traffic generators is not a completely adequate and properly conceived ordinance. Intelligent dispersal of traffic generators will lessen congestion because the volume of traffic the urban street must accommodate is directly related to the height, bulk and function of the buildings comprising the community. Further, if the character of traffic generated by the use is accepted as a criterion for inclusion in, or exclusion from, the various zoning districts, these districts can then be placed so as to reduce intermingling of various types of traffic on the same facility.

The corollary to this, of course, is that the zoning must provide elsewhere districts for the improvements not allowed in existing congested areas. But these zoning districts must be located geographically so that they do not overload existing or available arteries. The land use study conducted as a part of the Wisconsin Avenue research portrays vividly the need for a planned dispersion of traffic generators. However, a geographic distribution of traffic generators is not by itself sound planning. The distribution must have at least as a partial purpose the improvement of traffic conditions. Nothing is gained by moving, for example, a commercial venture to a location that will soon become virtually inaccessible for many residents in the market area.

Zoning and the Arterial Street System as Planning Tools

Implicit in balancing urban land uses and the transportation facilities that serve them is the use of both zoning and the arterial street system to aid in achieving planning goals. It is well known that, when coordinated with zoning, a street or highway, whether controlled access or not, can be used to give the city form and pattern, to demarcate land uses, and to protect neighborhoods by establishing barriers to the entrance of incompatible land uses. The research needed to apply these principles to Wisconsin Avenue was not performed as a part of this study. However, one significant city planning question kept recurring, especially during the land use study. Is the Wisconsin Avenue arterial giving this area of the District of Columbia the form and structure that sound planning goal analysis would prescribe?

Research Needed to Make Zoning Responsive to Needs of an Arterial System

A few of the critical needs in the field of zoning demanding immediate research are as follows:

1. To devise measures to determine the effect on the traffic requirements of a particular property of rezoning from less to higher intensity of use.
2. To study the relation between zoning and highway obsolescence and to establish a basis for realistic limits of land development.
3. To investigate further the friction between transportation and land uses as evidenced by the location of volumes, points of congestion, accidents and delays.

4. To lay a ground work for a new concept of zoning classification that will result in zoning districts adjacent to arterials, as well as at key intersection areas, that meet the needs of highway transportation.

5. To determine ways and means to develop, in the courts, new criteria responsive to traffic problems to be used by the courts when determining the validity of zoning actions.

Conclusion

Zoning, it seems clear, does have substantial promise as a means for maintaining the traffic-carrying capability of an urban street. Properly employed zoning can help achieve a desirable balance between (a) traffic generators of all types and sizes, (b) street capacity for moving vehicles, and (c) off-street terminal facilities for standing vehicles. But none of these goals can be accomplished unless the zoning ordinance is administered in a manner that recognizes the problems and needs of a highway transportation system, and unless much needed research is conducted.

Urban Renewal

The Wisconsin Avenue arterial, as the land use study shows, is bordered by development for the complete length of the District of Columbia portion of the arterial. For this reason, the more obvious benefits resulting from effective use of subdivision regulations are not available in this instance, and subdivision controls are therefore not discussed in this paper.

There is a possibility, however, that neighborhood design standards, similar to standards included in subdivision regulations, for areas undergoing a private renewal process could be developed and profitably promulgated. These standards would require that the private efforts be directed towards desirable goals. Since conservation and rehabilitation programs normally call for some public contribution, what could be more significant than making a part of this contribution the converting of the neighborhood street system from a grid pattern to a limited and controlled access pattern? Properly handled this approach could give the close-in neighborhood many desirable attributes. If this rehabilitation is undertaken along with adoption of meaningful density controls, significant strides towards lessening congestion can be made. This by itself will aid considerably in halting creeping blight.

Urban renewal includes at least four techniques:

1. Redevelopment—demolition and rebuilding in a project area.
2. Housing law enforcement—enforcing of municipal codes and ordinances in a uniform manner to insure maintenance of prescribed standards.
3. Rehabilitation—remodeling and renovating existing structures in a neighborhood or project area.
4. Conservation—preservation of existing structures.

Conservation and rehabilitation programs are frequently conducted together where a community wishes to continue the use and pattern of an area or neighborhood. Among the elements of a conservation program is a neighborhood plan conforming to the community's comprehensive plan providing for the installation of community facilities, demolition of unsound structures, removal of adverse uses, structural rehabilitation, new construction, and relocation of structures. Also important, of course, is an effective housing law enforcement program.

Most conservation and rehabilitation programs embarked upon today have not involved a realignment of the neighborhood street pattern. However, some have closed off existing streets, constructed cul-de-sacs, changed a four-street intersection to two 90-degree elbow turns, to obtain curved street alignment, and made other street improvements resulting in better neighborhood conditions. If the neighborhood street pattern is changed in this manner to increase the amenities of the neighborhood, the access control provisions outlined above that are so helpful in maintaining the traffic-carrying capability of an arterial, can be obtained at the same time. If the objective of aiding transportation is incorporated in the conservation and rehabilitation program, the result will be not only to aid the arterial system, but also to further the objectives of the conservation and rehabilitation program.

To achieve this goal, it is necessary to develop a two-way exchange of ideas between the local and Federal administrators of the housing and renewal legislation and highway officicials. This interchange of ideas should provide the groundwork for a cooperative use by these authorities of the arterial system as a planning tool to aid the urban renewal and housing official, and of the housing and renewal techniques to aid the traffic official.

The always desirable balance between land use and the transportation system serving it can be furthered by cooperative effort during the redevelopment process. If reuse of the land is made to be in balance with available transportation facilities, the benefit will be twofold. The redevelopment will be aided in accomplishing its objective because served by adequate transportation facilities and, in turn, these facilities will not be overtaxed. Such balance was probably intended by the drafters of the legislation to follow naturally as a result of the requirement that the renewal be in accordance with a comprehensive community plan.[21]

The existence along Wisconsin Avenue of a large privately renewed community (Georgetown) suggests the possibility that private renewal programs, encouraged by the application of rehabilitation and conservation techniques, could be generated in other areas along the corridor. These adjacent neighborhoods would then become controlled access neighborhoods with the accompanying favorable access and street design provisions.

Frequently, some of the traffic generators causing the most serious congestion will be located in blighted areas adjacent to the arterial. When this situation exists a great deal can be accomplished, through redevelopment, to alleviate congestion and promote balance between the arterial system and the land uses the system serves. Because congestion is a cause of blight, these areas should get a high priority. Such conditions may, or may not, obtain along Wisconsin Avenue, but the possibility should be investigated.

Official Map

The recommendations made in this report have been limited to measures that would not require acquisition of additional right-of-way. Nevertheless, should future traffic requirements necessitate either additional lanes or a parallel facility, additional property would be needed. Control of the building of structures in the beds of proposed improvements, prior to the time that the governmental body is in a position to acquire the land, can be accomplished through a competent use of mapped street powers, available if proper enabling legislation exists.

Mapped street powers can be used to prevent the owner from building in the areas which the city proposes to acquire at some future date. Compensation is paid him for property taken, but not for improvements made subsequently to the filing of the official map.[22]

The use of mapped street powers in connection with an arterial street system would

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21/ Sec. 105(a) of the Housing Act of 1949, as amended, provides that redevelopment project loan and grant contracts shall require a general plan to which the project conforms. 63 Stat. 416 (1949), as amended, 42 U.S.C.A., Sec. 1455(a) (1957).

22/ The procedure set forth in the State of Wisconsin official map law is typical of the usual procedures. The official map authorized by the 1947 Wisconsin law (Wis. Stat. 62.23(6)) shows existing streets, highways, parkways, parks and playgrounds. For the purpose of preserving the integrity of the official map, no permit may be issued for any building in the bed of any street, highway or parkway shown on the map. A landowner desiring to construct a building in the bed of a mapped street must apply to the city for a permit. If denied, he may apply for a variance and, if he can prove that his land is not yielding a fair return, the board of appeals may grant a permit for a building which will increase as little as practicable the cost of opening the street. The permit is to be denied where the applicant will not be substantially damaged by placing his building outside the mapped street, highway, or parkway.

permit substantial savings when the facility is expanded or reconstructed. For example, strip development along the arterial could be limited in a manner more strict and sure than zoning permits, since improvements can be limited altogether or at least kept to a minimum. Additionally, it is important to remember that although there are many ways and means of controlling access to arterial streets, each of these methods can be furthered by using them in connection with mapped street powers.

Control of Development

Roads and highways without full control of access make up the bulk of the highway transportation system. Billions of dollars have been spent on these roads. Highway authorities have for years recognized the deterioration of these roads as traffic-carrying facilities resulting from uncontrolled and haphazard frontage developments. The only control of this growth has been a limited use of zoning, subdivision regulations, and other regulatory devices. With traffic facilities worth millions of dollars becoming obsolete annually, the need for an effective method of controlling roadside or strip development has become what is probably the most pressing problem confronting highway officials today.

A recent trend in planning that is especially responsive to this need is the granting of authority for administrative control of development along existing and proposed roads and streets in both cities and counties. This control can be exercised in a workable manner by requiring that any building permit, issued for a structure along a major arterial, be referred to the official responsible for operating and maintaining the arterial for his report and approval. This approval may be given subject to stated conditions with reference to curb cuts or other means of access. Also approval should not be granted without taking into consideration the prospective character of the development, the traffic which it will generate, the effect of such traffic upon the existing street system, the design and frequency of access, and the extent to which such development may impair the safety and traffic-carrying capability of the arterials affected. Of course, a provision of this nature should be drafted so that requirements may be varied where there are practical difficulties or unnecessary hardships in the way of carrying out the strict letter of the traffic and street officials' report.

Although development control measures cannot correct existing arterial problems, they can be effectively used on Wisconsin Avenue, or any arterial, to avoid future problems. Specifically, development control measures incorporating the principles outlined can aid in guiding the development of major traffic generating uses that create traffic jams at points of access. Such control measures can be used to require adequate access features for gasoline stations, parking lots, shopping centers, and other roadside developments; and to require developers of residential and commercial subdivisions to provide for access to the lots adjacent to the arterial roads from a side street rather than from the arterial road.

The District of Columbia Zoning Regulations require that detailed plans of all curb cuts and driveway openings be submitted to the Highway Department for approval (sec. 7206.8). The standards set forth in the Zoning Regulations designate minimum widths and maximum grades for residential and nonresidential driveways (secs. 7206.6 and 7206.7) and require that entrances to parking garages be minimum distances from street intersections and alleys (sec. 7402.12). These driveway requirements, as spelled out in the Zoning Regulations, vary only with the broad use classifications of residential and nonresidential. They do not mention the type of street with which the driveway is to connect, the traffic on that street, or the volume or influence of the traffic which will use the driveway. Thus, although the District of Columbia Highway Department does have some control over driveway entrances, it does not have authority to exercise the comprehensive control of development that is contemplated in this paper.

To institute such control, it would be necessary to expand the regulations to cover more than mere width and grade requirements and to make them responsive to highway types, traffic conditions and the present and expected development which would affect or be affected by the proposed driveway. With such regulations, driveway entrances could be designed and located for the number and type of vehicles which would use them and also to fit in as well as possible with nearby roads and driveways to other lots.

For example, in the case of a proposed supermarket or shopping center on a busy street, instead of only having authority to require a minimum width driveway, the city could require that all access be located on a cross street, that the new driveway include a merging lane to the heavily traveled street, or that some other arrangement designed to reduce traffic friction be constructed. This type of control can eliminate the harmful uncontrolled dumping of traffic onto an arterial street without stifling private development to the extent of prohibiting the establishment of the traffic-generating business.

Law of Nuisances

Many authorities have concluded that substantial interference with safety and free passage of the highway will be enjoined even though the cause of the interference originates on privately owned land abutting the highway.[23] Since the essence of a roadside injunction case is the factual proof of the effect of the roadside use upon the traffic-carrying capability of the highway, this is a course of action in which the lawyer and the traffic engineer can cooperate in a vital program.

Thus, to reap benefit from nuisance law it is first necessary to study the arterial in question and determine whether or not the traffic flow is being hampered by adjacent land uses. Then results of a traffic study, such as the Wisconsin Avenue arterial research, can be used to show that an adjacent roadside use so hampers safety and traffic flow that the use should be enjoined as a traffic hazard.

If a traffic generator of the type that can cause congested conditions if located along a major thoroughfare and if it is also a nonconforming use, the courts are even more inclined to enjoin the use. Beuscher concluded:

> Injunctions in cases of roadside abuses can be justified on any one of three lines of court-made case law: (1) the roadside owner has violated his property law duty as owner of a "servient tenement" not to interfere with the "dominant" rights of the public; (2) the roadside abuse is enjoinable as a public nuisance; and (3) the roadside owner is guilty of continuing negligent or intentional conduct, in breach of his duty to permit free and safe passage on the highway.[24]

This is because of the weight usually given in nuisance cases to zoning findings about the character of the district.

Since there does not appear to be an adjacent use along Wisconsin Avenue that constitutes a public nuisance, it is not felt that a further discussion of nuisance law is pertinent to this report. On the other hand, it is apparent that conditions constituting a nuisance could arise in the future. Indeed, there are probably many instances of traffic hazard nuisances adjacent to arterials in cities throughout the country. It would seem then that research is needed to develop nuisance law so that it can be utilized to solve these serious problems. This is not a call for a radical extension of existing law, but rather for recognition of traffic hazards for what they are—a public nuisance.

23/ Beuscher, J.H., "Roadside Protection Through Nuisance and Property Law." HRB Bul. 113 (1956).

24/ Ibid. p. 66.

Tension Responses of Drivers Generated on Urban Streets

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The present study was an attempt to relate driver tension responses to those events in traffic which caused an overt change in speed or lateral location of a test vehicle. In order to measure tension responses the galvanic skin reflex (GSR) was employed, and measurements were made continuously during each trip along two urban streets. Traffic events influencing the test vehicle were determined independently by an observer and recorded on the GSR record. The traffic events were restricted to eight possible interferences, which accounted for 95 percent of all agents causing a change in test vehicle speed and placement.

Ten driver subjects were used on the two test routes. Runs were made during five time periods, including peak, offpeak, and night. Each subject drove the test route 25 times, distributed over a two-week period.

The results indicated that traffic events occurred, depending upon the street, at a rate of one every 21 to 35 seconds. Of these, 85 percent generated a measurable GSR response. Depending upon the street, the majority of responses were caused by other vehicles in the traffic stream, accounting for 60 percent or more of all events.

The events which generated the greatest mean tension response were those involving a maximum difference in speed between the object and test vehicle. Thus, turning maneuvers and crossing and merging were most tension inducing. The least stress inducing events were related to fixed objects in the environment, such as parked vehicles or islands. This ordering was statistically reliable among the subjects.

Using the magnitude of GSR response per unit of time as an over-all measure of driver tension, it was possible to compare the two test routes. It was found that the route subjectively preferred by drivers induced an average of 40 percent less tension response per minute than did the other route. An analysis of variance showed that these differences between routes were statistically significant.

The results of this study indicate that a road generates tension in drivers inversely with the predictability of the interferences and directly with the complexity of the traffic situation with which they must deal. In addition, the magnitude of tension response is directly related to the rate at which decisions are forced upon the driver by the traffic. Finally, the results indicate that the GSR

is a promising tool for the study of the conflicts occurring in driving.

● THE INDIVIDUAL VEHICLE is usually undifferentiated from the whole of traffic in most analyses of the operational characteristics of traffic on an urban street. Rather, the factors determining the operations of the street are inferred from certain physical measurements of the mass of traffic itself. There have been relatively few attempts to use driver behavior itself as a measure of traffic characteristics, or as a means for discriminating among different streets (1, 2). The present study was an attempt to develop a measure of driver behavior from which it would be possible to draw inferences about the highways under study. Two classes of questions were of particular interest:

1. Are these stable characteristics of different streets that can be discriminated by some measure of driver behavior?
2. Are there stable characteristics within a street and of the traffic on it which can be discriminated using some measure of driver behavior?

It may be seen then, that the basic purpose of this study was to explore the possibility of using driver behavior as an instrument for the analysis of highway and traffic characteristics.

The hypothesis which indicated the choice of behavioral measure was that the frequency and complexity of decisions required in driving urban streets is so great that the driver is under a high level of tension. This hypothesis implies that the frequency and magnitude of tension responses aroused in driving will vary in some relation to the nature of the street and of the traffic.

There are a variety of behavioral measures which may be employed to measure tension responses. However, for the purposes of this study it was desirable to have a measure that was directly relatable to events in traffic or the street on the one hand and also one that was a reliable indicator of driver tension response. A physiological measure that most nearly fulfilled these requirements is the galvanic skin reflex (GSR). This is a response occurring in the skin, manifesting itself as a change in the electrical resistance of the skin. The reflex is induced by activity of the autonomic nervous system and is initiated by unexpected stimuli that may be startling or tension inducing. The response appears as a decrease in skin resistance, and the magnitude of the reduction is correlated with the intensity of the inducing stimuli (3). Thus, the GSR represents one way to quantify the effects of emotion inducing stimulation.

One important characteristic of the GSR is its relation to the conscious experiences of the subject. McCurdy (4) has shown that there is a very high correlation between the GSR responses and the subject's awareness of the inducing stimuli. Thus, there is a fairly direct correspondence between the GSR itself and the event which caused its arousal. In most general terms, then, the GSR is a means for quantifying those conscious experiences which arouse tension. For the purposes of the present study this was ideal, for it allowed a reliable relation of the emotional response to the traffic event which generated it. It may be seen, then, that the present study was an attempt to explore the use of the galvanic skin response as a means for specifying the causes of and for quantifying tension responses aroused in driving.

PROCEDURE

Two urban arterial routes (Fig. 1) were used in this study. One, Wisconsin Avenue, was a major arterial to and from the downtown Washington area. The other ran roughly parallel and functioned as an alternate. Both were 4½ miles in length. The characteristics of each were quite dissimilar. Wisconsin Ave. served a considerable number of traffic and land use functions that were not found on the alternate. Detailed description of the characteristics of this primary street may be found in a report by Berman and Carter (5). The alternate route ran primarily through a residential area. It had almost no commercial traffic and transit use was over only a small portion of its length. In addition the street width varied from 4- to 2-lane over the 4½ mi. There was also considerable variation in both grade and curvature over this distance.

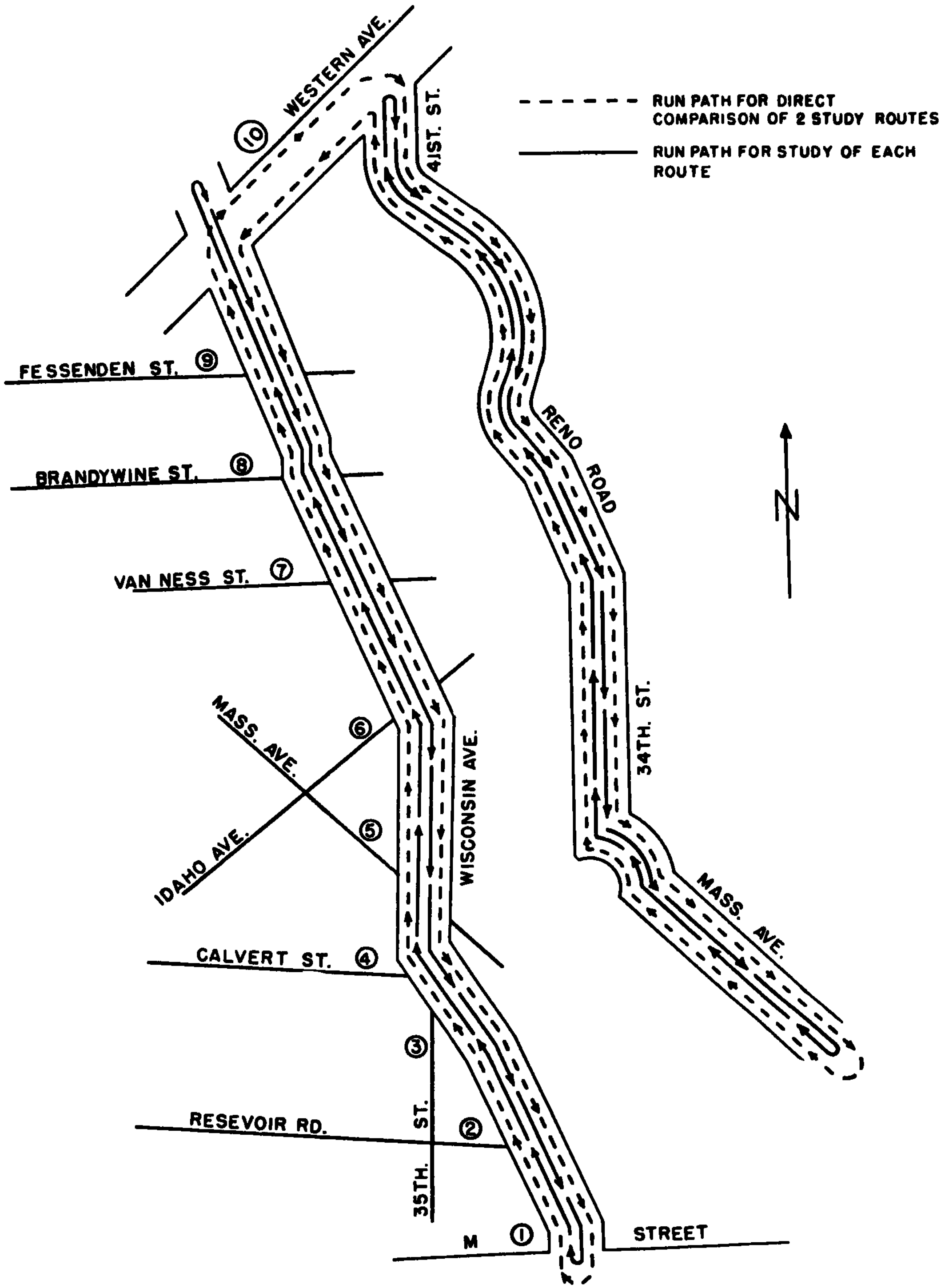

Figure 1. Study route locations and run paths.

In order to relate GSR responses to driving on the study routes, it was necessary to develop a list of traffic interferences. Thus, in addition to the physiological measure of tension, it was necessary to specify the causes of these responses. This required establishing some criterion of what constituted an interference with driving. Since the concern of the research was to relate street and traffic characteristics to driving behavior, it was decided that only those events that forced the driver to change either his speed or lateral location would be considered. This criterion implies that any change forced upon the driver will be potentially tension inducing. An additional restriction imposed was that only the most direct cause of these changes would be classified as the inducing traffic event. Thus, for example, the driver might be in a stream of traffic which is forced to stop for a traffic signal. If the test vehicle were not the first to approach the signal, then the event which caused his change in speed was considered to be the vehicle in front of him rather than the traffic signal. Although such a distinction was arbitrary it served two purposes: (a) it reflected what the test driver directly responded to, even though he might have been aware of other events that were actually involved; and (b) such a distinction greatly increased the reliability of observation.

This rationale oversimplifies the driving situation, for there is no question that the driver is aware of events considerably farther ahead than a car length. In addition, this system is limited in its ability to specify the multiple and fast-changing situations. However, it was felt that reliability of observation was far more important than detailed specification of traffic interferences. From these considerations, Table 1 was developed. These broad categories were determined in part by the nature of the street. Thus, on Wisconsin Ave., streetcar loading platforms were obvious interferences and were specifically included. On the alternate, however, this was replaced by a medial friction event. In addition to being based on the actual nature of the study routes, these events were also predicted upon certain friction concepts of traffic flow. As may be seen, Table 1 is a compromise between the general case of four frictions and the more specific individual conflicts that occur in traffic.

TABLE 1

OBSERVED TRAFFIC EVENTS

Code Number	Description
1	Parking maneuvers
2	Marginal pedestrians
3	In-stream moving
4	Transit loading platforms
5	Pedestrians in street
6	Turning vehicles
7	Merging and crossing vehicles
8	Traffic signals

For the conduct of the experiment, a regular government vehicle with automatic transmission was used. Study teams consisted of a driver, an observer, and a data recorder. The observer served as the team leader during the experiment. It was the task of the observer to specify when an event occurred and which of the eight traffic events caused a change in vehicle operation. These were reported to the third man who was seated in the rear seat of the vehicle. He in turn coded this information on the GSR recorder. Thus, the observer had no knowledge of the driver's responses.

Members of the study team were all in the junior engineer program of the Bureau of Public Roads. All were between the ages of 21 and 30 and had at least two years of driving experience. The drivers were instructed to travel the route by floating with the traffic wherever possible. With these instructions, the general pattern of driving was quite consistent among the test drivers. Although there were some differences noted among them these were generally quite minor and ordinarily very subtle.

To begin a run, electrodes were placed on the first and third fingers of the left hand of the subject driver. Although a variety of electrode placements were tried, these two fingers gave the most sensitive GSR, and were mechanically the simplest to place. In addition, this placement allowed the drivers to handle their vehicles normally. After placement, a normal resting level for skin resistance was determined. The recorder used contained a feedback circuit for balancing out drift in the base level. Thus, in these experiments only deviations from an arbitrary zero level were measured.

Sensitivity level of the recorder was adjusted empirically for each driver at the beginning of the run. Usually a startle stimulus was employed and the sensitivity raised until the full scale of deflection was obtained. For all the subjects the required sensitivity range was quite narrow. Once the sensitivity level was determined, it was not changed during the run. Such procedure does not, of course, eliminate individual differences among the subjects. It does, however, help to reduce the variability within a subject from run to run.

In the experiments in which the aim was to detect differences between the two streets the runs were conducted during the offpeak hours. Five drivers and two observers were employed. The runs followed the dotted path shown in Figure 1. During this study period four complete cycles were obtained for each test subject.

For the other phase of the study each route was studied individually. Five different subjects were used on each route. Runs were made during five periods of a work day: a.m. peak; a.m. offpeak; p.m. offpeak; p.m. peak; and night. During the peak hours three complete cycles of the route were obtained while during the offpeak there were two. All subjects drove all conditions at least twice. The design was such that every driver was observed by each of the two observers an equal number of times.

In either phase of the experiments the run was conducted approximately as follows. At the beginning of the run the time was noted and the drivers floated with the traffic from one end of the route to the other. The observer reported to the recorder any changes meeting the criteria and what events caused the change. At the end of the run there was a ten minute rest during which time the base level of skin resistance was again determined. Usually there was a slight increase from beginning to end especially on the first run. After the rest period, the driver proceeded in the opposite direction to complete the full cycle.

Observers were instructed to report events as quickly as possible to the recorder in order to minimize the errors in locating occurrences in time on the GSR record. A sample record of the GSR responses is shown in Figure 2. A notation was generally placed simultaneously with or slightly preceding the GSR response. Whenever an

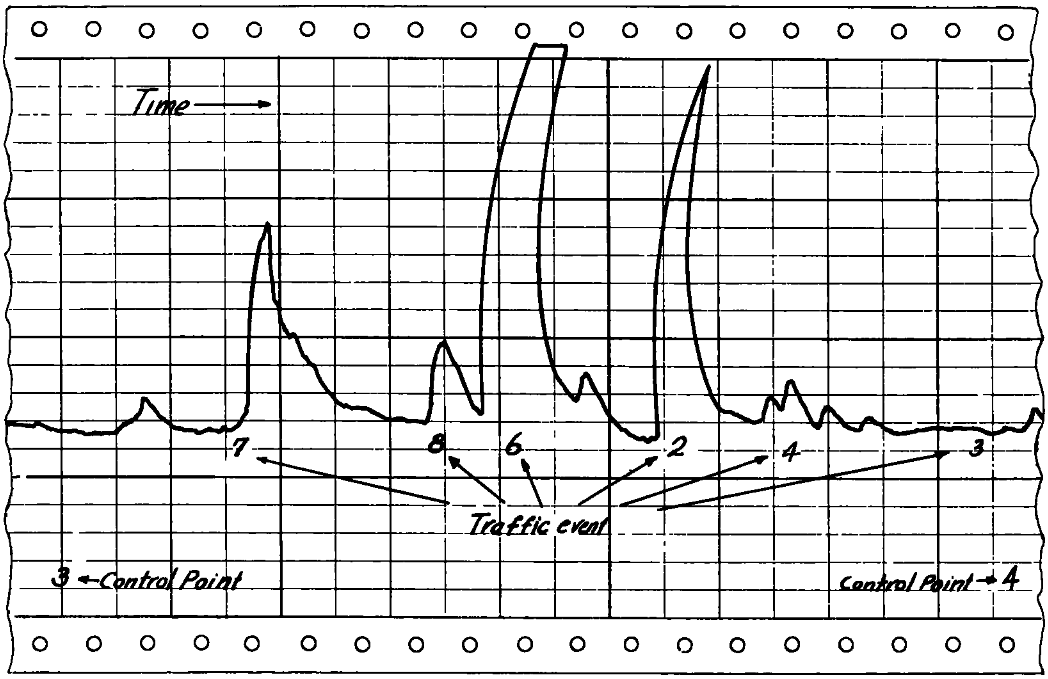

Figure 2. Sample of GSR record.

observation preceded a response by more than 5 sec, the two were considered unrelated. Similarly, an observation that followed a response by more than 1 sec was considered unrelated to the response. Both these criteria, and the latter especially, were predicated upon the assumption that the lag in the GSR response was longer than for the verbal response. In practice, uncertainty of association of observation and response occurred in no more than 5 percent of the cases.

As may be seen from Figure 2, some responses are not associated with traffic events such as the small peak before the first event (7). The GSR is sensitive to a variety of events, internal as well as external, so that this type of response is fairly common. Since only traffic related responses were of interest, these were not included for analysis. Also, the GSR does not occur every time there is a traffic event as exemplified in the case of the last event (3). These were included in the analysis. It was found that approximately 15 percent of the traffic events observed aroused no response on the part of the subject.

RESULTS

The data were tabulated for each subject for each run and each route. They were broken down by the observed events and the magnitude of GSR response associated with each event. In addition, the travel time for each trip was recorded. It was possible from these data to determine the average magnitude of GSR response for each event, and with the time measures to determine both the rate at which events occurred and the magnitude of responses that occurred in time.

The meaning of the magnitude of the GSR response needs some explanation. The recorder actually measures the GSR in units of log conductance. Basically, this unit is employed because the magnitude of change in skin resistance is more nearly linearly related to the magnitude of the inducing stimulus when resistance is measured in log conductance (6). Thus, in this study each successive division on the recorder chart represented equal increments of GSR. However, the absolute values of these divisions were not known, for these depended upon the setting of the sensitivity scale. With the method of calibration used, the values for each scale division were essentially relative to the base level. They are consequently, unitless, and may be termed "reaction units."

Table 2 gives the data for the two routes obtained from the same drivers. The data contain the frequency of occurrence of events and the average magnitude per event. All the subjects have been combined. There were considerably more traffic events occurring on Wisconsin Ave. than on the alternate route. However, the average magnitude of GSR response was approximately the same for both routes.

TABLE 2

COMPARISON OF TENSION RESPONSES ON ALTERNATE AND WISCONSIN AVENUE CONTINUOUS RUNS DURING OFFPEAK PERIODS

Item	Alternate	Wisconsin
Total events	237	445
Average magnitude	2.23	2.28
Events per minute	1.71	2.42
Magnitude response per minute	3.81	5.52

The difference in the total number of events (Table 2) in part reflects the difference in travel time for the two routes. In order better to equate the streets, a rate figure was computed and is shown as the events per minute. Here the differences between the two routes are reduced somewhat. Nevertheless, there were still 30 percent fewer responses per unit time on the alternate than on Wisconsin Ave. Thus, on Wisconsin Ave. there was a traffic event once every 24.7 sec while on the alternate there was an event every 34.9 sec. Since 85 percent of the events aroused the GSR, there was, consequently, a tension inducing event every 29.2 sec on Wisconsin Ave. and 41.4 sec. on the alternate route. Therefore, it is quite evident from these data that drivers on the alternate route faced considerably fewer interferences with driving than on Wisconsin Ave.

These results reflect only the frequency of occurrence of events and do not directly relate to the magnitude of the GSR responses. The average magnitude of response alone is inadequate since it does not reflect the differences in travel time for the two routes. One simple measure of the GSR is the total magnitude of response that occurs per unit of driving time. This measure cumulates all the GSRs independently of events and equates the routes on the basis of time. This ratio is, therefore, a statistic reflecting the behavioral response of the driver per unit time and under the assumptions of this study was considered as a measure of induced tension. This measure for the two routes is also shown in the last row of Table 2. Again, the alternate route is considerably less tension inducing than Wisconsin Ave.

The data (Table 2) were the result of pooling all the subjects. In order to test for differences among subjects as well as to determine whether there was a statistically significant difference between the two routes, the data were analyzed using the analysis of variance. Table 3 is the summary table of that analysis. Both the two routes and the four subjects differed significantly at better than the 0.01 level. It would seem reasonable to conclude that the alternate route induced significantly less tension in drivers than did Wisconsin Ave. In addition, the pooling of the different subjects ap-

TABLE 3

SUMMARY OF ANALYSIS OF VARIANCE OF MAGNITUDE OF GSR PER MINUTE FOR STUDY ROUTES

Source	Sum of Squares	Degrees of Freedom	Mean Square	F
Routes	19.57	1	19.57	11.51[1]
Drivers	302.05	3	100.68	59.22[1]
Rtes. x drvs.	22.89	3	7.63	4.48[2]
Within	16.95	10	1.70	-
Total	361.46	17	-	-

[1]Significant at the 0.01 level.
[2]Significant at the 0.05 level.

pears to be unwarranted. This is especially relevant to the GSR data shown in Table 2 where it appears that the average magnitude of the GSR is the same for the two routes. Actually, the average magnitude shows considerable variation among the subjects and the differences between the routes varies over a range of nearly two-to-one. Thus, the averages shown are quite misleading and, consequently, the combined GSR data must be interpreted cautiously.

In addition to the study of the two routes made simultaneously, studies of each route were conducted independently. Five subjects were used on Wisconsin Ave. and five different subjects were used on the alternate route. Also there were a total of three different observers employed in these two studies. One of the three acted as observer on both routes while the other two ran either Wisconsin Ave. or the alternate route.

WISCONSIN AVENUE DATA

Tabulating the occurrence of the traffic events, there was a total of 7,800 events observed over the 2-week period. These were distributed among the eight events as given in Table 4. The most frequently occurring event was instream friction (event 3). The remainder form a small portion of the total individually. Ranking the eight events in order of average magnitude of response which each generated leads to column 5 (Table 4). In addition, a separate analysis was carried out for the subjects. Individually a rank test was applied to these rankings of the events by average GSR.

TABLE 4

FREQUENCY OF OCCURRENCE AND MAGNITUDE OF GSR RESPONSES EVOKED BY TRAFFIC EVENTS ON WISCONSIN AVE.

Event	Frequency of Event	Percent of Total	Avg. Magnitude	Rank by Avg. Magnitude
1. Parking	724	9.2	2.47	6
2. Marg. ped.	330	4.2	1.51	8
3. Moving veh.	4,682	59.7	2.49	5
4. Load. plat.	633	8.0	2.20	7
5. Instream ped.	372	4.7	2.76	4
6. Turning	400	5.1	3.34	1
7. Cross. and merg.	285	3.6	3.15	2
8. Traffic contr.	416	5.3	2.94	3
Total	7,842	99.8	2.53	-

It was found that the ordering among the subjects was statistically reliable, and was the same as that shown.

Data collected during the different run periods were combined by direction. It was found that there was considerable variation among the runs much of which depended upon changes in the composition of the traffic during those periods. Table 5 gives the

TABLE 5

EFFECTS OF TIME PERIOD AND DIRECTION ON AVERAGE MAGNITUDE OF GSR RESPONSE

Event	Northbound		Diff.	Southbound		Diff.
	Offpeak	Peak	P-OP	Offpeak	Peak	P-OP
1	2.59	2.37	-0.22	2.25	2.87	+0.62
2	1.10	1.57	+0.47	1.88	1.98	+0.10
3	2.51	2.47	-0.04	2.36	2.64	+0.38
4	2.09	1.45	-0.64	2.27	3.15	+0.88
5	2.63	3.32	+0.69	2.29	2.80	+0.51
6	3.64	2.86	-0.78	3.37	3.49	+0.12
7	2.97	3.13	+0.16	2.50	3.96	+1.46
8	3.11	3.67	+0.56	2.25	2.65	+0.40
Total	2.50	2.52	+0.02	2.36	2.77	+0.41

average magnitude of response and the changes from offpeak to peak that occurred in each direction. The positive sign indicates that the response induced by that particular event increased during the peak hours, whereas the negative sign shows that it decreased. Over-all, the average magnitude per event was the same for both the northbound and southbound directions of Wisconsin Avenue. For the northbound direction there was no difference in average magnitude between offpeak and peak runs. In general, the data obtained in the northbound direction were more stable than that obtained southbound. Consequently, the differences between peak and offpeak are most clearly seen for that data. The greatest changes during the peak hours appear to be the increase in the average tension induced by instream pedestrians (event no. 5). This is consistent with the increase in mass transit use during the peak hours and, consequently, the high density of pedestrians at loading platforms during those hours. Major decreases occurred in the turning movements out of the stream of traffic (event no. 6). This, in part, reflects a reduction in the allowable turning movements during peak hours.

The data from the southbound runs are far less clear-cut. The average tension response for all events rises from the offpeak to peak period. The greatest increase occurred in the rise in merging and crossing conflicts. Interpretation of these differences in the southbound direction can only be limited due to the wide variability of the data obtained in this direction.

The data for night runs appear to follow the pattern for the peak hours during the day. Again, the most clear-cut differences are in the northbound direction. The only major change at night appears to lie in a large increase in response to marginal pedestrians. This is consistent with the large increase in pedestrians during the night shopping hours and also restriction in marginal visibility over much of the street.

Wisconsin Avenue was divided into nine control sections of approximately equal length. The ten control points (for these nine sections) were marked on the recorder chart so that it was possible to relate the events to their location on the street. Table 6 gives the average magnitude of tension response for each section both by direction and time of day. In addition, Figures 3 and 4 show a plot of the tension response by section on the street. Generally there was considerable variability in the data within a section, and the differences among sections were on the average not too great. There was no significant order of difficulty found among the sections for the five test drivers. Thus, there was no indication that there were fixed features in any of the sections which consistently influenced driving behavior.

Figure 3 shows that the differences between peak and offpeak were quite small for all but the section between control point 3 and 4. Whereas during the offpeak hours this section gave the maximum average tension response, during the peak hours it yielded the lowest average tension response. In order to test for the significance of this difference a "t" test of matched pairs was employed. Thus, the difference between each subject's tension responses during peak and offpeak was compared. It was found that the decrease from offpeak to peak was significant at better than the 0.05 level. It seems reasonable, therefore, that a real change in traffic characteristics took place in this section. This is a section of a fairly intense commercial development and also an area where the

TABLE 6

AVERAGE MAGNITUDE OF GSR RESPONSES IN DIFFERENT SECTIONS OF WISCONSIN AVE. BY DIRECTION AND TIME PERIOD

Section	Northbound		Difference	Southbound		Difference	Difference NB-SB	
	Offpeak	Peak	OP-P	Offpeak	Peak	OP-P	Offpeak	Peak
1-2	3.04	3.18	-0.14	2.34	2.34	0.00	+0.70	+0.84
2-3	2.50	2.58	-0.08	2.36	2.99	-0.63	+0.14	-0.41
3-4	3.58	1.95	+1.63	2.47	2.86	-0.39	+1.11	-1.91
4-5	2.50	3.18	-0.68	2.18	2.78	-0.60	+0.32	+0.40
5-6	2.56	2.55	+0.01	2.37	3.15	-0.78	+0.19	-0.60
6-7	2.05	2.57	-0.52	2.71	2.89	-0.18	-0.66	-0.32
7-8	2.78	2.90	-0.12	2.82	3.07	-0.25	-0.04	-0.17
8-9	2.28	2.25	+0.03	2.66	2.76	-0.10	-0.38	-0.51
9-10	2.23	2.20	+0.03	2.48	3.06	-0.58	-0.25	-0.86

street is relatively narrow. During the offpeak hours there is a high degree of marginal activity relating to the commercial area. The additional factor of the narrowing street reduces maneuver-ability and poses a severe restriction on the driver's freedom to make lateral avoidance movements. During peak hours, parking regulations, high traffic volume, and signal progression all help to minimize turbulence in the traffic flow. Thus, in this region the driver was faced with an extensive amount of marginal friction during the offpeak hours much of which was eliminated during the peak hours.

In the southbound direction there were no clear-cut differences between either time

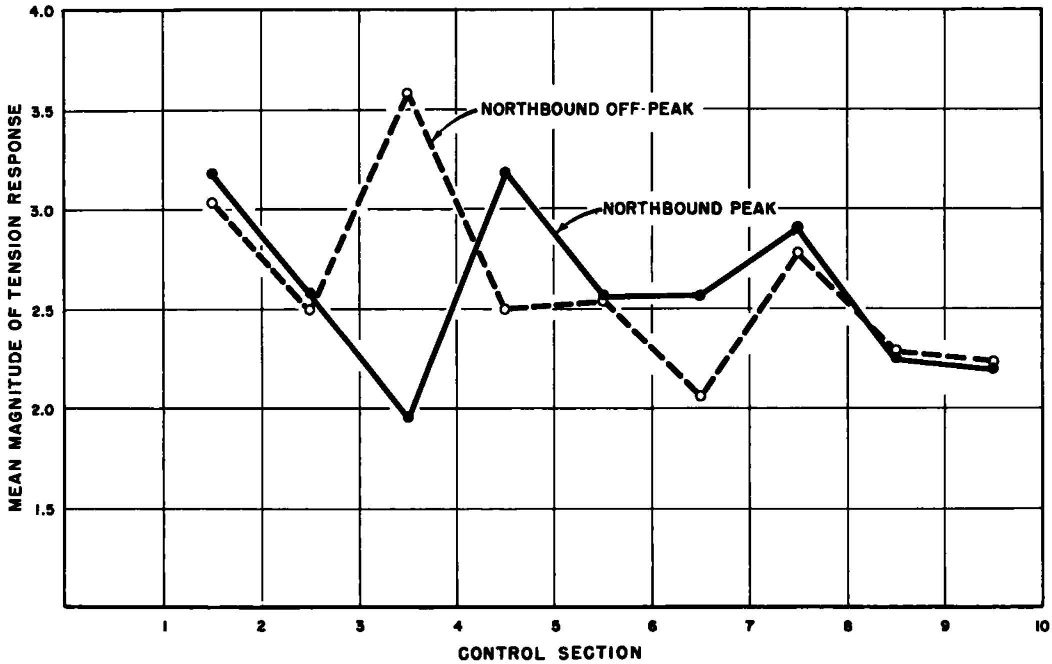

Figure 3. Average GSR by control section—northbound.

period or section. There does appear to be a peak in section lying between points 7 and 8, at least during the offpeak hours (Fig. 4). This region is a highly developed commercial area, so that there was considerable marginal activity complicated by turning movements onto and from radials entering the circle. The peak hours, besides showing a general rise in tension responses, do not appear to indicate any differences among the control sections. There is considerable variability in the data so that little can be said about these differences.

The final analysis of the Wisconsin Ave. data involved the determination of a relative frequency of events in time and the total tension response in time (Table 7). These data include all the runs for each of the subjects separated only by direction. These pooled data show that for all the subjects there are somewhat fewer events per minute northbound than southbound. This result indicates that driving northbound, the driver is faced with a traffic event every 25.0 sec while southbound he is so faced every 21.3 sec, or a tension inducing event every 29.4 sec and 25.2 sec, respectively. In terms of the over-all measure of tension, the differences between the two directions are on the whole quite small. There is little evidence to indicate that the two directions were different. The subjects also reported that there were no differences between directions.

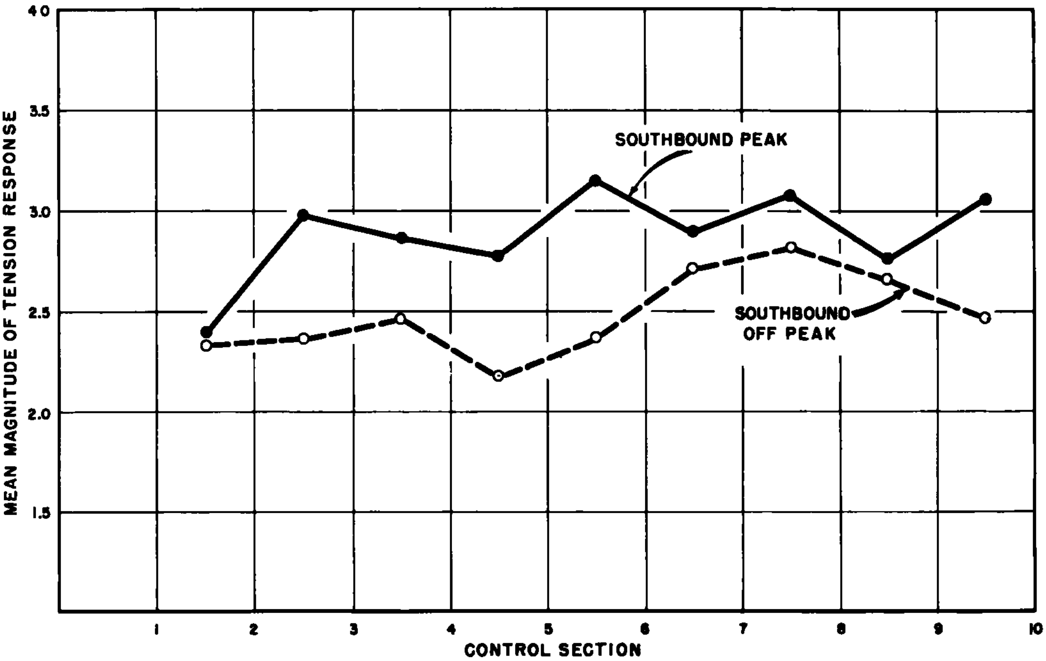

Figure 4. Average GSR by control section— southbound.

ALTERNATE ROUTE

In this phase of the study the alternate route was examined along the same dimensions as was Wisconsin Ave. A different group of driver subjects were employed and one new observer. This alternate route was a complex street itself. There was great variation in road width over the 4½ mi length, and it varied considerably in grade. Unlike Wisconsin Ave., it had no streetcars but did have bus service over part of its length. In addition, and in direct contrast, it had no commercial development. It was almost wholly residential area and the residences were, for the most part, single unit dwellings. Finally, almost all the traffic was passenger cars, again, in contrast to Wisconsin Ave. in which commercial vehicles made up a considerable portion of the traffic.

The methodology followed on the alternate route was the same as that used on Wisconsin Ave. The one change in the list of traffic events was the elimination of event No. 4 (loading platforms). Since this was irrelevant on this route, it was replaced by "opposing vehicles." This event was added because the route was two to three lanes

TABLE 7

FREQUENCY AND MAGNITUDE OF RESPONSES IN TIME

Driver	Events per Minute Northbound	Events per Minute Southbound	Difference Northbound Southbound	Magnitude of Response Per Minute Northbound	Magnitude of Response Per Minute Southbound	Northbound Southbound
A	2.4	2.9	+0.5	7.30	7.60	0.96
B	2.1	2.5	+0.4	6.59	8.30	0.79
C	2.7	3.1	+0.4	6.91	6.60	1.05
D	2.6	2.7	+0.1	4.11	3.81	1.08
E	2.3	2.7	+0.4	6.90	9.40	0.73
Total	2.4	2.8	+0.4	6.29	7.23	0.87

over much of its length. Consequently, there were many possibilities for the opposing traffic stream to come into conflict with the test vehicle.

TABLE 8

FREQUENCY OF OCCURRENCE AND MAGNITUDE OF GSR RESPONSES EVOKED BY TRAFFIC EVENTS ON ALTERNATE ROUTE

Event	Frequency of Events	Percent of All Events		Avg. Magnitude	
		Alternate	Wisconsin[1]	Rank	Obs.
1. Parking	70	5.3	9.2	8	1.30
2. Marginal ped.	9	0.6	4.2	7	1.56
3. Moving veh.	863	65.6	59.7	5	1.77
4. Opposing veh.	50	3.8	8.0[2]	2	2.14
5. Instream ped.	17	1.7	4.7	6	1.71
6. Turning	70	5.3	5.1	4	1.79
7. Cross. and merg.	93	7.0	3.6	1	2.58
8. Traffic contr.	142	10.8	5.3	3	1.97
Total	1,314	100.1	99.8	-	1.84

[1]Data from Table 4.
[2]On Wisconsin Ave., Event No. 4 was loading platforms.

All the data on the alternate route were combined according to the eight different events (Table 8). More than 1,300 events were observed during the study period. As on Wisconsin Ave., the most frequently occurring traffic event was that induced by other vehicles in the traffic stream. The remainder of events accounted for a small proportion of the total individually. Table 8 gives a comparison of the distribution of events for the two routes. Since the total number of observed events for all but the moving vehicles is rather small, direct comparisons are probably unwarranted. It may be noted, however, that these moving vehicle events constituted a 6 percent greater part of the total on the alternate route than on Wisconsin Ave. Making the arbitrary assumption of homogeneity a "t" test of the differences between these two proportions was carried out. A "t" of 4.21 was obtained which was significant at the 0.01 level. This would appear to indicate that the tension inducing characteristics of the alternate route seems to include a lesser proportion of peripheral events than that found on Wisconsin Avenue. Thus, most traffic conflicts on the alternate route appear to be somewhat more directly related to instream traffic activity.

The ranking of the events according to the average magnitude of response is also shown in Table 8. The most inducing situation is the one of crossing and merging traffic (event no. 7). Event No. 4, which is medial friction, is second highest in average magnitude of response. In general, the order of intensity of tension induction for each of the events is similar to that found on Wisconsin Ave.

In order to examine the tension responses as a function of time the data were combined and are shown for the different time periods in Table 9. The a.m. offpeak runs are not included in this tabulation because they were all carried out in conjunction with runs on Wisconsin Ave.

The over-all frequency of occurrence of traffic events was 1.79 per min of approximately one every 33 sec with a minimum during the morning peak hours of 1.45 events per min or one every 41½ sec. The maximum was during the p.m. offpeak when there were 2.65 events per min or one every 23 sec. The total magnitude of tension per minute is shown in the last column of Table 9. The maximum tension response per minute appears to have occurred during the offpeak hours, being almost twice as great as for the peak hours. Also, tension responses per minute for the night runs fall intermediate between the other two time periods. It should be pointed out once again,

TABLE 9

FREQUENCY AND MAGNITUDE OF RESPONSE ON ALTERNATE ROUTE BY TIME PERIOD

Time Period	Number of Events	Average Magnitude	Events Per Minute	Magnitude of Response Per Minute
AM peak	292	1.68	1.45	2.44
PM peak	363	1.41	1.86	2.62
PM offpeak	122	1.98	2.65	5.25
Night	346	2.21	1.89	4.18
Total	1,123	1.79	1.79	3.20

however, that these differences were obtained by pooling data from subjects who were dissimilar in their tension responses. They should, consequently, be interpreted carefully.

CONCLUSIONS

As was pointed out previously, the purpose of this study was to explore the possibility of using the GSR as a means for discriminating features of traffic and streets. The first goal was to detect differences between two streets serving approximately the same traffic function. The results of this study do indicate that the GSR reliably discriminates between these two arterial routes. The distinctions among different characteristics within a route are not as clear-cut. However, the results do indicate the complexity of decisions faced by drivers on an urban street. The variety of conflicts occurring on the street are sufficiently frequent and involved to place drivers under a fairly consistent level of stress.

One finding of particular interest was the significant ordering of the different traffic events in terms of the average magnitude of GSR. The events inducing the highest average tension on both routes were the conflicts occurring with vehicles entering or leaving the traffic stream and, on the alternate route, the opposing vehicles. These are events in which the rate of change of location of the conflicting vehicles is a maximum. These are situations that require the driver to solve a complex set of differential equations in order to predict a course of action. With the human's limited accuracy in speed estimation and angular closing rate, and the limited time for such decision, these situations have a high degree of unpredictability for the driver and may reasonably be most threatening.

The two events which rank next in order are the traffic signals and instream pedestrians. Both of these may be considered as "instream uncertainty." In the present study the driver was influenced by traffic signals only when there were no other vehicles interposed between him and the signal. There was, then, a fairly high probability that the driver arrived at a signal at the point where it had just changed or was in the process of changing. This would appear to be a particularly indeterminate situation for the driver. The effect of instream pedestrians is quite similar. The driver has no way to predict the action of a pedestrian. Any conflict will arise strictly by action of the pedestrian. Both of these events probably represent a straight risk type decision operation, and the observed magnitude of tension response may well reflect the degree of uncertainty in each situation.

A third pair of events which appear to go together are the moving vehicle events and parking. These may be considered "instream interferences." In the first case the relative differences in velocity between the test vehicle and other vehicles in the stream is relatively small. Consequently there is adequate time for compensation for any changes in the characteristics of the ongoing traffic stream. Parking maneuvers were generally found to be quite conspicuous so that the test driver was able to adapt his speed or location relatively smoothly and simply. Both appear to be relatively predictable actions for which the driver can adequately compensate, and for which there is adequate time for decision making.

The last two events may be termed "fixed objects," and include marginal pedestrians and the streetcar loading platforms. For all practical cases observed, conflict between pedestrian and vehicle occurred when the pedestrian was standing or just beginning to move into the street. At this point it seems reasonable to consider this as a fixed obstacle situation. In general, it appeared in both of these situations that the driver had more or less complete control over his actions. Thus, these events may be conceived as simply choice points, and the responses were a reflection of the driver's having made a choice rather than a reflection of tension or stress.

One general implication of these results is consistent with current knowledge of the GSR. It is that the more highly unpredictable the situation the more dynamically does the driver respond. The unique thing in the present study is the fact that there appears to be a very high level of unpredictability in driving on urban streets. The data indicate that two to three times a minute an event occurs which forces the driver to take some compensatory action. Furthermore, the more complex the demands made on him by the traffic situation the greater is the tension aroused by the situation.

These results indicate that the driving environment generates a tension response in inverse relationship to the predictability of the conflicts. The significant rank ordering probably demonstrates those situations which are hardest for the driver to predict and thus to compensate for. In addition to the element of predictability may be added the complexity of the driving environment. In the only section where there was a significant difference in time period, the change in average GSR came when the complexity of the traffic situation was reduced. In addition, the differences between the two routes in terms of their percentage of marginal interferences also indicate a difference in complexity between the two routes. Thus on Wisconsin Ave. over 40 percent of all the observed events arose from interferences occurring along the margins of the street. This would indicate that the driver is faced with a highly complex field of very broad area. In such a situation the driver is forced to attend to a wide range of stimuli. He must sort, select, and then operate on this heavy load of information. With this excessive information load, his ability to select and predict is inherently restricted, one consequence of which is an increased level of stress and a greater responsiveness to events arising in the field.

Finally, the data indicate the high rate of decision making with which the driver is faced on an urban street. Where the driver must respond to a fixed object such as a streetcar loading platform, for example, the average response is relatively low. This is a situation where the driver can usually make a decision on his own terms in his own time. However, in the case of merging vehicles, the situation forces the driver to make decisions both very rapidly and with a minimum amount of information, much of which he cannot handle accurately or efficiently. Under these circumstances the driver must depend upon other drivers to make consistent responses. In complex traffic then, the individual driver is often forced to give up a certain amount of control to others in the environment. A fundamental question is: How does this delegation affect traffic operations and capacity? It would seem reasonable that the driver will compensate for this loss of control by any means that will serve to reduce his uncertainty. He can, for example, increase the headway between himself and the vehicle ahead, or he can reduce his speed. These, as well as other devices, can reduce the capacity of the street, and cause turbulence in traffic flow.

As was pointed out, the essential aim of this study was exploratory in nature. The purpose was to examine the utility of the GSR as a measure of driver behavior. These preliminary results do indicate that the GSR is promising. There are, however, many questions relating to the GSR which have not been covered in this study. One thing that should be examined far more intensively is the reliability of the response (6). It is well-known, for example, that there is a rather consistent adaptation of the GSR (8, pp. 150-152) so that the same stimulus intensity may not arouse the same magnitude of GSR on repetition. This is in part compensated by the calibration procedure used in the present experiments, and the fact that no event occurred twice in the same way.

Nevertheless, the changes occurring during a run were not examined in detail. In addition, some very simple assumptions have been made about the relation of the responses to the situation that aroused the GSR. The problem is essentially one of determining what the GSR means in a traffic situation. It is an oversimplification to assume, as was done in this study, that the GSR is aroused only by the occurrence of a traffic event. The GSR is sensitive to a wide variety of behavioral responses (9) whose relationships may be only indirectly related to the traffic event. There is little doubt, for example, that the GSR accompanies preparatory muscular activity or muscular response itself (8, pp. 157-158). Although this does not eliminate the relationship between the GSR and the traffic event, it does indicate that the relationship between the two may be quite indirect.

Another problem is the statistical nature of the GSR. In the present study the magnitude of response was a positively skewed distribution. The range of conductance was from zero to some maximum value. Such distributions pose some difficult problems of statistical analysis. Thus, in this study, the use of the arithmetic mean and the usual statistical tests of inference are in question. It may be seen, therefore, that there are many questions relating to the statistical nature of the data which were not answered in the present study.

There are, in addition, certain methodological problems of specifying and interpreting the traffic events. For the purposes of this study all the traffic events were treated as discrete. It is obvious, however, that conflicts in traffic are not discrete but develop continuously in time. Thus, the schedule of observation arbitrarily collapses what is a complex and continuous behavioral response to a single point in time. There is no way of knowing from the present study whether the observed GSR response occurred at the approach to a conflict, the conflict itself, or the point in time where a decision was made. It is conceivable that any or all of these processes could evoke a GSR.

Not only did the observation program eliminate temporal differences, it also eliminated intensity differences within each event class. It was assumed that all occurrences of any event represented the same stimulus intensity. In essence, this procedure eliminates within stimulus class variability. It is quite apparent that the affective intensity of an event may be quite variable depending upon a variety of temporal and spatial factors in the environment as well as perceptual and emotional factors in the driver. It should be obvious, therefore, that the present situation grossly oversimplifies the nature of the traffic interferences and simply places them into one of eight qualitative categories none of which have any measure of intensity attached to them. Thus, precision of stimulus measurement was sacrificed to obtain reliability of observation.

Within the limitations outlined, this study indicates that the two streets studied do differ in the rate and magnitude of galvanic skin response aroused in driving. The results, in general, indicate that the GSR may be a promising means for using driver behavior for discriminating between different kinds of streets and the interferences on them. There are, however, several statistical and methodological problems inherent in the use of the GSR which restrict its operational utility at the present time.

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Capacity of Traffic Signals and Traffic Signal Timing

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● SIMILAR CONDITIONS on a road produce similar behavior among motor vehicle users of that road. The principal research problem is to recognize and isolate the conditions and then measure traffic behavior under these conditions. Having done this for a sufficient number of varying conditions, practical application can be made covering other varying but similar conditions.

Although traffic on the open road may travel at random, traffic signals regiment this traffic into narrow bands of variation.

TABLE 1

US 1, SOUTHBOUND, AT AVENEL STREET

$$T_p = 1.2N + \frac{.95}{52}\sqrt{\left\{D + 25(N-1)\right\}\left\{D + 25(N-1) + 676\right\}}$$

PASSENGER CARS

N	D = 55 FEET				D = 381 FEET				D = 629 FEET			
	Samples	Field	Calc.	Diff.	Samples	Field	Calc.	Diff.	Samples	Field	Calc.	Diff.
1	225	4.45	4.87	+.42	213	12.62	12.80	+.18	206	17.01	17.75	+.74
2	182	6.59	6.89	+.30	167	14.73	14.51	-.22	167	19.69	19.45	-.24
3	130	8.62	8.83	+.21	123	16.86	16.22	-.64	120	21.08	21.12	+.04
4	102	10.64	10.72	+.08	90	18.60	17.92	-.68	92	22.66	22.81	+.15
5	72	12.68	12.56	-.12	60	20.36	19.63	-.73	64	24.16	24.49	+.33
6	56	14.59	14.38	-.21	45	21.87	21.32	-.55	48	26.27	26.16	-.11
7	48	15.72	16.16	+.44	35	22.06	23.03	+.97	38	26.99	27.84	+.85
8	28	18.74	17.95	-.79	13	25.08	24.73	-.35	21	30.05	29.53	-.52
9	14	20.97	19.70	-1.27	5	26.60	26.40	-.20	11	31.93	31.22	-.71
10	8	23.58	21.45	-2.13	2	27.45	28.10	+.65	6	34.18	32.91	-1.27
11	6	25.53	23.19	-2.34	1	32.50	29.80	-2.70	4	36.53	34.59	-1.94
12	5	27.30	24.93	-2.37	1	32.50	31.49	-1.01	3	40.33	36.26	-4.07
13	7	28.01	26.67	-1.34					3	36.23	37.93	+1.70
14	6	29.73	28.38	-1.35					2	36.45	39.59	+3.14
15	4	32.05	30.09	-1.96								
16	4	35.05	31.80	-3.25								

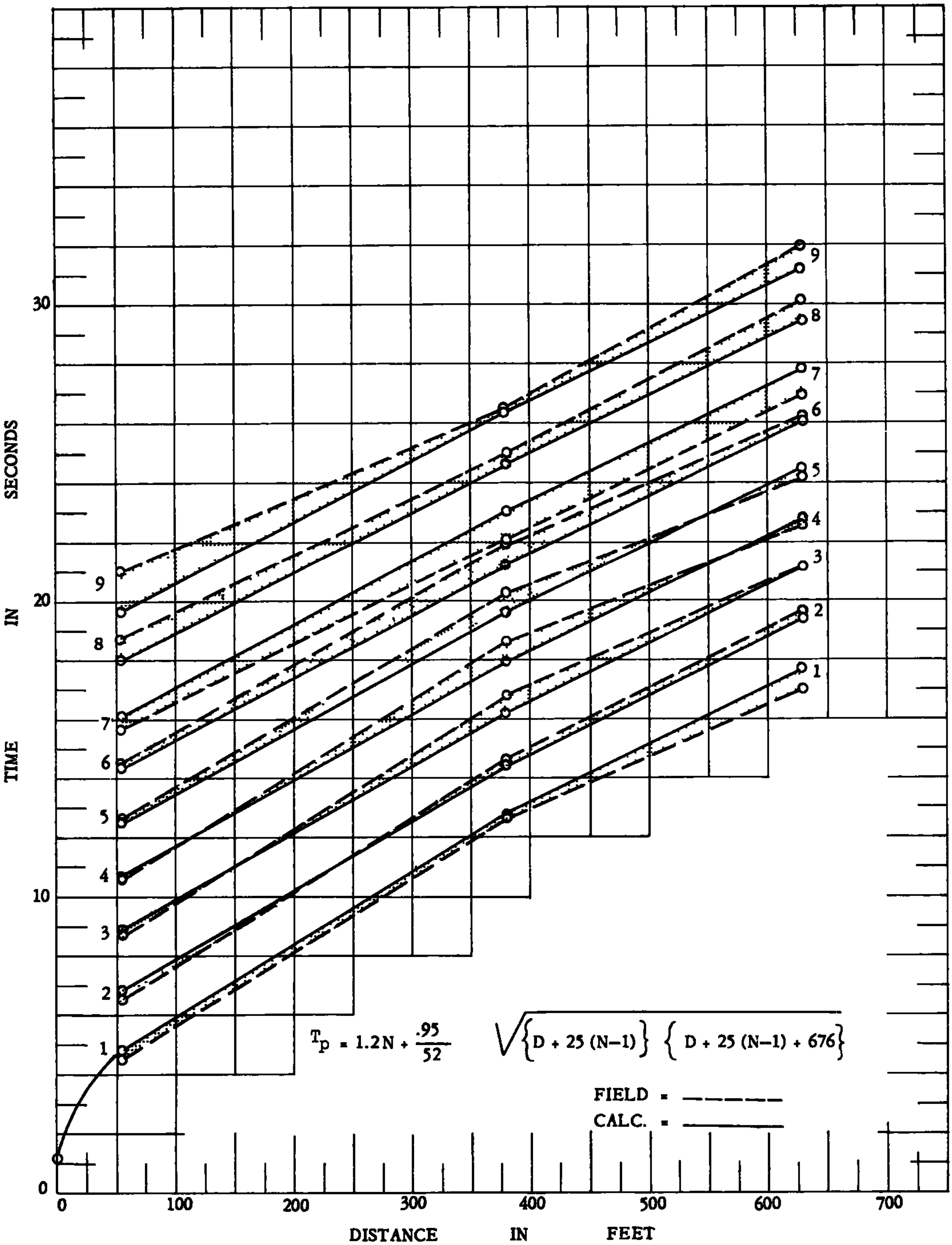


Figure 1. US 1, southbound, at Avenel Street—passenger cars.

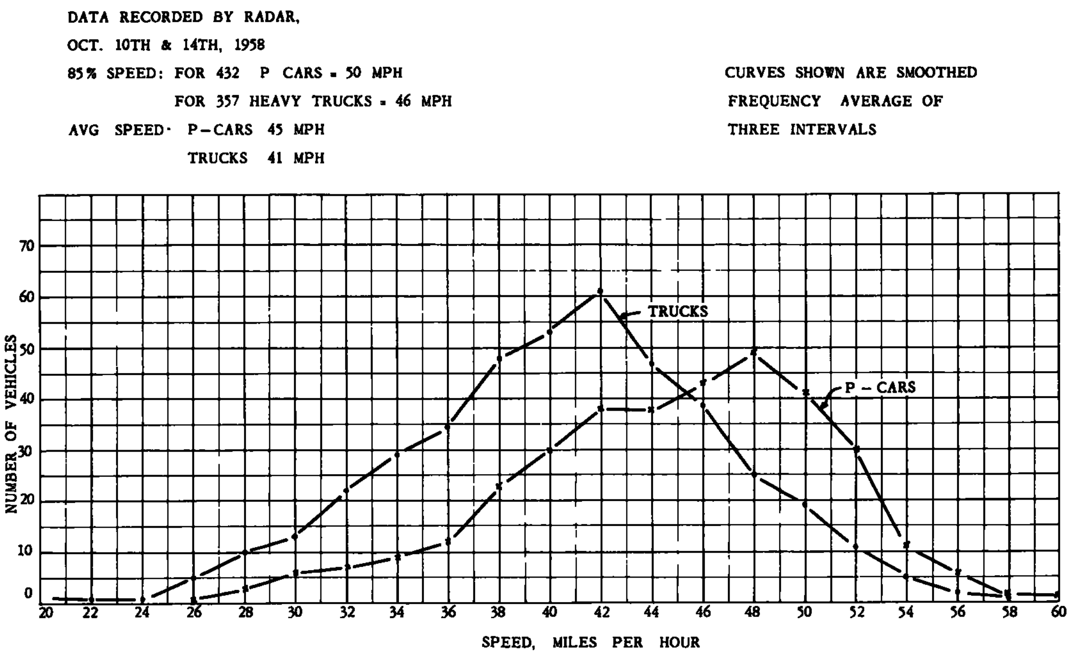


Figure 2. Smoothed frequency diagram, US 1, northbound, at Avenel Street.

The behavior of vehicles responding to the green signal, after waiting during the red signal can be described by:

$$T = PN + \frac{K}{S} \sqrt{\left\{ D + C(N-1) \right\} \left\{ D + C(N-1) + \frac{S^2}{4} \right\}} \qquad (1)$$

in which T = time, in seconds, after the beginning of the green signal, to arrive at the distance D;

T_p = passenger car reaction time;
T_t = truck reaction time;
P = perception and reaction time, in seconds;
N = Nth vehicle stopped in line (single line);
K = constant of acceleration;
S = speed limit (real), in miles per hour;
D = distance in feet measured from the stop line of the first car; and
C = spacing in feet measured front to front of standing vehicles.

The perception and reaction time P for the first car is the time between the beginning of the green signal and the beginning of the vehicles forward motion. It includes the time for the first driver in line to perceive that the signal has turned green, the mental and physical reaction time of the driver to start the vehicle in motion, and the time for the mechanics of the vehicle to overcome inertia. The perception and reaction time for other drivers following is similar except that each driver must perceive that the vehicle immediately ahead has started its forward motion rather than perceive that the signal has turned green.

The constant K varies with the acceleration capabilities of the vehicle, within the desirable limits of the driver. Passenger car drivers seldom exercise the maximum or close to maximum capability of the vehicle.

The speed limit S is that speed limit which is reasonable. Where the posted speed limit is based on the 85 percentile method this speed limit is S but where the posted speed limit is higher or lower than the 85 percentile, the 85 percentile is used.

COMPARISON OF EQ. 1 WITH FIELD DATA

Table 1 and Figure 1 show a comparison of field data with calculated data on US 1, southbound at Avenel Street, Woodbridge, N.J. Field data were collected by a five man party pressing telegraph keys wired to an Eaterline—Angus 20 pen. recorder during the summer of 1958. US 1 has 37,000 cars per average day with 10 percent heavy trucks and 25 percent total trucks. The posted speed limit is 50 mph for 8 mi to the

TABLE 2

US 1, NORTHBOUND, AT AVENEL STREET

$$T_p = 1.2N + \frac{.95}{48}\sqrt{\left\{D + 25(N-1)\right\}\left\{D + 25(N-1) + 576\right\}}$$

PASSENGER CARS

N	D = 52 FEET				D = 153 FEET				D = 222 FEET			
	Samples	Field	Calc.	Diff.	Samples	Field	Calc.	Diff.	Samples	Field	Calc.	Diff.
1	159	4.74	4.78	+.04	24	8.62	7.81	-.81	72	10.29	9.53	-.76
2	111	6.84	6.83	-.01	5	9.28	9.64	+.36	17	11.68	11.33	-.35
3	69	8.90	8.81	-.09					3	16.43	13.10	-3.33
4	46	10.63	10.72	+.09								
5	29	12.61	12.59	-.02								
6	17	14.18	14.42	+.24								
7	11	16.15	16.24	+.09								
8	11	18.02	18.05	+.03								
9	1	21.90	19.84	-2.06								
10	1	25.20	21.62	-3.58								
11	1	27.40	23.39	-4.01								

$$T_t = 2.25N + \frac{1.32}{48}\sqrt{\left\{D + 50(N-1)\right\}\left\{D + 50(N-1) + 576\right\}}$$

TRUCKS

1	117	6.38	7.23	+.85	32	10.89	11.45	+.56	103	13.59	13.83	+.24
2	63	10.88	11.74	+.86	17	14.95	15.39	+.44	60	18.02	17.70	-.32
3	28	14.97	15.91	+.94	10	18.83	19.34	+.51	32	21.72	21.55	-.17
4	14	19.00	19.89	+.89	5	22.90	23.19	+.29	16	25.86	25.34	-.52
5	6	23.33	23.79	+.46	3	26.20	26.99	+.79	8	29.52	29.10	-.42
6	3	26.83	27.65	+.82					2	33.05	32.82	-.23
7	3	30.63	31.65	+1.02								

TABLE 2

US 1, NORTHBOUND, AT AVENEL STREET (Cont'd)

$$T_p = 1.2N + \frac{.95}{48}\sqrt{\left\{D + 25(N-1)\right\}\left\{D + 25(N-1) + 576\right\}}$$

PASSENGER CARS

	D = 237 FEET				D = 471 FEET				D = 685 FEET			
N	Samples	Field	Calc.	Diff.	Samples	Field	Calc.	Diff.	Samples	Field	Calc.	Diff.
1	110	10.00	9.89	-.11	155	15.00	15.09	+.09	19	19.77	19.59	-.18
2	90	12.08	11.68	-.40	96	16.98	16.83	-.15	5	24.36	21.32	-3.04
3	72	13.90	13.46	-.44	69	18.98	18.56	-.42				
4	52	15.63	15.21	-.42	49	20.55	20.30	-.25				
5	30	16.82	16.98	+.16	30	21.48	22.01	+.53				
6	19	18.54	18.74	+.20	17	23.44	23.75	+.31				
7	12	20.80	20.47	-.33	10	25.12	25.46	+.34				
8	11	22.76	22.23	-.53	7	26.50	27.17	+.67				

$$T_t = 2.25N + \frac{1.32}{48}\sqrt{\left\{D + 50(N-1)\right\}\left\{D + 50(N-1) + 576\right\}}$$

TRUCKS

N	Samples	Field	Calc.	Diff.	Samples	Field	Calc.	Diff.	Samples	Field	Calc.	Diff.
1	44	13.67	14.35	+.68	99	20.73	21.56	+.83	43	25.96	27.82	+1.86
2	19	18.49	18.18	-.31	56	25.33	25.29	-.04	18	30.72	31.48	+.76
3	4	22.88	22.00	-.88	30	28.78	29.00	+.22	4	33.95	35.23	+1.28
4	2	24.20	25.80	+1.60	16	33.65	32.70	-.95				
5					8	36.68	36.40	-.28				
6					2	39.45	40.08	+.63				

south and 1.5 mi to the north. Beyond these points the posted speed limit is 45 mph. The highway is level and tangent with 32 ft of concrete pavement on each side of a 16-ft raised median. The pavement is lane lined for three lanes in each direction. There are very few pedestrians but some marginal friction exists because of frequent gas stations, etc. Data collected were for passenger cars in the left-hand lane.

Field data shown are the average time for the number of samples; that is the sum of the individual times divided by the number of samples. A frequency speed diagram is shown in Figure 2.

For 100 percent passenger cars not affected by turning vehicles, the perception and reaction time P is found, by experiment, to be 1.2 and to be the same for the Nth car as for the first car. This value is found to increase as the speed decreases and to be different for trucks and passenger cars. For heavy trucks the value is 2.25.

The value for K for passenger cars is found to be 0.95 and for heavy trucks, 1.32. These values satisfy the test samples observed. The passenger car value seems to be constant for all locations. This is probably true because there is very little difference in the average passenger car at different locations. If all passenger cars were small low priced cars at one location and large high priced cars at another location, there probably would be a difference. The value for trucks undoubtedly varies from location to location. Predominantly loaded trucks will give a different value than unloaded trucks and there is a wide variation in performance ability of different makes and models of trucks.

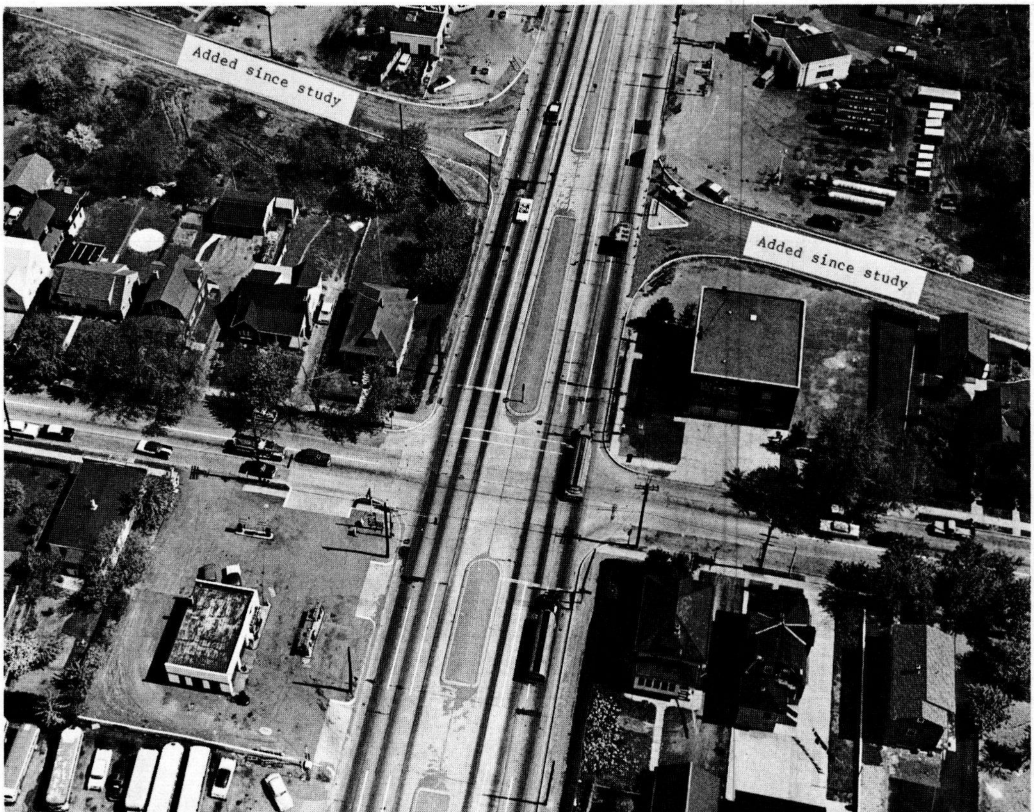


Figure 3. US 1 at Avenel Street, Woodbridge (looking north).

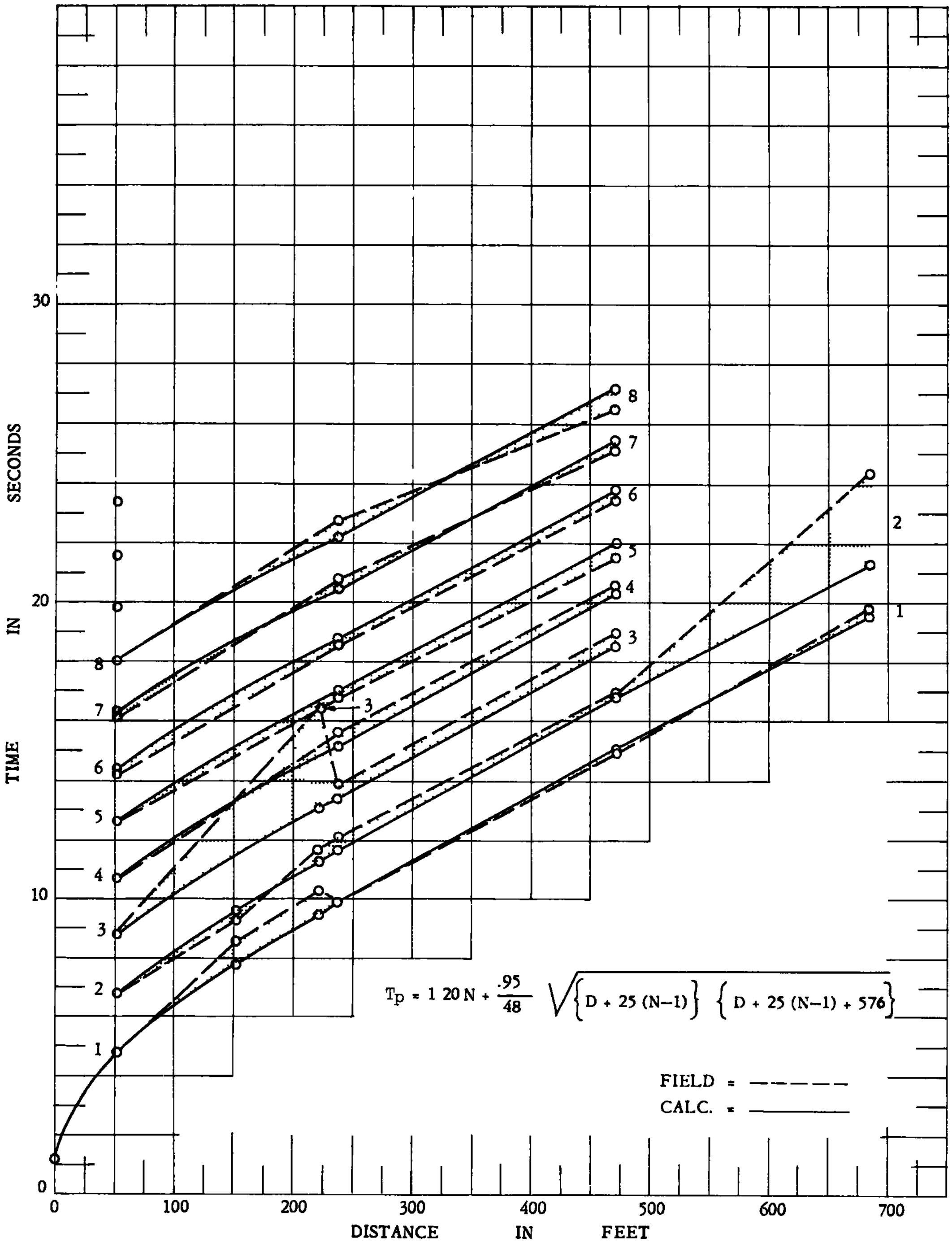


Figure 4. US 1, northbound, at Avenel Street—passenger cars.

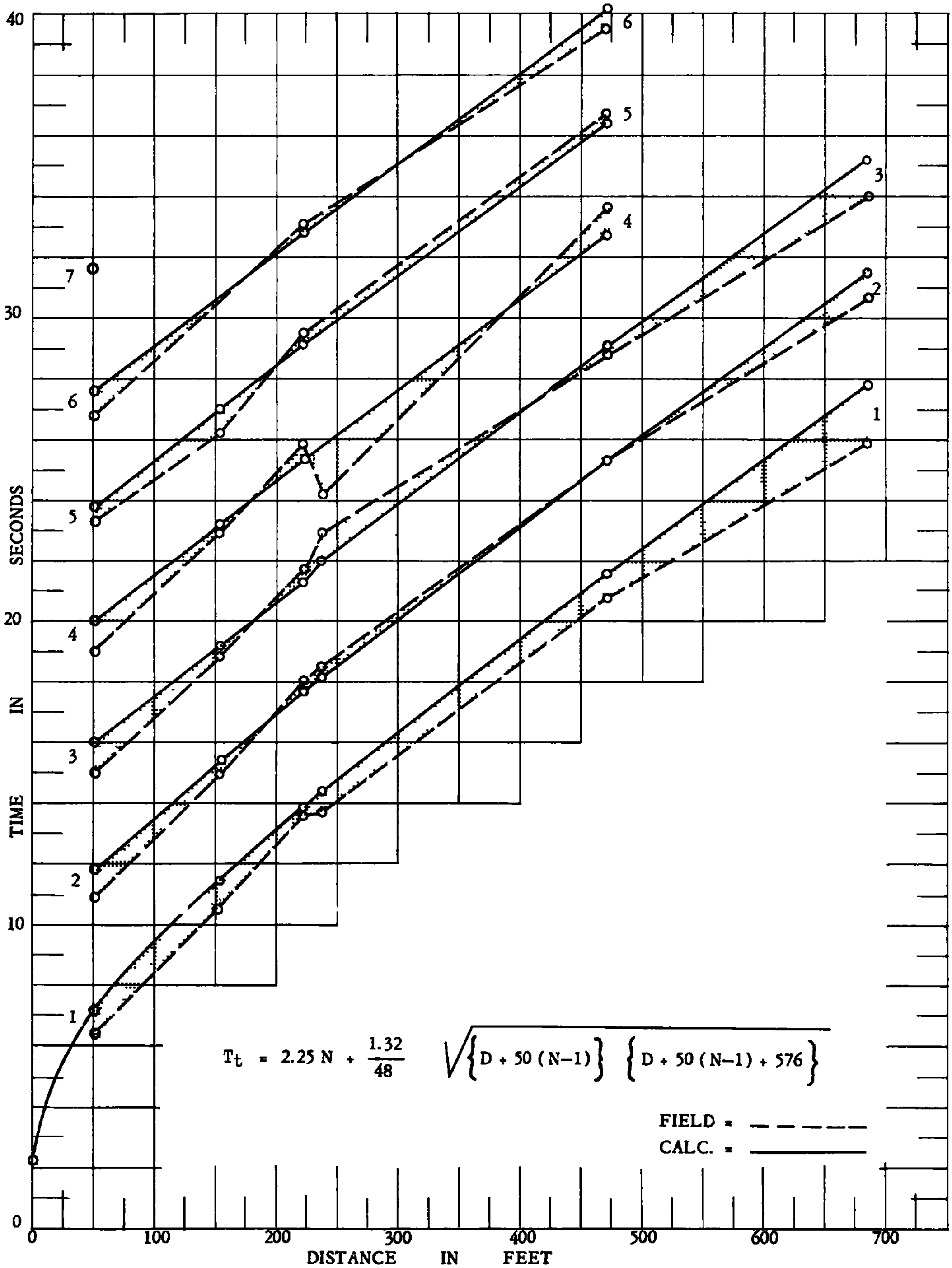


Figure 5. US 1, northbound, at Avenel Street—trucks.

TABLE 3

CALHOUN STREET, SOUTHBOUND, AT INGHAM AVENUE

$$T_p = 2N + \frac{.95}{29} \sqrt{\left\{D + 25\,(N-1)\right\} \left\{D + 25\,(N-1) + 210.25\right\}}$$

PASSENGER CARS

	D = 30 FEET				D = 240 FEET				D = 441 FEET			
N	Samples	Field	Calc.	Diff.	Samples	Field	Calc.	Diff.	Samples	Field	Calc.	Diff.
1	64	4.48	4.72	+.24	62	12.22	12.78	+.56	52	19.11	19.56	+.45
2	42	7.48	7.96	+.48	42	15.17	15.63	+.46	34	22.69	22.38	-.31
3	19	11.47	10.98	-.49	18	18.34	18.48	+.14	16	25.24	25.23	-.01
4	8	13.69	13.96	+.27	8	21.41	21.33	-.08	7	28.07	28.05	-.02
5	2	15.85	16.88	+1.03	2	23.45	24.28	+.83	2	30.40	30.87	+.47

TRUCKS

1	9	4.07			8	13.96			8	22.30		

The value of C for passenger cars is 25 ft. This consists of the length of the average passenger car measured from bumper to bumper plus the average spacing between standing vehicles measured from the rear bumper of one vehicle to the front bumper of the vehicle immediately in back. The length of the average passenger car is taken as 17 ft and the space between as 8 ft.

The C for heavy trucks is 50 ft for the US 1 location and assumed to be the same for locations with similar types of trucks. The 50 ft is taken as composed of 42 ft for the length of vehicle and 8 ft for the space between vehicles. It is possible that this is in error in that the average heavy truck may be less than 42 ft long and the space between trucks may be longer than 8 ft.

US 1 northbound, at Avenel Street (Fig. 3), data are given in Table 2 and shown in Figures 4 and 5. Samples selected from field data include only 100 percent samples. That is, the Nth truck was preceded by N-1 trucks. Passenger cars were selected similarly. Where the Nth vehicle was preceded by some trucks and some passenger cars, data were tabulated but not included in this part of the study.

Calhoun Street northbound, at Ingham Avenue, in Trenton has one moving lane with parked vehicles along the curb. It is an urban location close to the central business district with a legal speed limit of 25 mph. Comparative data are shown in Table 3 and Figure 6.

Brunswick Avenue southbound, at Olden Avenue, in Trenton (Fig. 7), is an urban area similar to the Calhoun Street location. Comparative data are shown in Table 4 and Figure 8.

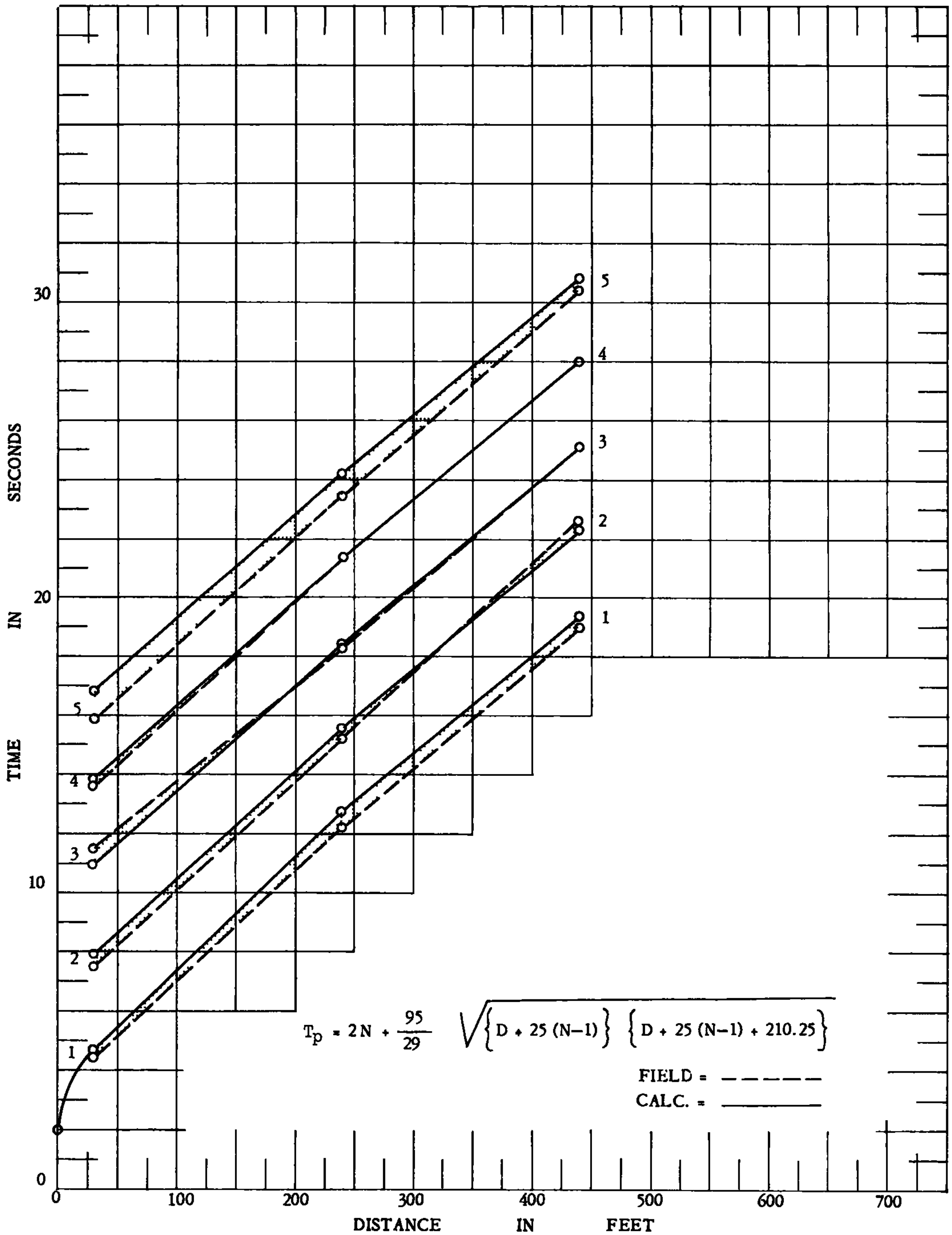


Figure 6. Calhoun Street, northbound, at Ingham Avenue—passenger cars.

TABLE 4

BRUNSWICK AVENUE, SOUTHBOUND, AT OLDEN AVENUE

$$T_p = 2N + \frac{.95}{30} \sqrt{\left\{ D + 25(N-1) \right\} \left\{ D + 25(N-1) + 225 \right\}}$$

PASSENGER CARS

	D = 40 FEET				D = 400 FEET				D = 485 FEET			
N	Samples	Field	Calc.	Diff.	Samples	Field	Calc.	Diff.	Samples	Field	Calc.	Diff.
1	49	5.51	5.26	-.25	47	17.25	17.83	+.58	44	19.51	20.59	+1.08
2	21	9.19	8.34	-.85	21	20.98	20.66	-.32	20	23.40	23.38	-.02
3	11	11.99	11.32	-.67	11	23.48	23.45	-.03	10	25.90	26.20	+.30

TRUCKS

1	13	6.22			12	19.44			11	21.63		
2	4	12.25			2	22.30			2	24.55		

TRAFFIC SIGNAL CAPACITY AND SIGNAL TIMING

Free flowing traffic on an open highway has time intervals between successive vehicles which vary according to laws of probability. Figure 9 shows the maximum number of vehicles approaching in short time intervals for given hourly volumes of approach traffic based on Poisson's theory of probability. Part vehicles are dropped off and it is limited to one such hour. Theoretically a million such hours would give a larger maximum number per short time interval than that shown.

Figure 10 shows the number of seconds required to pass a given maximum number of vehicles per short time cycle in accelerating from a stopped position as occurs under traffic signal control. At a traffic signal the number of vehicles arriving during a traffic signal cycle of red, amber and green, must be passed during the green period of that cycle in order to avoid backing up and requiring vehicles to wait during more than one red period. This figure applies for uninterrupted passenger cars on a road where the real speed limit is 50 mph. It can be used to determine the signal timing and cycle required for design hour volumes or to determine the capacity of a given cycle and timing.

A traffic signal can carry the maximum number of cars during each cycle which results in the absolute capacity but this occurs when the signal is greatly over-loaded and traffic is backed up for a long distance with vehicles must waiting for many changes of signal before passing through. This is a degree of congestion to be avoided. The signal timing should be such that the maximum number of vehicles per cycle occurs only once during the design hour. This is the design capacity of the signal timing.

Figures 11, 12, 13 show similar charts for use on 40-, 30- and 20-mph roads for passenger cars on level grades and with normal daylight and weather conditions.

Figure 14 is a similar chart for heavy trucks on a 50-mph road on level grades and with normal daylight and weather conditions.

Figure 7. Brunswick and Olden Avenues, Trenton.

These charts are developed from the use of Eq. 1 with the following variables:

	S	P	K	C
Passenger Cars	50	1.2	0.95	25
Passenger Cars	40	1.6	0.95	25
Passenger Cars	30	2.0	0.95	25
Passenger Cars	20	2.4	0.95	25
Heavy Trucks	50	2.25	1.32	50

Figure 15 shows the timing required for each of the above charts for ease of comparison of the effect of speed and vehicle type. Also included are cycle lengths up to 300 sec. Some of this is extended beyond the limits of practical application but this is done for analytical purposes only. Certainly to have 70 heavy trucks in line go through a signal cannot be expected but this should have a bearing on possible application for a short cut method of signal timing on the bases of percentage of trucks to total hourly volume.

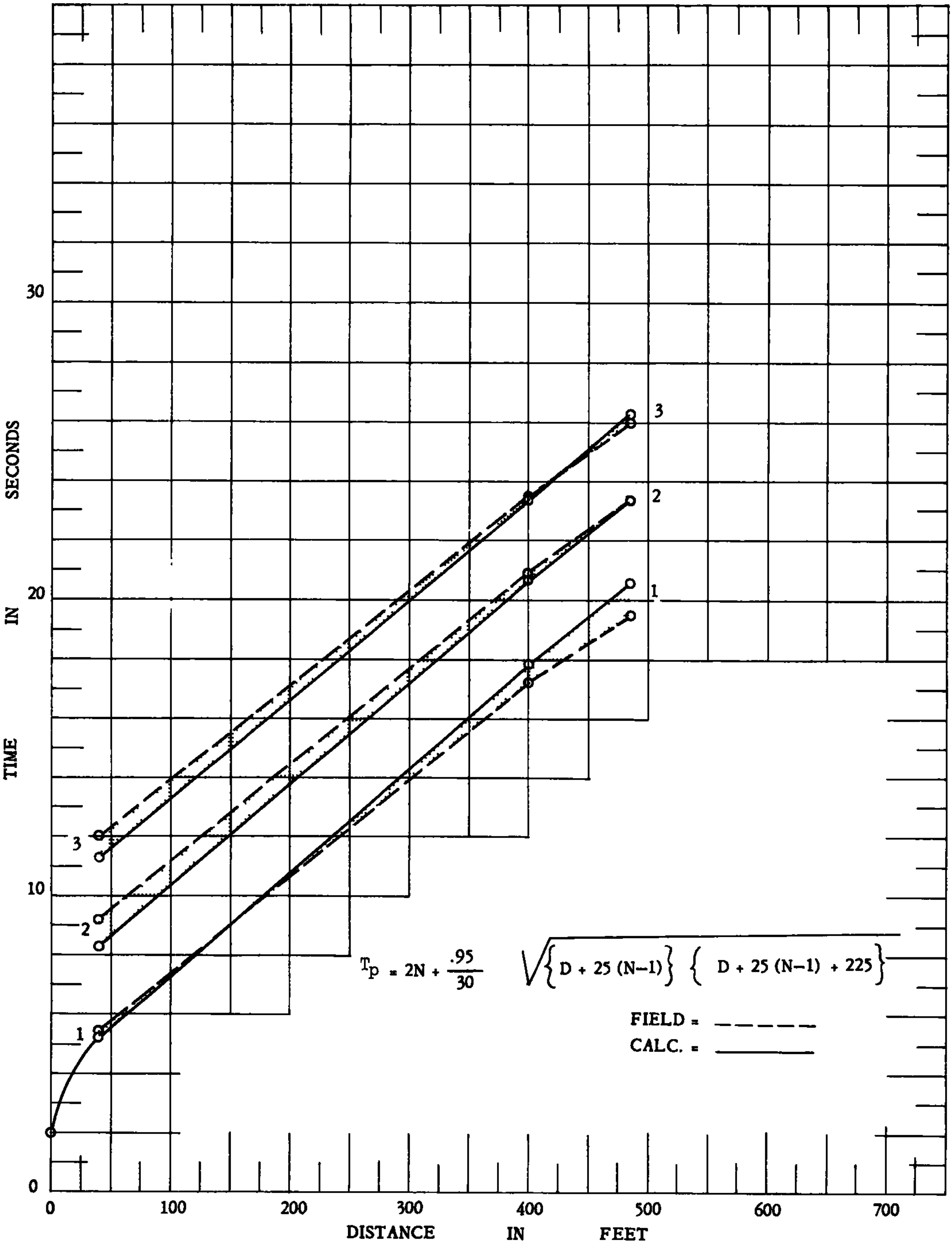
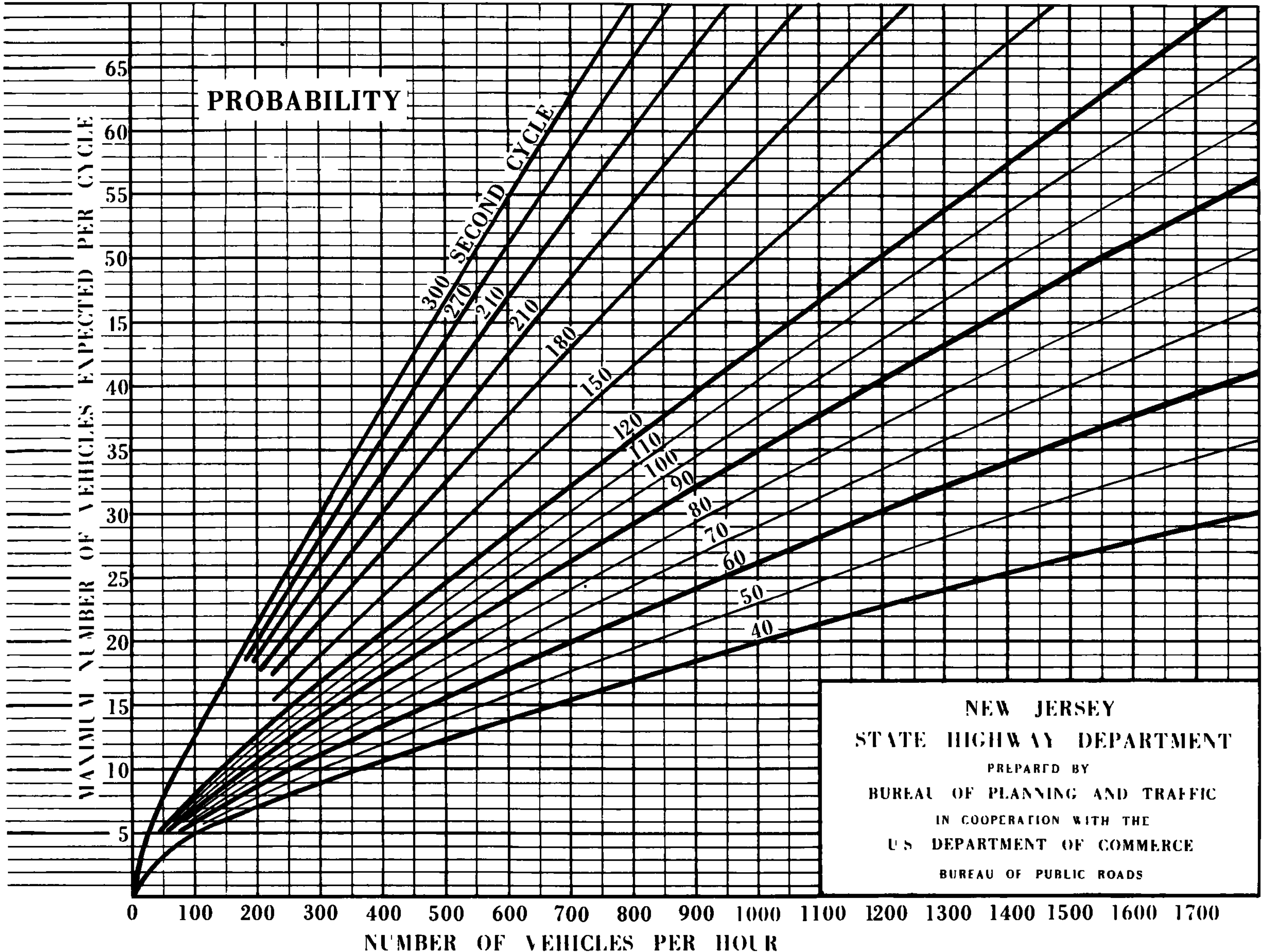


Figure 8. Brunswick Avenue, southbound, at Olden Avenue—passenger cars.

It is planned to continue this study to include the effect of upgrade, downgrade, nighttime and rainy weather.

It is also planned to extend this study to include the effect of closely spaced signalized locations, such as experienced in high type complex channelization.


PROBABILITY
300 SECOND CYCLE
270
210
210
180
150
120
110
100
90
80
70
60
50
40
MAXIMUM NUMBER OF VEHICLES EXPECTED PER CYCLE
NUMBER OF VEHICLES PER HOUR
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700
5 10 15 20 25 30 35 40 45 50 55 60 65
NEW JERSEY
STATE HIGHWAY DEPARTMENT
PREPARED BY
BUREAU OF PLANNING AND TRAFFIC
IN COOPERATION WITH THE
U S DEPARTMENT OF COMMERCE
BUREAU OF PUBLIC ROADS

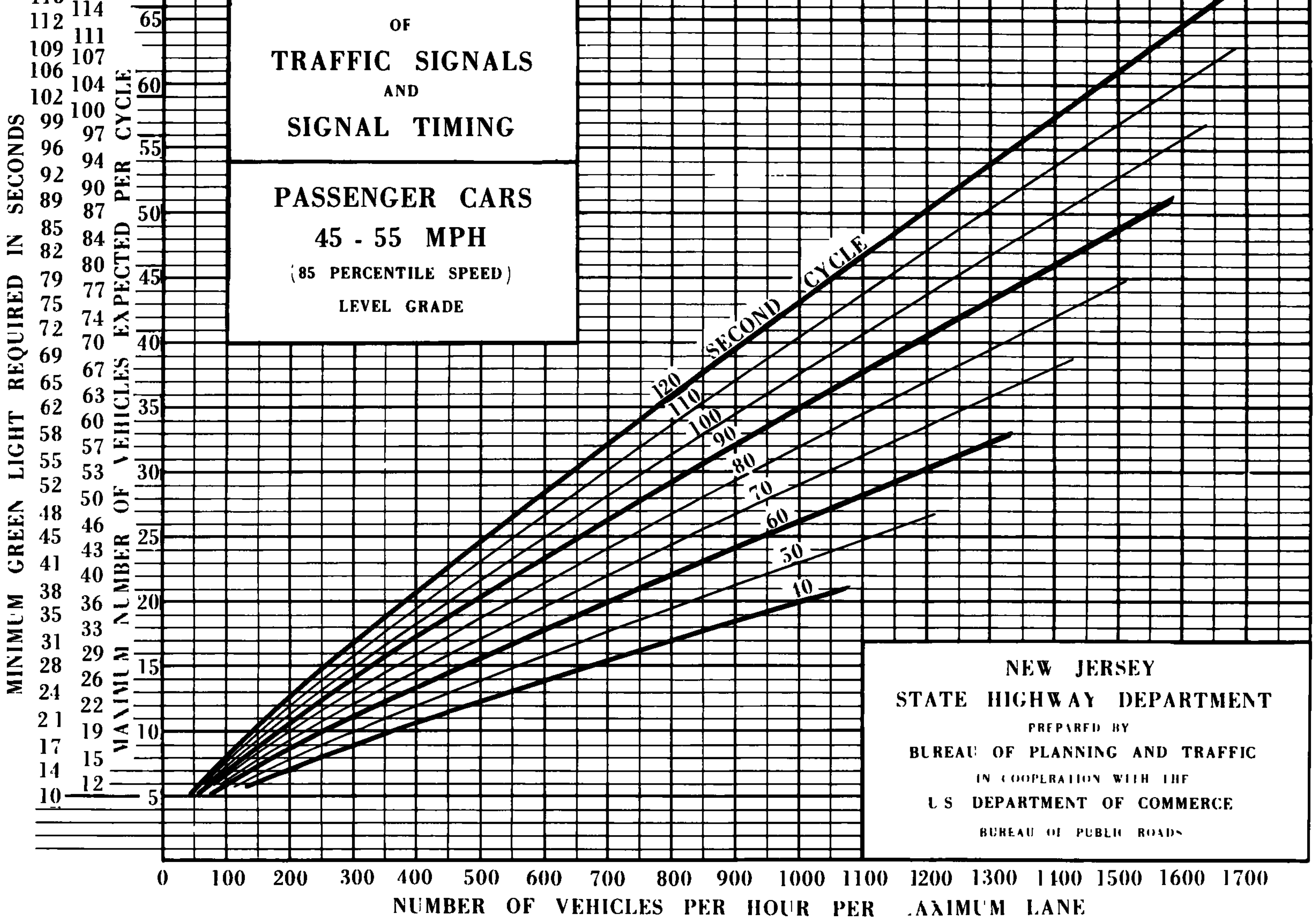
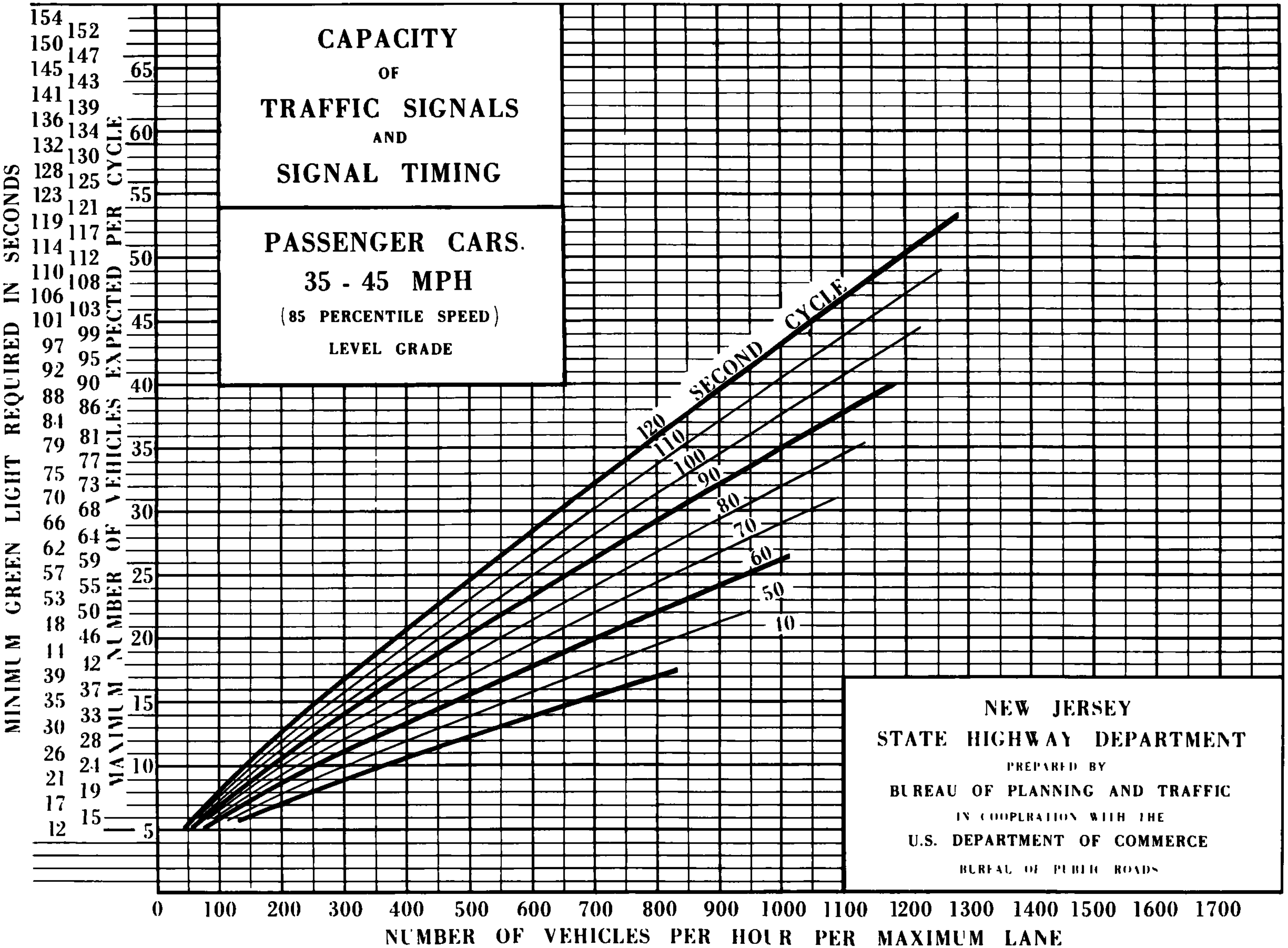

OF
TRAFFIC SIGNALS
AND
SIGNAL TIMING
PASSENGER CARS
45 - 55 MPH
(85 PERCENTILE SPEED)
LEVEL GRADE
120 SECOND CYCLE
110
100
90
80
70
60
50
40
NEW JERSEY
STATE HIGHWAY DEPARTMENT
PREPARED BY
BUREAU OF PLANNING AND TRAFFIC
IN COOPERATION WITH THE
U S DEPARTMENT OF COMMERCE
BUREAU OF PUBLIC ROADS
MINIMUM GREEN LIGHT REQUIRED IN SECONDS
MAXIMUM NUMBER OF VEHICLES EXPECTED PER CYCLE
NUMBER OF VEHICLES PER HOUR PER MAXIMUM LANE
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700

Figure 10.


CAPACITY
OF
TRAFFIC SIGNALS
AND
SIGNAL TIMING
PASSENGER CARS.
35 - 45 MPH
(85 PERCENTILE SPEED)
LEVEL GRADE
120 SECOND CYCLE
110
100
90
80
70
60
50
40
MINIMUM GREEN LIGHT REQUIRED IN SECONDS
MAXIMUM NUMBER OF VEHICLES EXPECTED PER CYCLE
NUMBER OF VEHICLES PER HOUR PER MAXIMUM LANE
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700
NEW JERSEY
STATE HIGHWAY DEPARTMENT
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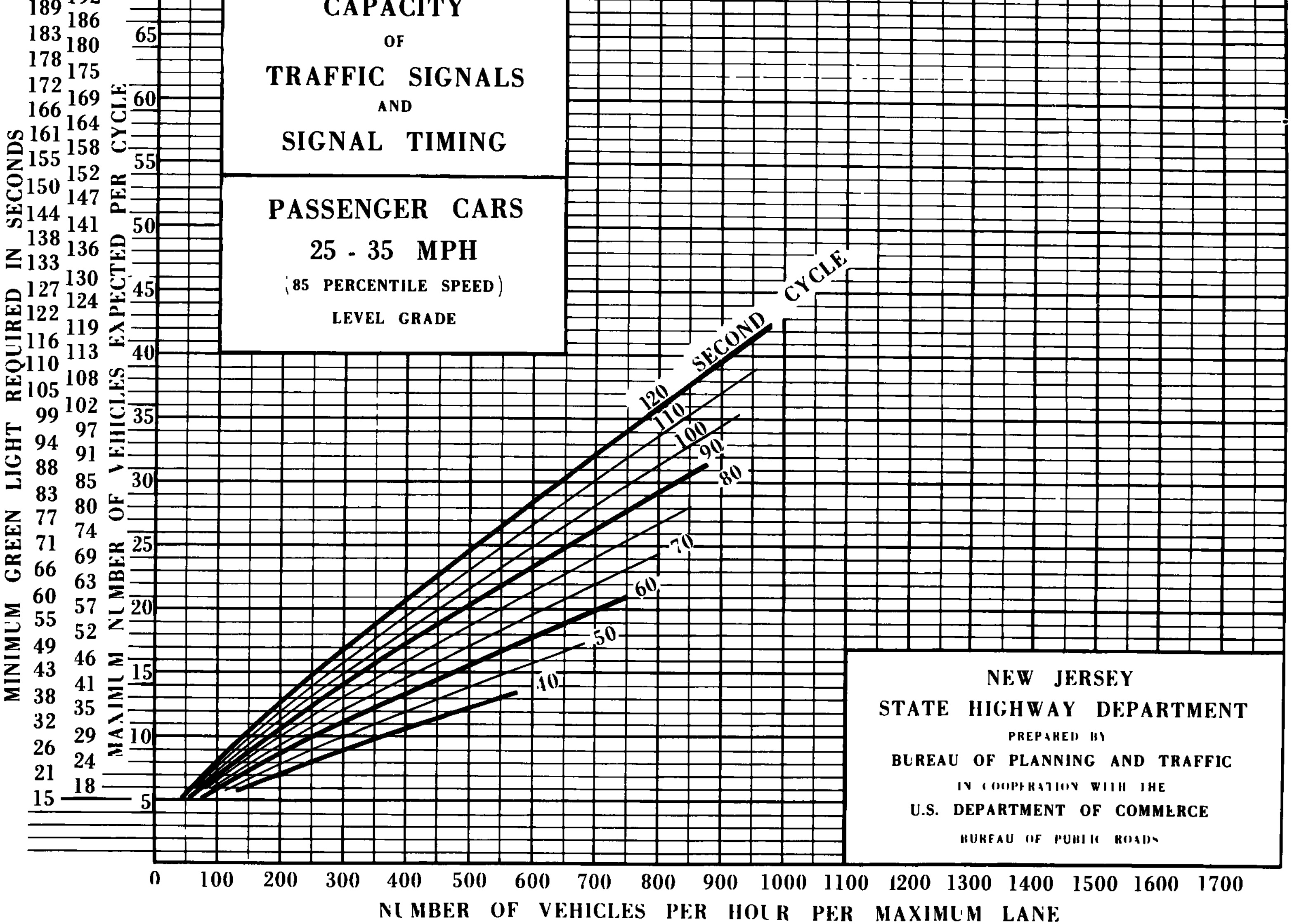
CAPACITY
OF
TRAFFIC SIGNALS
AND
SIGNAL TIMING
PASSENGER CARS
25 - 35 MPH
(85 PERCENTILE SPEED)
LEVEL GRADE
120 SECOND CYCLE
110
100
90
80
70
60
50
40
MINIMUM GREEN LIGHT REQUIRED IN SECONDS
MAXIMUM NUMBER OF VEHICLES EXPECTED PER CYCLE
NUMBER OF VEHICLES PER HOUR PER MAXIMUM LANE
NEW JERSEY
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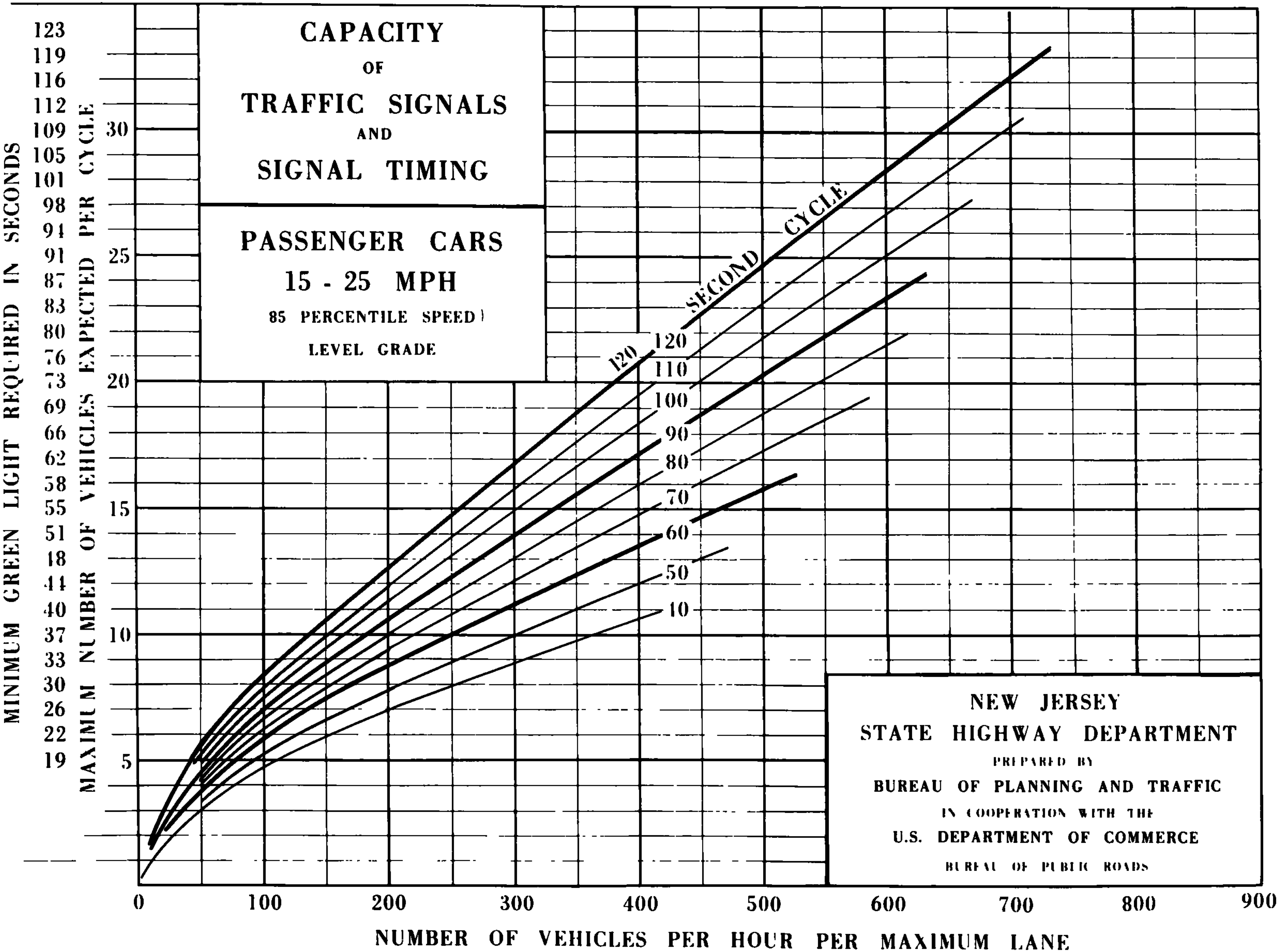
Figure 12.


CAPACITY
OF
TRAFFIC SIGNALS
AND
SIGNAL TIMING
PASSENGER CARS
15 - 25 MPH
85 PERCENTILE SPEED)
LEVEL GRADE
120 SECOND CYCLE
120
110
100
90
80
70
60
50
40
MINIMUM GREEN LIGHT REQUIRED IN SECONDS
123
119
116
112
109
105
101
98
94
91
87
83
80
76
73
69
66
62
58
55
51
48
44
40
37
33
30
26
22
19
MAXIMUM NUMBER OF VEHICLES EXPECTED PER CYCLE
30
25
20
15
10
5
0
100
200
300
400
500
600
700
800
900
NUMBER OF VEHICLES PER HOUR PER MAXIMUM LANE
NEW JERSEY
STATE HIGHWAY DEPARTMENT
PREPARED BY
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IN COOPERATION WITH THE
U.S. DEPARTMENT OF COMMERCE
BUREAU OF PUBLIC ROADS

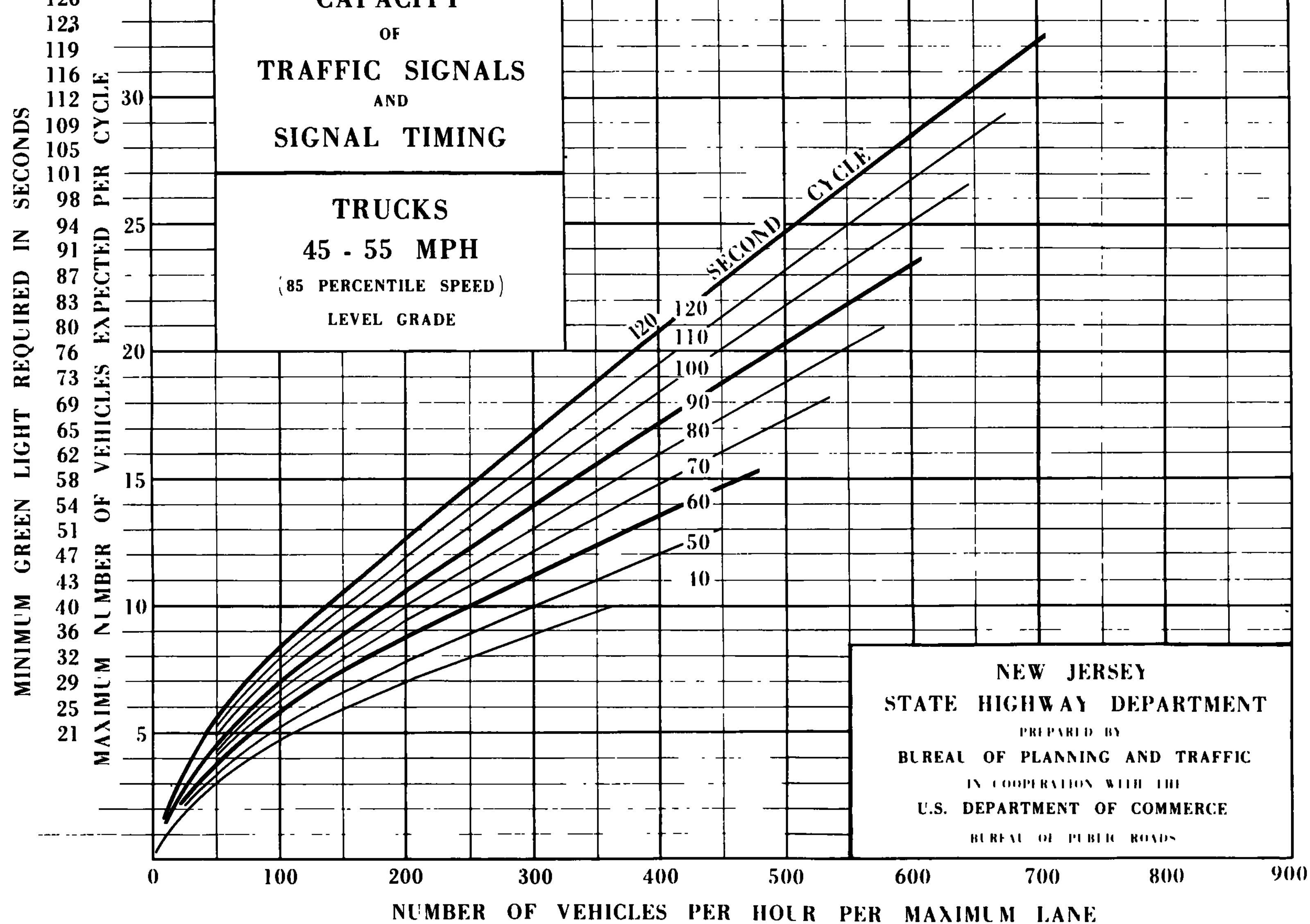
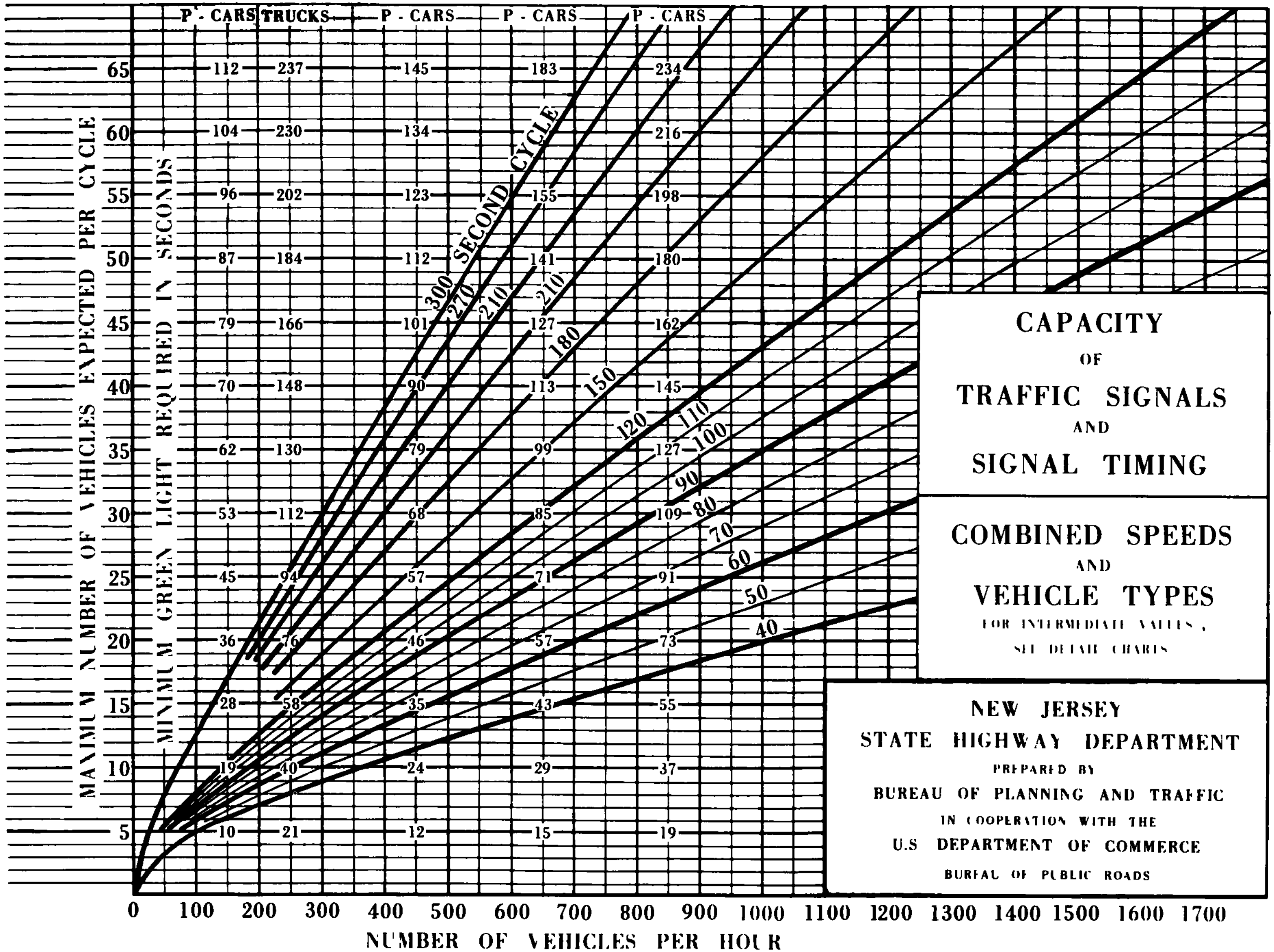

OF
TRAFFIC SIGNALS
AND
SIGNAL TIMING
TRUCKS
45 - 55 MPH
(85 PERCENTILE SPEED)
LEVEL GRADE
120 SECOND CYCLE
120
110
100
90
80
70
60
50
10
NEW JERSEY
STATE HIGHWAY DEPARTMENT
PREPARED BY
BUREAU OF PLANNING AND TRAFFIC
IN COOPERATION WITH THE
U.S. DEPARTMENT OF COMMERCE
BUREAU OF PUBLIC ROADS
MINIMUM GREEN LIGHT REQUIRED IN SECONDS
123
119
116
112
109
105
101
98
94
91
87
83
80
76
73
69
65
62
58
54
51
47
43
40
36
32
29
25
21
MAXIMUM NUMBER OF VEHICLES EXPECTED PER CYCLE
30
25
20
15
10
5
0
100
200
300
400
500
600
700
800
900
NUMBER OF VEHICLES PER HOUR PER MAXIMUM LANE

Figure 14.


CAPACITY
OF
TRAFFIC SIGNALS
AND
SIGNAL TIMING
COMBINED SPEEDS
AND
VEHICLE TYPES
NEW JERSEY
STATE HIGHWAY DEPARTMENT
PREPARED BY
BUREAU OF PLANNING AND TRAFFIC
IN COOPERATION WITH THE
U.S DEPARTMENT OF COMMERCE
BUREAU OF PUBLIC ROADS
MAXIMUM NUMBER OF VEHICLES EXPECTED PER CYCLE
MINIMUM GREEN LIGHT REQUIRED IN SECONDS
NUMBER OF VEHICLES PER HOUR
P - CARS
TRUCKS
P - CARS
P - CARS
P - CARS
300 SECOND CYCLE
270
210
210
180
150
120
110
100
90
80
70
60
50
40
5
10
15
20
25
30
35
40
45
50
55
60
65
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
112 237 145 183 234
104 230 134 216
96 202 123 155 198
87 184 112 141 180
79 166 101 127 162
70 148 90 113 145
62 130 79 99 127
53 112 68 85 109
45 94 57 71 91
36 76 46 57 73
28 58 35 43 55
19 40 24 29 37
10 21 12 15 19

Appendix

After having the benefit of comments by the Division of Traffic Operations of the Bureau of Public Roads, the Department of Traffic and Operations of the Highway Research Board, and others, the author wishes to add the following:

Although the paper makes no reference to the methodology utilized to derive the acceleration equation (Eq. 1), the experienced researcher realizes that there was much preliminary work. It may be possible, with the given field data, to arrive directly at the desired equation, but not so with this researcher.

The first attempt to write this paper included a description of the procedures and methods used but this seemed useless. The only useful part is the equation and its application. It would have been easy for highly rated mathematicians to "prove" that the procedure was wrong (and most of it was) even though the conclusions had practical value. Possibly the author did not care to display his ignorance compared to some of the fancy mathematics floating around these days.

The method used was "trial and success." Different basic mathematical equations were tried for fit with field data. Much field data were collected, most of which was finally treated as pilot studies. Assuming that Eq. 1 receives widespread application (as the author hopes) very few, if any, individuals will really care how it was derived.

Reference is made to adding feet and speed squared under the radical—which it seems is not "cricket." The author has no reply except that this was necessary to make a close fit.

Consideration was given to vehicles anticipating the green signal and accelerating before the signal changed. This behavior is included in these data collected. Some cars did start before the green signal and some were caught napping. Reference is made to an apparent disagreement with a paper "Starting Delay and Time Spacing of Vehicles Entering Signalized Intersections" by Bartle, Skoro and Gerlough, in HRB Bul. 112. It is quite possible that the two papers are in agreement, with the variables different but interpreted as the same. The value of P in the equation was not assumed; it was determined by trial and success to fit these data and gives the same value for the first car as for the Nth car.

A question has been raised as to how the capacity charts were developed from the acceleration equation. On the probability chart, the time for each maximum number of vehicles expected per cycle to arrive at the 50-ft point beyond the stop line after the beginning of the green signal was placed along side each corresponding maximum number of vehicles expected per cycle. These times were determined from Eq. 1 substituting 50 ft for D and applicable values for each of the other variables. Having done this the chart plotting is reduced to the applicable ranges.

The author cannot explain the unit values of K. It developed from the trial and success method to make a fit.

In the text S has been defined as equal to the speed limit (real). In the equation S is the speed reached after completing acceleration. This is a limit and in this sense each car has its speed limit. The value of S was determined by trial and success for each test location for a fit with these field data. The values for fit did not equal the legal speed limit or the 85 percentile speed. For US 1 southbound passenger cars S was 52: for US 1 northbound passenger cars it was 48, for US 1 northbound trucks it was 48. Here the posted speed limit is 50 mph based on the 85 percentile test. For Calhoun Street passenger cars S was 29 and for Brunswick Ave. passenger cars it was 30 and the posted speed limit is 25 mph. It so happens that the speed in the equation and the posted speed limit (if real) are reasonably close and, therefore, in the use of the charts the 85 percentile speed is used. Where the posted speed limit is based on the 85 percentile speed, the posted speed limit is used. Where it is known that the posted speed limit is not reasonable a reasonable speed should be used. At the Calhoun St. and the Brunswick Ave. locations the posted speed limits are 25 mph. A knowledge of the location would show that this is on the low side although justified rather than a speed limit of 30 mph. For these locations the 25 to 35 mph chart would be used rather than the 15 to 25 mph chart.

The application of speed to traffic is a very easily confused factor. When a posted speed limit is needed what should it be? Certainly it should be a speed somewhere between the lower limit and the upper limit of the individual speeds. For enforcement purposes it was agreed that it should be higher than the average or the mean so it was set at the 85 percent point as determined during off hours. It could have been 80 percent, 90 percent, 95 percent or other. At 85 percent the posted speed limit will be exceeded by 15 percent of the drivers who may very well be among the best citizens but all made to look like law breakers. All 85 percentile speed determined on a Sunday, weekday or Saturday could vary widely. It could differ if determined in the a.m. or p.m. or by hours. Morning commuters travel faster than midafternoon traffic. Hot or cold weather makes a difference. There are many influencing factors but the aim is to arrive at an acceptable, reasonable and enforceable speed limit. For some other applications it is better to use the average speed. In clocking speeds of all cars on a multilane one-way roadway, through a distance, it is found that speeds are highly variable even where acceleration is not a factor. The speed of the same car varies through the distance; the speed of, even, successive cars varies; and the speeds in different lanes vary. The best that can be done is to arrive at a speed which is representative and usable for the purpose at hand. Very confusing observations have been made in attempting to apply speed to traffic problems but they are too complex to discuss here.

It so happens that the S in Eq. 1 is reasonably close to the speed limit as determined by the 85 percentile method and this provides a convenient value to use in the application of the signal charts.

It has been suggested that the S be made equal to the 85 percentile speed and compensate for this with a constant. The 85 percentile speed is not conveniently available but the posted speed limit very often is available. If the posted speed limit is used there is no constant to take care of the change. From data available there is no constant to equate S to an 85 percentile speed.

USE OF THE CHARTS

Example 1.—Given; a 60-sec cycle with 27 sec green in an area where the posted speed limit, as determined by the 85 percentile method, is 30 mph; find the capacity per maximum lane. Solution: on the 25-35 mile per hour chart (Fig. 12) find 27 sec minimum green light required. Here we must use 26 seconds which is the next lower time given. The use of 27 interpolated would give 9⅓ cars during the maximum cycle. Only whole cars can be used. From this 26-sec point go to the right horizontally to an intersection with the 60-sec cycle line and then go down vertically to obtain 210 passenger vehicles per hour per maximum lane as the design capacity per maximum lane. To find the absolute capacity per maximum lane: from the 26 sec go to the right and find 9 as the maximum number of vehicles expected per cycle. Multiply 9 times the number of cycles in an hour or (3,600 sec divided by 60 sec) 60 to obtain 540 passenger cars which is the absolute capacity per maximum lane.

Example 2.—Given a design hour of 400 passenger cars per hour per maximum lane in an area where the posted speed is 40 mph determined by the 85 percentile method; find a signal timing that will have a design capacity of the 400 passenger cars per maximum lane per hour. Solution: On the 35 to 45 mph passenger car chart (Fig. 11) find 400 vehicles per hour per maximum lane then go up vertically to intersect a cycle length line; then go horizontally to the left to find the minimum green light required. If a 60-sec cycle had been selected, a green time of 33 sec would be required. The 31 sec matches 13⅓ cars so the 33 sec must be used to avoid the part car. With 3-sec ambers this would give 21 sec on the crossroad. It may be desirable to have equal greens on the crossroads. In this case an 80-sec cycle, or longer, will satisfy. Using an 80-sec cycle start at 400 vehicles per hour per maximum lane and go up to in-

tersect with the 80-sec cycle line, then to the left to read 37-sec minimum green light required. Adjacent to the 37 sec is 16 as the maximum number of cars per cycle, so 16 times 3,600 sec divided by 80 sec equals 720 cars as the absolute capacity.

Report of Committee on Highway Capacity

O.K. NORMANN, Chairman; Deputy Assistant Commissioner for Research, U.S. Bureau of Public Roads

● AT THE January 10, 1960 meeting of the Highway Capacity Committee it was generally agreed that the 1950 edition of the Manual should be rewritten as quickly as possible and published to include more current information now available even though admittedly there are many areas where further research is necessary. The subcommittees were reorganized and each will attempt to prepare a rough draft of the various chapters by June 1960.

It was agreed that no wholesale rewriting of definitions was necessary. This work will be coordinated with the work of other committees on definitions, and in general, will be in agreement with the AASHO definitions where applicable.

The capacities of rural highways and facilities with uninterrupted flow need some refinements, but in general, it is apparent that there will be no major changes. The refinements will include more reliable data regarding the effect of trucks, particularly on grades, and the effect of marginal friction conditions. It is also evident that rural highway speeds have increased during the past ten years but that this fact will probably not change practical capacities appreciably since higher speeds are now desired for rural conditions. A new table showing maximum observed volumes on existing facilities will be included in the revision.

The principal need in connection with the capacities of weaving sections is to properly present the results of studies so that they will not be misused. This is especially true for compound weaving sections where more than two basic weaving movements occur. The need for information and its application to compound weaving sections is one of the more pressing problems in connection with freeway design.

During the past several years many studies have been made to determine the capacities of "on" and "off" ramps. Most of these studies have been in great detail but include a very limited number of locations. To supplement these data with less detailed but adequate information covering a large number of ramp locations throughout the country, the committee will soon initiate a nationwide study which will relate traffic volumes on ramps that are approaching their capacities to the traffic volumes on the freeway and to the geometric features at the ramp terminals. This information will supplement the more detailed studies which it has been possible to conduct at relatively few locations and the work that has been done in simulating traffic conditions at ramps for capacity and design purposes. This chapter of the Manual cannot be completed until the fall of 1960 since most of the field data must be obtained during the summer months.

Intersection capacities have increased during the past ten years, especially for the wider streets. The extent to which improved vehicle and driver performance have contributed cannot be determined but it is believed that most of the increase is the result of better use of improved traffic-control equipment. The analysis of the data obtained by the nationwide study of traffic volumes handled by intersections operating at or near their possible capacities has been a major undertaking and will not be completed before mid-1960.

It is expected that the content and format of the revised manual will be much the same as the present manual.

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