DESIGN OF THE WAR DEPARTMENT BUILDING ROAD NETWORK

(Pentagon Building)

By Joseph Barnett

Principal Highway Design Engineer, Public Roads Administration

SYNOPSIS

This paper describes the problems encountered and the solution adopted when, upon the already congested roads in Arlington County across the Potomac River from the District of Columbia, there was superimposed a new road pattern and high traffic volume engendered by a new building to provide office space for 40,000 workers of the War Department and by other buildings nearby for 16,000 other Government workers The Network as finally designed and now nearing completion consists of 17 miles of one-way through roads, 7 7 miles of one-way ramps and 21 grade separation structures, one a triple decker These lengths do not include several miles of service roads connecting through roads to the building and parking areas designed in connection with the building

Design proceeded on the basis of one-way roads and liberal use was made of spline alinements and profiles instead of hard and fast tangents and curves Traffic was analyzed for both war times and normal times and the widths of pavements determined both by the traffic analysis and the relation to the number of lanes on the existing and potential bridges across the Potomac River Standards for the various geometric phases of design were related to the assumed design speeds and compromise was necessary to some extent

Interchange traffic streams of high volume were provided with directional paths in preference to the customary inner loops of cloverleaf grade separations Important intersecting routes and connections to the building and parking areas were so close together that it was not practicable to provide distances between points of ingress and egress considered desirable for high speed operation It was impracticable to provide inner loop ramps which can be driven at speeds considered desirable in relation to the assumed design speeds of the through express roads Such loops are so large that the extra travel distance and the large area to be maintained are additional factors against their construction Added lanes and tapers for speed-change were provided where necessary Several details such as pavements of contrasting color and surface texture, reflectorized curb noses facing traffic, signs and planting were designed to encourage desirable traffic behavior and enable traffic to flow without interruption

It is felt that in metropolitan areas traffic, of high volume with varied origins and destinations can best be served by express types of one-way highways with all interference from cross traffic eliminated by separation of grades, all access limited to carefully designed points of ingress and egress and directional paths provided for the major traffic streams

When our early planners decided to place the nation's capital at the head of navigation on the Potomac River, they little realized to what degree the river would be a barrier to travel and the interchange of goods No doubt ferries served adequately at first but as time and convenience grew in value such crossing facilities were replaced by bridges in tune with the time. A major example was the Long Bridge of Civil War fame which carried railroad, pedestrian, equestrian and vehicular traffic As the capital grew, the construction of bridges kept pace, to a greater or less degree, with the traffic across the river until at the present time there are four bridges for motor vehicle traffic · Highway Bridge, four lanes wide; Key Bridge, four lanes for vehicular traffic and two occupied by trolley tracks; Memorial Bridge, six lanes wide; and Chain Bridge of two lanes but located a considerable distance upstream from Washington so that it need not be considered in the immediate traffic picture. The three major bridges in 1941 had an average weekday traffic of 118,000 motor vehicles with a peak hourly load close to 11,000. These traffic loads are considerably below the capacities of these bridges for continuously moving traffic yet the bridges were jammed repeatedly because of inadequate approaches and a lack of collecting and distributing facilities which would enable traffic to keep moving In this respect the problem in Washington was similar to that of most of our large cities which themselves or in combination with suburbs straddle large streams, particularly those which must be kept open for navigation

Arlington County, Virginia, is that part of the original District of Columbia square, 10 miles on a side, which lies on the right bank of the Potomac This area was returned to the State of Virginia and did not expand as rapidly as the remainder, Washington, D. C, proper. Its close proximity to the downtown district, however, made it a potential high density area and with the expansion of Federal activities in the late thirties these potentialities materialized, resulting in congestion in cross river traffic and traffic through the downtown section of the city. In September 1941, it was decided to consolidate as far as practicable the numerous scattered offices occupied by the War Department and construct the largest office building in the world in Arlington County. This building is pentagonal in shape with each side about a fifth of a mile long It is known as the Pentagon Building and houses 40,000 employees. Parking space for 6,500 private vehicles is provided and despite staggered hours over 400 buses are required for mass movement of workers during the peak hour The National Airport already had been located on the Virginia side of the river and a temporary office building for 8,000 employees of the Air Corps later was constructed on the grounds Another office building for Navy personnel upwards of 6,000 also had been constructed nearby

A survey of War Department employees showed that 7 out of 8 lived in the District of Columbia or Maryland, so that by shifting their place of business across the river 7 out of 8 instead of 1 out of 8 would cross it in the peak hours. Fortunately the peak load for this traffic is opposite in direction to that of traffic to and from Washington and there will be a gradual shift in residence of some War Department employees But taking all favorable factors into consideration the construction of the Pentagon Building and other facilities in Arlington County superimposed upon the already heavy traffic across the river an additional load that would have far exceeded the capacity of the bridge approaches if not of the bridges themselves

This traffic problem had to be solved in the record breaking time set for the construction of the Pentagon Building, about 15 months, and it was decided that the solution also should be of lasting benefit to through and local traffic. This required the development on both sides of the river of a system of adequate bridge approaches and adequate express types of collecting and distributing highways that would enable all traffic to flow without interruption. These improvements would increase the capacities of the river bridges by at least 40 per cent, which would bring them up to the expected traffic loads and develop the fullest possible return on the large investment in these bridges These improvements would connect to the distributing and collecting streets of the District of Columbia well beyond the bridge heads and they would connect to existing and proposed through routes in Virginia at points beyond the area of congestion adjacent to the Pentagon Building

Another important factor was the critical housing shortage which was being relieved to some extent by large-scale housing developments, both public and private, in Arlington County where space was available close to downtown Washington and the Pentagon Building In one area alone three apartment developments total 5,700 units that are located less than three miles from the Pentagon Building and about five miles from downtown Washington When the improvements on both sides of the river are completed so that traffic is free flowing to and from these housing developments, they will be but five minutes from the Pentagon Building and ten minutes from downtown Washington

It is the purpose of this paper to describe the geometric phases of the design of the network of roads constructed adjacent to the Pentagon Building in Arlington to effect the general objectives of providing free flowing facilities between (1) the bridges across the Potomac and the through traffic arteries in Virginia, (2) the bridges across the Potomac and the Pentagon Building and other government facilities nearby, (3) Arlington County and the Pentagon Building, and (4) different sections of Arlington County Comparable facilities on the District of Columbia side of the river were provided or designed but these are not discussed here

GENERAL DESIGN REQUIREMENTS AND SOLUTION

Figure 1 shows the general location of the Pentagon Building and the Road Network in its relation to other Federal areas and buildings, to the existing roads which remain, and to the Potomac River Crossings. The roads connecting the through roads to the building and parking areas, the parking areas themselves and the highway facilities inside and adjacent to the building, an elaborate system of roads in themselves (shown as service roads) were designed by and constructed under the supervision of the U S Engineers Office The network of through roads, the grade separations, and the interchanges between through roads were designed by and constructed under the supervision of the Public Roads Administration of the Federal Works Agency. Thus as a whole the network was a cooperative undertaking of both organizations.

To comprehend fully the reasons for the over-all general design it is well to keep in mind the character of the terrain The original ground adjacent to the Potomac River was very low A large part of it consisted of the old Washington airport, approximately at elevation 10, which was flooded frequently The highest known water level occurred in October 1942 reaching about elevation 14 in this vicinity The ground rises only gradually for some distance and then very rapidly, reaching elevation 150 near Arlington Ridge Road To keep well over high water, the building, the Network, the service roads and parking areas, in fact the whole area between the river and the high ground, had to be raised well above existing elevations, necessitating a borrow of over 4,000,000 cu. yd , yet the high standards set for the Network necessitated a cut of 40 ft. for the lower of the two parallel roads which cross at the location of Arlington Ridge Road.

The Network finally resolved itself into a triangle of major routes around the Pentagon Building One route called Heavy Duty Road is a truck traffic route contemplated for many years in the general plan for the area It runs parallel to the Potomac River and lies between it and the building , see Figures 1 and 4. A second route, also contemplated for many years, is known as Army-Navy Boulevard and runs diagonally from the Virginia end of Memorial Bridge to the high ground to the west of the building. The third general route starts at Highway Bridge, swings south of the building and meets

Army-Navy Boulevard at the top of the hill. It is herein referred to as U S 1 Road. The most important through route through traffic to and from the south, and is being developed as a limited access express route throughout its length of 17

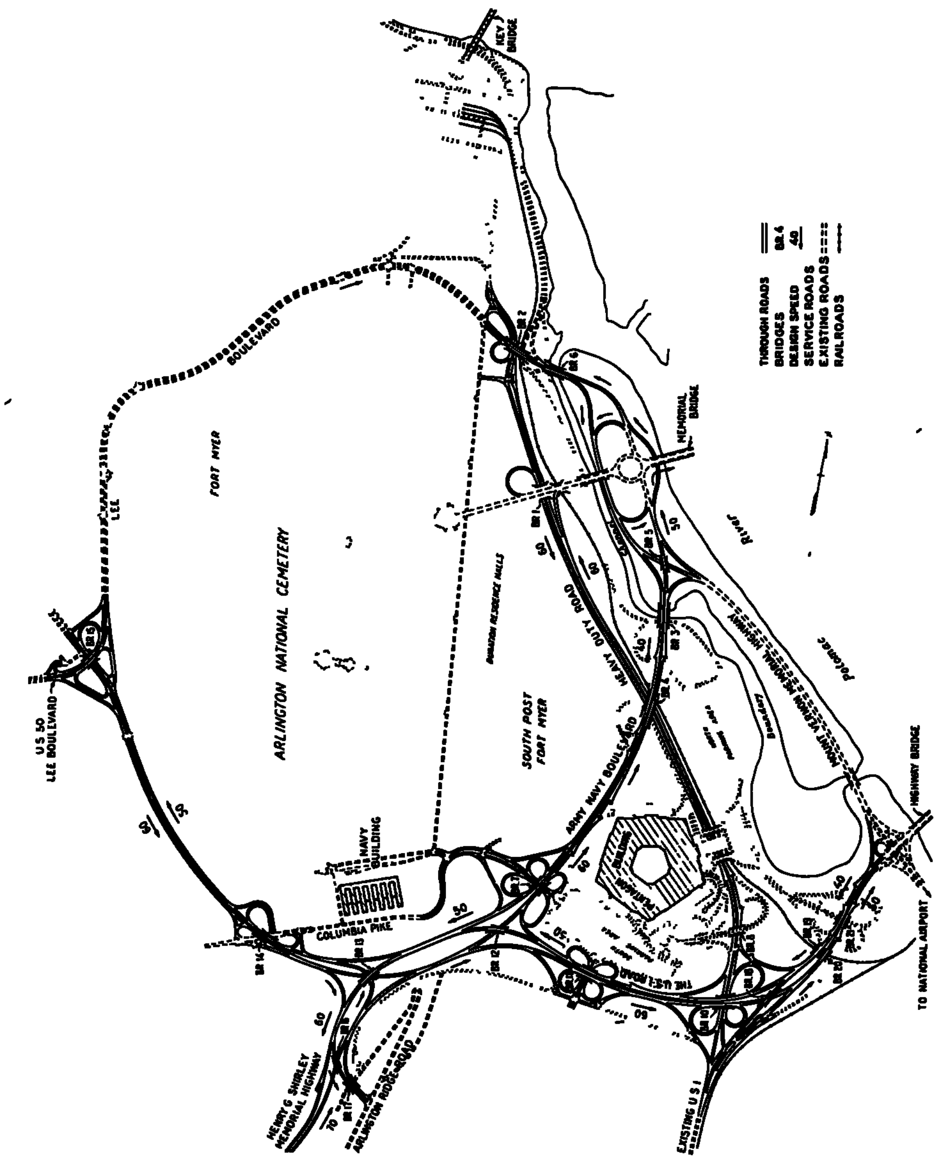

Figure 1. The Road Network Near the Pentagon Building

to which this system will connect is the Henry G. Shirley Memorial Highway, the first section of which is now under construction. This highway, passing to the west of Alexandria, will be preferred by miles. It is of high military value because it will shorten the time to the base of the U. S. Marines at Quantico, Virginia, will by-pass Fort Belvoir, run close to a large quartermaster depot near Alexandria, Virginia, and connect extensive housing developments with the Pentagon Building, Navy Building and Washington itself. Existing U S 1 which runs southerly from Highway Bridge is and will continue to be an important route for local traffic to and from a southerly direction Lee Boulevard, an existing divided highway which skirts Arlington Cemetery and Fort Myer to the north, was considered of such importance that the Network included an express connection to it. Note that this connection joins with Army-Navy Boulevard and Lee Boulevard to form an inner belt line with radial take-offs in all directions The Mount Vernon Memorial Highway is a heavily traveled limited access route adjacent to the river and is of additional importance because of its connection to Key Bridge and future connection to Chain Bridge farther upstream. Columbia Pike and Arlington Ridge Road also are important, but largely for local traffic

Origins and destinations of traffic on the Road Network are diverse. The extent of the movement to any single destination is not materially greater from one origin than from another. This led to a fundamental requirement of the network, namely, that the design provide a system which as a whole would be as flexible as possible A driver should have considerable latitude in the choice of a route to a general destination and it should be easy for him both to make the choice and to follow it In these critical times flexibility of destination is of added importance. In a flexible system emergency movements can be organized so that military vehicles use one route and civilian vehicles another or a bombed out route can be closed for repairs with little hindrance to through movements when alternate limited access routes are available.

That a network of roads as widespread and complicated as this should be flexible is also desirable when considered in another and totally different light. We are not infallible and all our carefully considered plans may be found to be faulty when the results are subjected to use by mass movements of vehicles guided by human drivers who assume the right to travel in any direction. When the system is put in operation and the "bugs," if any, are discovered, it should be possible, with but little added expense and with little disruption to traffic, to construct facilities as required for additional capacity In the design used there is sufficient space at the critical points, such as the major mixing roads referred to elsewhere, to provide relief if needed in the form of additional lanes or additional separate roads for part of the traffic. It is believed that in any system of limited access express highways in metropolitan areas the requirements of flexibility outweigh every other general design consideration.

A second design requirement is that the movements insofar as practicable be direct in character. Where roads cross each other at grade it is easy enough for vehicles to follow direct paths by the simple and natural maneuver of turning left or right as required. However, where traffic is to be free flowing it is necessary to separate the grades of all intersecting roads and provide ramps for traffic changing from one road to another Simple connections for right turns are direct but loops which provide for left turn movements are far from direct. They require drivers to turn right when they wish to turn left Many drivers have a poor sense of direction and many have had little experience in heavy traffic, so that even if they do not actually lose their way they frequently hesitate, make wrong turns or keep to the wrong side of the road As a result they disrupt the free flow of the through movements and in many cases are the direct or indirect cause of accidents Aside from the convenience to the motorist, direct roads are necessary for movements of large numbers of vehicles in order to provide the required capacity.

It is extremely difficult to encourage drivers to drive side by side around a loop. No matter how wide the loop is made, the capacity is little more than that of one traffic lane. New Jersey recently reported difficulty with a 270-deg loop on a radius of 120 to 160 ft., a pavement 33 ft wide and a downgrade under 4 per cent Traffic frequently backed up on the through divided highway leading to the intersection, even though the section across the structure was widened to 35 ft, because drivers were too timid or inexperienced to form two lanes of moving traffic around the loop.

Paths for directional movements are desirable also for economy Ramps for high standard roads are rather expensive and the additional travel time and distance required on extensive loops when multiplied by the thousands of vehicles in a daily mass movement result in additional operation costs which justify considerable capital expenditures for their elimination

Any attempt to eliminate loops entirely and provide direct paths for all interchange movements will lead to so many grade separation structures that the cost will be prohibitive. To effect the differences in levels on reasonable grades such large areas and spreading of the various roads would be necessary that the lengths of the paths and the radii of the turns would themselves defeat the very purpose of the direct paths. In this network an attempt was made to provide direct paths for nearly all important through movements and to utilize the conventional cloverleaf types of grade separations for the less important traffic streams Direct interchange for the through traffic streams leads to spreading the one-way roads near a separation structure to the extent that the designer finds that he is not dealing with the center line of a divided highway but instead is using separate alinements and profiles for one-way roads The experience in the design of this and other networks of express types of highways leads strongly to the conclusion that the entire concept of "divided highways" or "double barreled highways" or "highways with parkway medians" or whatever they may be called should be discarded in metropolitan areas in favor of a system of one-way roads. It will free the designer and encourage him to think in terms of smooth flowing direct movements

The War Department Building Road Network as constructed consists of 17 miles of one-way through roads, 7.7 miles of one-way ramps, and 21 grade separation structures, one of which provides for the separation of three intersecting roads It also includes 2 3 miles of local service roads These lengths do not include service roads connecting through roads to the Pentagon Building and parking areas

The requirements of flexibility and simplicity of operation for through movements resulted in an over-all design based on two mixing roads, one for each direction of traffic, located just east of the 3-level bridge No. 13 The two heaviest traffic streams merge into and emerge from these mixing roads in a natural manner. Traffic headed right veers to the right and traffic headed left veers to the left The design of these mixing roads is discussed later

First examination of the plan shown in Figure 1 may lead to the conclusion that the network is unduly complicated. But closer examination will show that when the through roads and main connecting roads are separated from the service roads to the building and the parking areas, as shown by the solid lines in Figure 1, the main roads form a relatively simple network that is direct in character In testing a network of roads for simplicity it is unwise to view the network as a whole, a view that is seen only from the air The driver sees only the road he is traveling, with the various points of ingress and egress and the directional signs along it If the path from origin to destination is easy to travel, direct in character and free from sections that might confuse drivers it is simple in design regardless of its appearance on paper. Each through route for important traffic was tested with the above thought in mind Let us follow a few of these through routes

Figure 2 shows the path of a driver crossing Highway Bridge and headed for the Shirley Memorial Highway, the route which will be most direct for through travel to and from the South If he ignores minor access roads he has but two choices; at point 'a' he must decide to proceed straight ahead and not veer to the left towards old U S 1 and at point 'b' he must take the natural choice of proceeding left because he desires to go left If he desired to go right toward U S 50 or Columbia Pike or the Navy Building (in full view at this point) he would naturally swing right at 'b' While signs are necessary and extremely helpful note that the paths are in the directions desired and are the ones which drivers naturally would take if there were no directional signs.

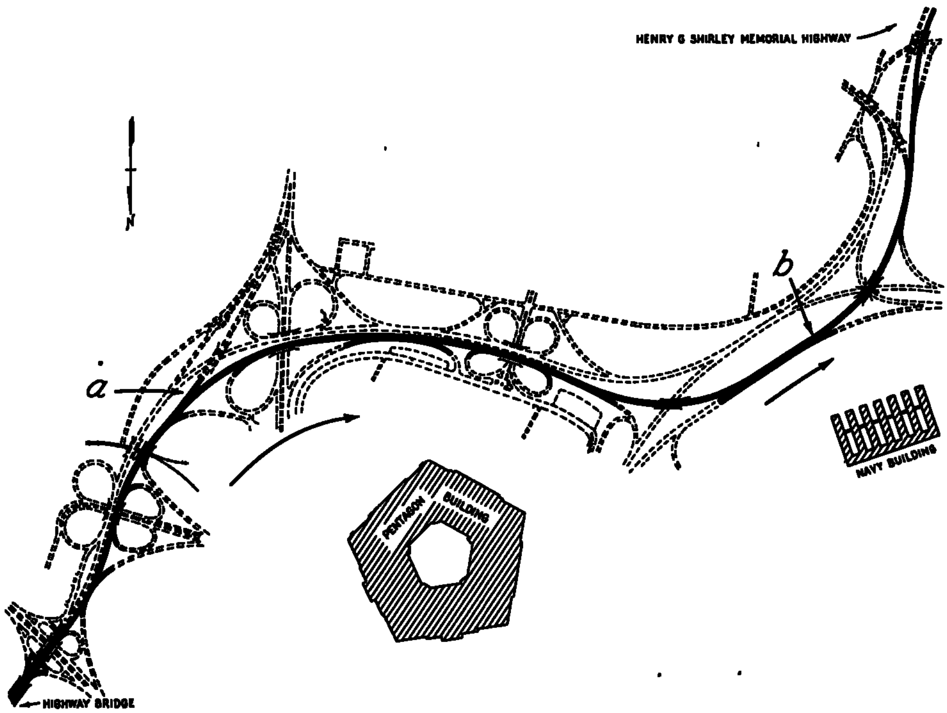

Figure 2. Path from Highway Bridge to Henry G. Shirley Memorial Highway

Figure 3 shows the path of a driver entering the area from the south on the Shirley Memorial Highway and proceeding to Washington via Memorial Bridge At point 'a' he must make the only important decision, to veer left to go toward Memorial Bridge If he desired to go right toward Highway Bridge he would have to decide to take the road which swings to the right Both decisions are natural and would normally be taken in the absence of directional signs.

Figure 4 shows the path of a vehicle on U S 50 headed toward downtown Washington via Highway Bridge He enters the Network at point 'a' by turning right and his first and only major choice is at point 'b' on the inbound mixing road

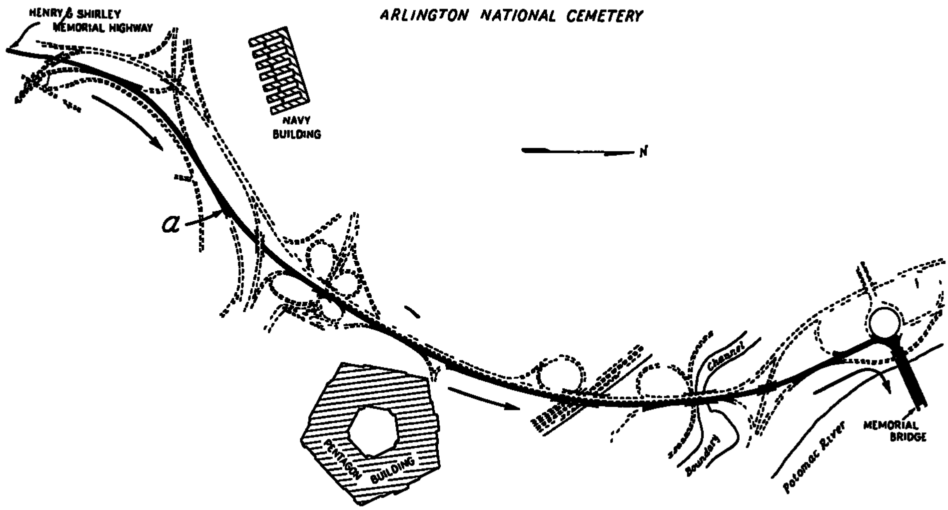

Figure 3. Path from Henry G. Shirley Memorial Highway to Memorial Bridge

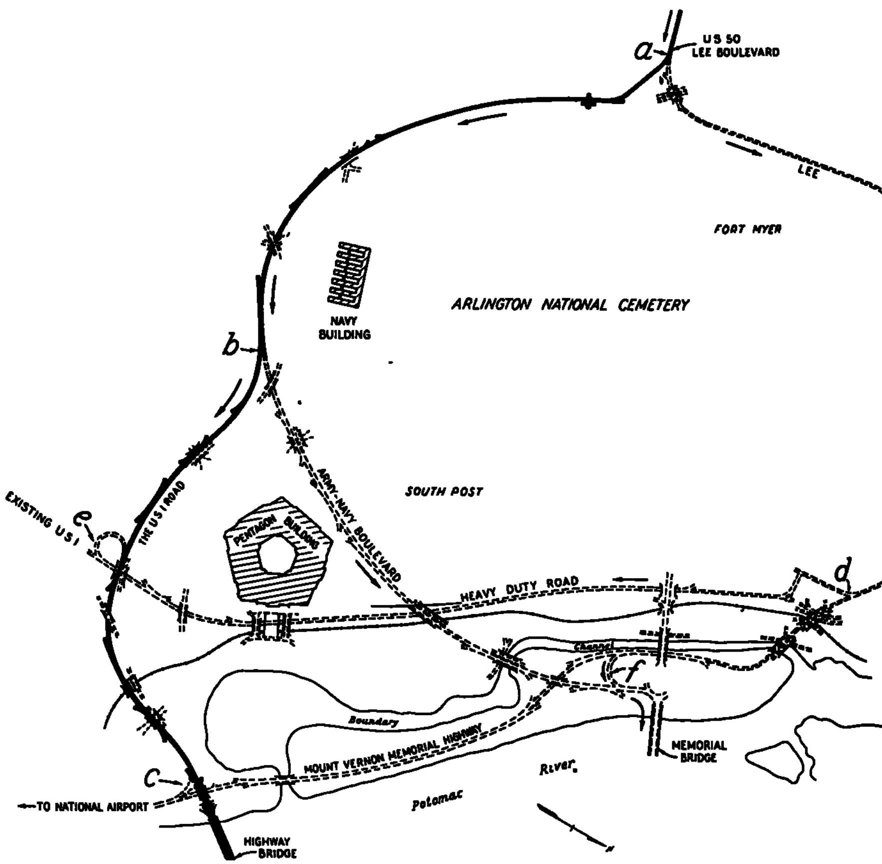

Figure 4. U S 50 to Washington via Highway Bridge

where he must decide to keep right to reach Highway Bridge This figure also is one illustration of the flexibility of the system as regards choice of routes. The driver may reach Highway Bridge even if he turns left at point 'a' by continuing on Lee Boulevard and the Memorial Highway and then using the loop at the clover leaf at point 'c', or he may change to Heavy Duty Road at point 'd' and use the loop at point 'e' If he is headed for Memorial Bridge he can either follow the first described path and choose the natural path to the left at point 'b' or if he turns left at the point of entry he continues on Lee Boulevard past point 'd' and is directed to Memorial Bridge at point 'f' where a liberal turn is provided.

TRAFFIC ANALYSIS

In checking the design of the through roads on the network and the capacity of the Potomac River Bridges against the expected traffic load it was necessary to consider wartime and normal loads separately Since about half the estimated traffic load will have origin and destination in the three major government buildings erected in Arlington, it is reasonable to expect that the number of workers and their habits, such as the staggering of working shifts, are appreciably different in normal times and during the war. The daily peak load normally occurs during the evening rush hour and the analysis shown here covers one-way operation in the direction of maximum flow, towards Washington The additional load created by the construction of government offices in Arlington actually has reversed the direction of the maximum flow across the river Table 1 shows an analysis for wartime operation and Table 2 for normal operation in the future.

To operate at capacity, as shown in Table 1, the margin of 1,100 vehicles per hour indicates that normal traffic can increase by 25 per cent above that for the 1941 count This margin appears to be more than adequate for wartime operation in view of the necessity for conserving tires and motor fuel, but the population of metropolitan Washington has boomed, the drop in traffic is not so great as elsewhere and additional safety margins are desirable These are embodied in the use of 75 as the percentage of workers traveling eastward to Washington and in the assumption that working shifts will be staggered over a one-hour period The percentage of workers traveling eastward will decrease in time as the housing developments in Arlington County are completed, also shifts can be further staggered if necessary

To operate at capacity as shown in Table 2 the margin of 1,800 vehicles per hour indicates that normal traffic can increase 40 per cent over that of the 1941 count when the war is over, the buildings for military personnel staffed for peacetime operation, the improvements made in the approaches to Key Bridge and existing Highway Bridge replaced.

The Pentagon Building is designed to provide space for about 30,000 workers under normal operations, but under the more crowded wartime conditions it can accommodate about 40,000 The Navy Building is a permanent type of structure constructed to be a warehouse It may be used for as many as 6,000 workers during the war but is expected to revert to a warehouse status after the war. The Air Corps Building is of temporary construction and will be demolished in time.

The factors of $\frac{1}{3}$ and $\frac{2}{3}$ for the workers who will travel by private vehicles and bus respectively are based on observations for this area. Where bus facilities are poor such as at the old War Department quarters, as many as half the workers traveled by private automobile, but in the case of the Pentagon Building, the bus terminal is inside the building with direct ramps and halls to all portions, discouraging the use of private automobiles On the other hand, parking space for about 6,500 vehicles is provided adjacent to the building and expansion to 8,000 spaces can be effected readily. For this reason it is believed that only one half of the peak traffic will travel by bus in normal operations

Observations indicate that each passenger vehicle normally carries 1 7 persons. With the present rules regarding gas rationing and the increasing tendency to share rides and save tires, it is conservative to expect this factor to jump 50 per cent to 2 5 persons per vehicle as used in Table 1 After the war with likely reduced cost of private transportation and free parking spaces at the front door, the factor is expected to drop somewhat below the observed value. A factor of 1 5 was used in Table 2.

The number of shifts and the time interval between shifts is the largest controllable variable and thus constitutes a very effective means for varying the

TABLE 1

ANALYSIS OF TRAFFIC ACROSS THE POTOMAC RIVER
WARTIME OPERATION

(Vehicles per hour eastbound during the evening peak)

TRAFFIC LOAD

1941 TRAFFIC COUNTS

	Total	Per cent eastbound	Number eastbound	Estimate
Highway Bridge	3,300	46 2	1,530	
Memorial Bridge	4,400	38 0	1,670	
Key Bridge	2,900	41 5	1,200	
Total	10,600		4,400	
		Assumed $\frac{1}{4}$ reduction		3,300

WORKERS IN BUILDINGS

Pentagon Building	40,000
Navy Building	6,000
Air Corps Building	8,000
Total	54,000

Assumed 75 per cent of total workers will travel during peak period
75 per cent of workers will travel eastward
$\frac{1}{3}$ by private vehicle, $\frac{2}{3}$ by bus
2 5 persons per private vehicle, 50 per bus
5 working shifts, 15 minutes apart resulting in a peak of 1 5 hours

Passenger vehicles $= 54{,}000 \times 0\ 75 \times 0\ 75 \times \frac{1}{3} \times 1/2\ 5 \times 1/1\ 5$		2,700
Buses $= 54{,}000 \times 0\ 75 \times 0\ 75 \times \frac{2}{3} \times 1/50 \times 1/1\ 5$	270, say	300
Total load		6,300

TRAFFIC CAPACITY

Highway Bridge—2 lanes at 1,200	2,400
Memorial Bridge—3 lanes at 1,000	3,000
Key Bridge—2 lanes at 1,000	2,000
Total capacity	7,400

traffic load as found necessary. Not all metropolitan areas are fortunate enough to have the handle of a traffic valve under the control of one agency but the principle can be applied in any congested city by the cooperative effort of several large businesses and other organizations Limited to peaks of less than an hour's duration) probably will not occur because the major traffic is that to and from the Pentagon Building, which traffic is controllable. In addition, the principle of staggered-hour shifts is accepted in the District of Columbia proper and observations of traffic

TABLE 2

ANALYSIS OF TRAFFIC ACROSS THE POTOMAC RIVER
NORMAL OPERATION

(Vehicles per hour eastbound during the evening peak)

TRAFFIC LOAD		
1941 TRAFFIC COUNTS		
		Estimate
As listed in Table 1		4,400
WORKERS IN BUILDINGS		
Pentagon Building	20,000	
Navy Building	2,000	
Air Corps Building	none	
Total	22,000	
Assumed 75 per cent of workers will travel during peak period 75 per cent of workers will travel eastward ½ by private vehicle, ½ by bus 1 5 persons per private vehicle, 50 per bus 3 working shifts, 15 minutes apart resulting in a peak of 1 0 hours		
Passenger vehicles $= 22{,}000 \times 0\ 75 \times 0\ 75 \times \frac{1}{2} \times 1/1\ 5 \times 1\ 0/1\ 0$		4,100
Buses $= 22{,}000 \times 0\ 75 \times 0\ 75 \times \frac{1}{2} \times 1/50 \times 1\ 0/1\ 0$	120, say	200
Total load		8,700
TRAFFIC CAPACITY		
Highway Bridge—3 lanes at 1,500		4,500
Memorial Bridge—3 lanes at 1,000		3,000
Key Bridge—2 lanes at 1,500		3,000
Total capacity		10,500

observations of habits since occupation of the building indicate that the assumptions that 75 per cent of the workers will clear the buildings over a period beginning 15 minutes before the end of the first shift and ending 15 minutes after the end of the last shift and that the peak hour can be computed by direct proportion are conservative. In the case of the network short period congestion (congestion due before the construction of these buildings indicated a spread of the load. Another factor in the use of hourly densities is the express limited access characteristics of the roads where free-flowing movements can be expected for appreciable distances. Short period excessive peaks generally result in long period congestion only where intersecting roads cross at grade, possibly with traffic lights which are inefficient in freeing congestion once begun unless their time intervals can be temporarily and intelligently varied

Each bus was considered one vehicle in the traffic load. Where frequent stops are necessary, the acceleration of buses is so much less than that of private passenger vehicles that each bus may be considered the equivalent of two or three private cars, and the loads and capacities compared on the basis of the latter only In free-flowing movements buses occupy no more space than private cars because the larger length is compensated for by greater use of brakes and the habit of bus drivers to travel close to preceding vehicles. The 1941 traffic counts included and the capacities used assumed a reasonable percentage of trucks and buses

In computing capacity it was assumed that Highway Bridge could carry only 1,200 vehicles per lane per hour even though the bridgeheads will be entirely free because it has a non-divided pavement less than 40 ft. wide between curbs with through trusses very close to the traffic lanes. In the analysis for normal operation it was assumed that the bridge will be replaced by a new structure with one-way pavements at least 36 ft wide for which a capacity of 1,500 vehicles per lane per hour is conservative Memorial Bridge has six full lanes but only 1,000 vehicles per lane per hour was used because the bridge is non-divided and its capacity is limited by curved rotary approaches at each end Key Bridge also has six full lanes but the two middle lanes are occupied by trolley tracks so that no more than the equivalent two lanes in each direction can be assumed Since the bridge approaches are not free an existing capacity of 1,000 vehicles per hour per lane may be optimistic. But when improvements now on plans are ultimately realized there is no reason why the capacity cannot be increased to 1,500

DETERMINATION OF WIDTHS OF THROUGH ROADS

The calculation of precise vehicular traffic loads for the network was somewhat academic because the limiting factor, the development of bridges across the Potomac River, is fairly well fixed A recent bridge commission tentatively concluded that any additional river crossings should be located downstream from Highway Bridge If it is located a considerable distance downstream it will have little effect on the Network and if it is located between Highway Bridge and the railroad bridge it will in effect be a replacement of Highway Bridge for which provision was made in the design. A new Highway Bridge probably would have three traffic lanes in each direction to match the express developments on both sides of the river.

In a system of express type limited access facilities with liberal design for interchange, the capacities of the through roads are in direct proportion to the number of through traffic lanes. In a balanced design for this area the number of traffic lanes on the through roads and old roads combined should bear some relation to the number of traffic lanes on the river crossings. The number of traffic lanes on the approaches or bridgeheads should be greater than the total number on any group of bridges to insure free flow to and from the expensive river crossings and to provide space for vehicles which travel through the area but do not cross the river. A comparison between the traffic lanes on the river crossings and those on the Virginia approach roads were made at three different distances from the bridgeheads, as shown in Figure 5. The comparison is shown in Table 3. As in previous analyses the number of traffic lanes in one direction of traffic is used. Future widths are expected to be greater in the case of Highway Bridge and Lee Boulevard and their ultimate widths were used in the comparison Where existing roads are not limited access highways, their smaller capacities were recognized in the use of a figure actually smaller than the physical number of traffic lanes as in the use of 1½ lanes for Columbia Pike which is paved 40 ft wide.

Army-Navy Boulevard and Heavy Duty Road (see Fig 1 also) were originally conceived as two lanes wide in both directions but when it developed that the accesses were numerous, close together and expected to have considerable use these through roads were made three lanes wide, with the outer lane of a bituminous surface contrasting with the concrete pavements of the inner lanes The outer lane is in effect a continuous speed change lane. Just how much the capacity of this type of road is greater than that of a 2-lane road without points of ingress and egress is a moot question but the capacity was assumed to be the equivalent of 2½ traffic lanes. On U S 1 Road, capacity for three full lanes in each direction was provided by the construction of three concrete traffic lanes and by providing additional width, bituminous surfaced, at speed-change areas.

The comparison shown in Table 3 indicates considerable excess capacity of through roads close to the bridgeheads with decreasing excess capacity as the distance from the bridgeheads increases This indicates a desirable balance in the case of the Network because of the large percentage of vehicles which are expected to travel between the bridges and the Pentagon Building which lies between lines 1 and 2 of the comparison

Figure 5. Comparison of Through Traffic Lanes Between River Crossings and Approach Roads at Three Distances from Bridge Heads (See Table 3)

DESIGN STANDARDS

Assumed Design Speed

In any network of through roads operation of vehicles will be smooth if there is a balance in the design of the various parts so that driver behavior will be approximately the same. A desirable common denominator to which all geometric phases of highway design can be reduced is that of assumed design speed. This has been defined in a general way in "A Policy on Highway Classification"[1] and an analysis of speed observations[2] leads to the conclusion that it may be defined as the speed which is not exceeded by more than 2 or 3 per cent of drivers In the case of the network the alinements and profiles of the through roads had been fixed for all practicable purposes by the locations and elevations of river bridges, buildings

TABLE 3

COMPARISON OF THE NUMBER OF THROUGH TRAFFIC LANES BETWEEN RIVER CROSSINGS AND APPROACH ROADS

(See Figure 5)

ON LINE 1—CLOSE TO POTOMAC RIVER

Across river		Roads	
Highway Bridge	3 lanes	Parkway	2 lanes
Memorial Bridge	3 lanes	New U S 1	3 lanes
		Army-Navy Blvd	2½ lanes
		Memorial Avenue	2½ lanes
		Lee Boulevard	3 lanes
Total	6 lanes	Total	13 lanes

Excess 117 per cent

ON LINE 2—BEYOND PENTAGON BUILDING

Across river		Roads	
Highway Bridge	3 lanes	Parkway	2 lanes
Memorial Bridge	3 lanes	Old U S 1	1½ lanes
Key Bridge	2 lanes	Columbia Pike	1½ lanes
		Mixing Roads	4 lanes
		Lee Boulevard	3 lanes
		Lee Highway	1½ lanes
		Parkway	2 lanes
Total	8 lanes	Total	15½ lanes

Excess 94 per cent

ON LINE 3—BEYOND NETWORK

Across river		Roads	
Highway Bridge	3 lanes	Parkway	2 lanes
Memorial Bridge	3 lanes	Old U S 1	1½ lanes
Key Bridge	2 lanes	Shirley Highway	3 lanes
		Columbia Pike	1½ lanes
		Lee Boulevard	3 lanes
		Lee Highway	1½ lanes
		Parkway	2 lanes
Total	8 lanes	Total	14½ lanes

Excess 81 per cent

[1] "A Policy on Highway Classification" by the Special Committee on Administrative Design Policies, A.A.S H O, 1940

[2] "Percentile Speeds on Existing Highways by D. W Loutzenheiser, *Proceedings*, Highwa Research Board, Vol 20, 1940

and adjacent parking areas, by the existing transportation facilities through and adjacent to the area and by the presence of other public domains, such as the National Cemetery, the Park System, and Fort Myer In choosing the assumed design speeds for the various sections of roads, alinements had to be given little consideration because the curvatures determined on the general plan were well above the minimums required for the probable speeds based on other considerations The choice of design speeds was principally governed by the location of the various sections of road with respect to the river crossings to downtown Washington and with respect to the highways, both existing and proposed, approaching from other directions

The chosen assumed design speeds are shown on Figure 1 varying from 40 to 70 m.p.h. Note that the speed of inbound traffic was assumed to be 70 m p h. on the Henry G Shirley Memorial Highway, an express facility with little curvature and moderate grades, and that the assumed speeds were reduced at intervals as the roads traversed the building area, were joined by the ramps and direct interchange roads and approached the river crossings Outbound traffic was assumed to travel at 40 m p h as it crosses the river, having just passed through the central portion of Washington where all travel is at lower speed, but as traffic continues to the outskirts of the area it is logical to assume increasing speed In all cases on the Network the inbound speed was assumed higher than the outbound speed because of the well-known inability of drivers to quickly adjust their sense of speed Drivers on open roads approaching a city have difficulty in slowing down appreciably and drivers leaving metropolitan areas take some time to attain the high speeds characteristic of travel on the open road

Curvature

Curvature on the through roads presented little difficulty because the general design requirements previously referred to resulted in flat curves Maximum curvature on Heavy Duty Road was 3 deg. 30 min., on the Army-Navy Boulevard 4 deg, and on U S 1 Road 4 deg except for the turn into existing Highway Bridge which was 4 deg 30 min. All curves sharper than 2 deg. were transitioned The transition was made at least as long as the minimum recommended in "Transition Curves for Highways" [3] which is based on the formula $L_s = 1.6 \frac{V^3}{R}$ in which L_s is the length of transition in feet, V the assumed design speed in miles per hour and R the radius of the curve in feet.

The spline was used to good advantage in developing both the alinements and profiles of the various one-way roads Topographic maps were prepared for all of the area and the various control points were plotted thereon to scale. The initial line was projected by placing the spline (a flexible plastic strip about the size of a pencil and 4 to 8 ft long) on the map, holding it down with weights and adjusting it until all curves were smooth and passed through all the control points as far as practicable A spline is sufficiently stiff to prevent abrupt bends in the line and by squinting along the spline with eye close to the paper the weights can be adjusted to insure smooth flowing alinement Once adjusted the spline is then used as a curved template for marking the alinement (or profile) on the working map Where both alinement and profile must be considered jointly several trials may be necessary to insure their correct relationship Because of the closeness of the

[3] "Transition Curves for Highways" by Joseph Barnett, for sale by the Superintendent of Documents, Washington, D C, price 60 cents

various controls, such as location and elevations at grade separation structures and points of ingress and egress, it is difficult to imagine laying out a network of this character without the use of the spline. The natural bend of a spline closely fits curves with transitions and since all centerlines were computed initially on the basis of curves with transitions it was not difficult to compute lines which closely fitted the spline line, particularly since a coordinate system was used. The gracefulness of and ease of driving on the completed roads are proof of the desirability of this method, at least for road systems of this character, but the fact that no additional cost of engineering or additional effort is involved also is worthy of note.

No attempt was made to establish base lines and relate centerlines to them. A coordinate system was used for the entire area, and coordinates for points on the centerline of each one-way through road were computed. The field forces were provided with the coordinates of all control points, such as P.C.'s, P.I.'s, etc. The field forces established their own survey control points free of the numerous simultaneous construction operations both for the building and for other roads and thus were free to locate any point desired.

Superelevation

Experience has demonstrated that for through highways it is desirable to superelevate at the rates based on the assumption that all centrifugal force resulting from a speed of three-fourths of the assumed design speed be counteracted by superelevation, up to a maximum practicable limit of 0.10[4]. Superelevation on this basis is shown in "Transition Curves for Highways."[3] However, in the case of the Network, points of ingress and egress are numerous, close together and are used by a great many vehicles turning to and from the ramps. It was deemed undesirable, therefore, to use full superelevation on the through roads and the values arbitrarily adopted were those in "Transition Curves for Highways" for speeds 10 m.p.h. less than the assumed design speeds. The superelevations used are shown in Table 4.

All curves sharper than 1 deg were superelevated except one or two where

TABLE 4

SUPERELEVATION RATES

Degree of curve		Superelevation rate, foot per foot, for assumed design speeds of			
		40 m.p.h	50 m.p.h	60 m.p.h	70 m.p.h
Through roads	2	0.01	0.02	0.03	0.05
	4	0.02	0.04	0.06	0.09
Service roads and ramps	6	0.03	0.06	0.10	
	8	0.05	0.08		
	10	0.06	0.10		
	12	0.07			
	14	0.08			

[4] "Safe Side Friction Factors and Superelevation Design" by Joseph Barnett, *Proceedings*, Highway Research Board, Vol. 16 (1936).

the architectural effect would have been undesirable

Profiles

Profiles also were projected by the use of the spline with frequent checks for sight distance control With grade separations and points of ingress and egress so close together splines were most convenient in juggling the profiles to fit the several clearances and other controls.

Upgrades on the two major truck routes, Heavy Duty Road and U S 1 Road were limited to 3 per cent, except for one short roll over a structure where a grade of 3 5 per cent was used Downgrades were also kept to a minimum but one of 4 per cent and one of 4.5 per cent were used. On Army-Navy Boulevard, which is restricted to passenger vehicles, one upgrade of 4 per cent was used.

The concept of one-way roads with separate centerlines and profiles is demonstrated to good advantage in the design of profiles where downgrades can be made steeper than upgrades and the one-way roads in opposite directions can be located at different levels to fit the topography, decrease costs of grading, reduce headlight glare, etc [5]

The profiles of the two one-way mixing roads were given special consideration It was felt that most efficient operation would result if they were made level or at least with flat grades, particularly for downgrade traffic where a steep grade might encourage drivers to speed up and make weaving difficult, but it was impracticable to do so The topography and their great length, about 900 ft between noses, made it necessary to place them on a grade of 3 per cent. One road is considerably higher than the other to effect the differences in levels at the grade separations beyond both ends.

[5] For a discussion of this subject see "A Policy on Highway Types (Geometric)" by the Special Committee on Administrative Design Policies, A A.S H O, 1940.

Sight Distance

Sight distance requirements used in design were those recommended in a "Policy on Sight Distance for Highways" [6] Since all roads are one-way the minimums for non-passing sight distance were used for the various assumed design speeds, values ranging from 200 ft for a 30-m p h design to 600 ft for a 70-m p h design. The sight distances are based on a height of eye of 4 5 ft and a height of object of 4 in Generally the minimum values were exceeded by considerable margins but in some cases the abutments of the grade separation structures forced the use of minimum sight distance as based on horizontal curvature. In two cases it was necessary to increase the span of the structure to obtain the minimum sight distance. The clearance between abutment and edge of pavement was made 15 ft in one case and 10 ft in the other.

Clearances

At all of the grade separation structures a vertical clearance of 14 ft was provided at the face of curb in accordance with A A S H O standards Curved soffits on most of the structures allowed additional clearance toward the center of the pavements.

Horizontal clearance to railings on overcrossings was at least 3 ft. Where a sidewalk was necessary a clearance of 6 ft. was used except on bridges 3 and 4 where 8 ft was considered the minimum which would be in keeping with the scale of the structures.

Horizontal clearance to abutment walls or piers at undercrossings was 6 ft in most cases. However on Heavy Duty Road the limited space for the two one-way roads permitted only a 12-ft median width at structures and the lack of curva-

[6] "A Policy on Sight Distance for Highways," by Special Committee on Administrative Design Policies, A A S.H O, 1940.

ture made it impossible to widen the median without forcing the alinement with reverse curves The architectural requirements of the structures made it necessary to provide middle piers 6 ft. wide, resulting in a lateral clearance of 3 ft at the left edge of pavement The clearance at the right edge, where space for sidewalk had to be provided, was 9 ft., which helped develop a desirable sense of openness

For the most part the roads in opposite directions were not parallel and hence were separated by medians of varying widths At the narrowest sections of the median careful checking of the profiles of the separate one-way roads was required to insure that the differences in elevations across the median were such that a graceful ogee curved slope could be used which would not require guardrail Where bridges of considerable length carried both roads, such as bridges 3 and 4 on Army-Navy Boulevard the one-way roads were brought close together for economy of structure, forming a length with a constant-width median strip at least 6 ft wide. On shorter structures no direct attempt was made to bring the roads together If the space between roads was too great two separate structures were used as bridges 19 and 20 where the roads are about 60 ft apart and if the space was not considered excessive one wide structure was used. At bridges 7, 10 and 11 the spaces between roads were about 18, 12 and 15 ft, respectively, and it was deemed safer and no less economical to provide a single structure Where the opposing roads were on a curve the alinements, profiles and superelevations of both roads had to be designed jointly to obtain a practicable cross section for the grade separation structure. A design in which both roads and the median area were inclined across the structure on a plane would result in one excessively thick face or in an inclined soffit, either of which would be uneconomical and unattractive. In some cases this was avoided by placing the lower edge of one road below the high edge of the opposing road and grading with flat ogee curved cross sections between them

THE MIXING ROADS

The design of the mixing roads was of major importance because the free-flowing movement of through traffic and the flexibility of the system depends to an appreciable degree on their successful operation The outbound road receives traffic from both the Army-Navy Boulevard and the U S 1 Road, and enables vehicles to enter either the road toward U S 50, with interchange at Columbia Pike, or the Henry G. Shirley Memorial Highway with a connection to South Arlington via Ridge Road The reverse operation, of course, is performed by the inbound mixing road The roads were made parallel, on the same constant gradient, 300 ft apart but at different elevations to meet the respective levels of the grade separation structures beyond both ends of the mixing roads, bridges 12 and 13. This results in a very pleasing appearance Wide flat shoulder areas were provided to permit widening or the construction of separate relief roads if found necessary Flexibility in future capacity was deemed important here

The mixing roads were made four lanes or 48 ft in width to accommodate traffic on the three lanes of the U S 1 Road and on the two through lanes of Army-Navy Boulevard and at the same time provide for weaving of traffic No doubt some slowing down on the mixing roads will be required during periods of simultaneous peak flow on both approach roads This is desirable in a weaving area provided it is not severe enough or of long enough duration to cause approach traffic to slow down and back up In the latter remote case the space for widening or separate relief roads will be invaluable

It is felt that practically all weaving will take place on the two middle lanes because repeat drivers approaching and leaving on the outside will be directed by signs and will soon learn that it is easier to keep to the outside lanes. Weaving will be confined to about half the traffic which will be directed to and will find it easier to keep to the inside lanes However, it was felt that the mixing roads should be long enough to enable an occasional driver easily to move from an outer lane to the inner lane of the road, leaving the mixing road without undue reduction in speed

The determination of the lengths of the mixing roads to meet the foregoing requirements was a design point subject to considerable speculation; in a design sense their lengths are most similar to weaving distances in rotary design. But since their alinement is very flat and anticipated speeds are rather high at times other than periods of peak flow, determination of their length was somewhat different than for rotary design

Most observers agree to recently published observations [7] demonstrating that a majority of drivers of their own volition utilize roadway lengths of 300 to 500 ft in crossing over a single lane's width in any weaving maneuver For crossovers of more than one lane's width, longer lengths yet are needed, and any roadway designed for such maneuvers certainly should include allowances for some distance at each end for maneuvers that must be delayed to clear other traffic. Thus while no definite design length could be determined, all available data and experience suggested that for roadways of the type desired the length of the mixing road should be well above 600 ft and preferably as long as 1,000 ft. The alinement design resulted in lengths of about 900 ft for each of these mixing roads.

[7] "Evaluation of Design Data for Crossover Distances" by S M Spears, *Proceedings*, Highway Research Board, Vol 21 (1941)

WIDTHS OF PAVEMENTS AND SHOULDERS

Traffic lanes 12 ft. wide were used. Narrower widths were considered insufficient because of the heavy truck concentrations on Heavy Duty Road and U S 1 Road and the use of mass transportation buses on all the roads The curvature on the through roads was not sharp enough to justify widening at any point. Curbs were used throughout, but they were constructed outside the 12-ft width for through traffic lanes In general curbs were 6 in. high on the right of traffic

TABLE 5

WIDTHS OF PAVEMENT FOR RAMPS[8]

Radius	Pavement width, for			
	One-lane operation		Two-lane operation	
	No provision for passing	Provision for passing stalled vehicle	Normal traffic	Bus Routes
ft	ft	ft	ft	ft
50	17	28	32	34
100	14	24	27	29
150	14	22	26	28
200	14	22	26	28
300	14	21	26	28
400	14	20	26	28
500	14	20	26	28

where sidewalks are planned for the adjacent space and were 3 in high elsewhere Curbs were sloped back 1½ in and rounded at the top to insure a minimum of effect on lateral placement of vehicles and to permit mounting in an emergency. At approaches to structures the right curbs were gradually increased to 8 in. in height.

The widths of pavement used for ramps, Table 5, which are those shown in Table 20 of "A Policy on Intersections at Grade" [8] for "T" type of traffic or traffic

[8] Values for "T" type traffic as shown in Table 20, page 94, of "A Policy on Intersections at Grade," by the Special Committee on Administrative Design Policies, A A S H O, 1940

with an appreciable percentage of trucks and buses Where it was expected that provision for only one traffic stream would be sufficient, the widths in the third column were used to permit passing in emergencies. Where it was felt that provision for two streams of traffic should be made, the widths in the fourth or fifth column were used In the fifth column for the projected bus routes, an additional width of 1 ft has been provided for each traffic lane because of the larger wheel bases and over-all lengths of buses compared to single unit trucks [9]

Shoulders should be provided on all express type facilities to insure continuous smooth operation during periods of peak flow It has been observed that at such times a vehicle stopped for any reason whatsoever will not only disrupt traffic in its lane but affect traffic in all adjacent lanes. This is brought about by vehicles behind the stopped vehicle slowing down and veering to the left to pass, causing vehicles in the second lane to do likewise and so on for every other lane To insure continuous operation on express type highways a vehicle should be required to use the shoulder when forced to stop But the shoulder should not be used by through traffic

The proximity of the Network to the park system of the nation's capital and to other public areas precluded the use of a stabilized shoulder surface such as compacted gravel Instead grassed shoulders at least 11 ft wide were provided and blended into the side slopes which were 1 on 2 or flatter. While a standard cross section was used as a guide, actually the area was completely regraded to fit the numerous and closely spaced controls Complete grading (contour) plans were prepared for this purpose Grassed shoulders are difficult to drain and maintain without the use of curbs No voluntary stopping of vehicles will be permitted and it is intended that the occasional stopped vehicles will mount the curb to use the shoulders as soon as they have had the opportunity of being well stabilized by a good growth of grass

[9] See Figure 4 in "A Policy on Intersections at Grade"

RAMPS OR INTERCHANGE ROADS

Where roads for direct interchange had not been provided, ramps between through roads were of the conventional clover-leaf type, that is, outer connections for direct right turns and inner loops for left turns Nearly all major through streams of traffic had been provided with direct one-way roads, so that the ramps, for the most part, were for secondary traffic, but volumes even there were high The successful operation of the through roads was dependent on the efficient operation of the ramps to avoid traffic backing onto through roads The ramps carrying heavy concentrations of passenger vehicles and buses to and from the Pentagon Building and parking areas were designed to standards considered desirable for major traffic interchange

Observation of speeds on existing highways [10] indicates that the median speed of travel is about seven-tenths of an assumed design speed based on a 97 or 98 percentile definition That is, at least half the motorists will travel slower than seven-tenths of the assumed design speed Faster drivers can reduce speed to this value readily, generally by little if any use of brakes, particularly when they are aware of the turn ahead. A turnout which can be traveled at this speed may be considered ideal

Ramps designed for travel at seven-tenths of the assumed design speed are readily provided on the outer connections but on the inner loops it may be impracticable to provide the radii required even after due allowance is made for high fric-

[10] "Percentile Speeds on Existing Highways," by D W Loutzenheiser, *Proceedings*, Highway Research Board, Vol 20 (1940)

tion factors permissible on turnouts[11] For example, an inner loop designed for a speed of 40 m p h which is approximately seven-tenths of an assumed design speed of 60 m p h would require a minimum radius of 250 ft With proper transitions at the ends and adequate widths of pavement and shoulder, an area about 600 ft across is necessary, exclusive of slopes For a turning speed of 50 m p h twice this diameter or four times the area is required It is evident, therefore, that compromise with the ideal is necessary to conserve space (generally valuable in express roads of this character), to reduce first cost and to reduce maintenance The compromise was embodied in the standards shown in Table 6

form of an added lane across a structure between the point of ingress from one inner loop to the point of egress to the next inner loop At some points the outer connection at one grade separation was so close to the outer connection at an adjacent grade separation that it was deemed desirable to provide an additional lane between the adjacent points of ingress and egress Though no need for speed-change area is apparent, it will provide space for weaving and maneuvering The cost of the additional area in this case is not as great as when providing an additional lane between adjacent inner loops where it is necessary to widen the structure.

Figure 6 shows a section of U S 1 Road to illustrate the locations where additional

TABLE 6

STANDARDS FOR CURVATURE ON INNER LOOP RAMPS

For 70-m p h road try	40 m p h	23° (R = 249 11)	and 200 ft transition
For 60-m p h road try	35 m p h.	32° (R = 179 05)	and 150 ft transition
Make no ramp less than	30 m p h	44° (R = 130 22)	and 100 ft transition
Preferably		38° (R = 150 78)	and 150 ft transition

Ramps designed on this compromise basis are supplemented by areas for speed change in the form of tapered sections and additional parallel lanes along the through roads On Heavy Duty Road and Army-Navy Boulevard the additional lane was made continuous but of bituminous surface to contrast with the concrete surface of the through traffic lanes. It remains to be observed to what extent a continuous added lane of this character will act as a speed-change lane, to what extent it will act as an additional through traffic lane, and whether the inevitable conflicts because of it will be appreciable Three traffic lanes were provided in each direction for U S 1 Road. Where speed-change area was required, an additional lane was provided. Generally this took the

lanes were provided Points 'a' and 'b' at bridges 10 and 11 indicate additional lanes between adjacent inner loops An increase in width of structure is required in each case Note that in the case of bridge No 10 additional width was not provided on the opposite side of the structure because there is no inner loop in the upper left quadrant and the loop in the upper right quadrant is designed for entrance to the through road at a fairly high speed Also note the added lane between the outer connections at point 'c.'

The gradients of ramps should be kept to a minimum to prevent slowing down too much on the up ramps and speeding up too much on the down ramps This is particularly desirable on inner loops where the sharp curvature and the confusion developed by large changes in direction add to the difficulties of maneuvering in an area where it is desirable that maneuvers be as simple as possible. Drivers entering

[11] See chapter on Speeds Above Minimum in "A Policy on Intersections at Grade" by the Special Committee on Administrative Design Policies, A A S H O, 1940

the loop must look for and read signs, and maneuver to the right to leave the through road When leaving the loop they must maneuver to merge with higher speed through traffic Designs which require additional operations such as application of brakes and negotiation of steep grades on sharp turns should be avoided

In the ramps on the Network where heavy truck interchange was expected, profiles were limited to 3 to 4 per cent upgrades Where the predominant traffic was expected to be passenger vehicles, level and meets a through road that is on an upgrade at the lower level presents one of the worst combinations as far as profile is concerned A complete discussion of the design of ramps is being developed by the Special Committee on Administrative Design Policies, A.A S.H O , for incorporation in "A Policy on Grade Separation for Intersecting Highways," but unfortunately this work has been interrupted by the war and is not yet available for reference The recommendation therein for the use of splines in the design

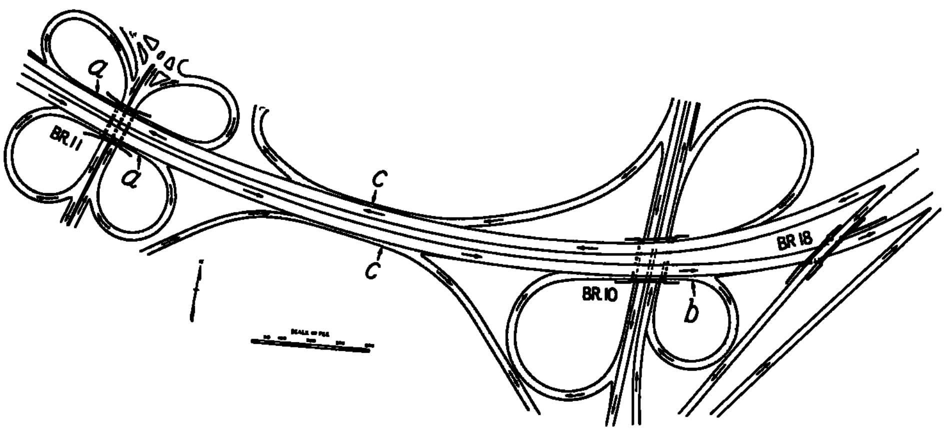

Figure 6. Additional Lanes on U S 1 Road

gradients up to 6 per cent were used. Ramp profiles were limited to 5 5 per cent downgrade, but most were on lesser gradients. The use of smaller gradients necessitates longer ramps but the effect of gradient on length of ramp is less than thought generally. The conditions at ramp terminals and their design have equally as great effect The profile of a ramp leaving a through road must necessarily begin on the same grade as the through road and can only gradually change direction through a vertical curve. This vertical curve together with the control of cross slope may require a considerable distance before the ramp grade proper can be reached A ramp which leaves a through road that is on an upgrade at the higher

of ramp profiles is strongly supported by our experience in the design of the Network

Smoothness of operation and graceful appearance of ramps and their connections to the through roads will result only if care is exercised in the design of the edges of pavement and of the changes of cross slopes especially at the ramp terminals. The customary practice of running centerline profiles and tying in to the through road centerlines at both ends with computed vertical curves will not result in as smooth a connection at terminals, cannot be visualized as readily and accordingly will take more time and effort than a design by the use of splines.

The ramp gradients, vertical curves and

cross slopes must be designed jointly At first trial horizontal alinement may need adjustment to meet a gradient limitation but as a general rule the alinement can be established and held with little change because of profile design In the Network the computed horizontal base line of each ramp profile was made the right edge of pavement in the direction of traffic For inner loops this edge is always the inside of the horizontal curve and the same is true on outer connections which do not reverse in direction. These lines tie in to the outer edge of pavement of the through roads and thus insure smooth flowing alinement and profile for the continuous edge of pavement that is most conspicuous Irregularities in profile of the center or other sections of a pavement are not apparent but at the edge of pavement, particularly if curbed, such irregularities are quickly noticed. Another minor advantage of the computed inner edge of pavement is flexibility in the choice of width as the design progresses A change in width can be made without recomputing the base line, whereas a change in width where the centerline is used as a base means recomputation if the edges of pavements are to fit

The cross slope on a ramp as on any other road should be sufficient to fully counteract the effect of centrifugal force when a vehicle travels at about three-fourths of the assumed design speed, with a maximum of 0.10 However, in the design of ramps it is not always practicable to attain the desirable cross slope in a short distance from the connection to the through road without too rapid a transition in cross slope or sharp crests and dips in the profile. On some ramps it was necessary to use cross slopes less than desirable to avoid these unfavorable conditions

Figure 7 shows a plan and Figure 8 profiles of the ramps in two adjacent quadrants to illustrate the method used.

The profile is laid out to station scale, preferably large, using the base line as the length At each terminal the profiles of the edge of pavement and of the adjacent lane line or centerline of the through road are drawn in position on the base line scale Control points at each terminal are also indicated. These generally are. the point of take-off (common point to through road and ramp), several points along the ramp inner edge with the width and superelevation from the through road edge taken into consideration and the location of the nose between the ramp and through road. Along the length of the ramps other controls such as elevations to tie in with an adjacent ramp or off pavement drainage inlets also are indicated, sometimes as top and bottom limits. With the controls plotted the spline is placed to fit, a trial profile drawn and then adjusted as required to meet desirable maximum gradients and minimum sight distance for the assumed design speed of the ramp. Hardly ever on the Network was the resulting vertical curve at either end one which was symmetrical or which could readily be computed as a single vertical curve Profile scales of 1 in = 50 ft. horizontal and 1 in. = 2 ft vertical and sometimes larger were used, and with them it was found practicable to scale the elevations of the edges of pavement at any point to the nearest 0 02 ft Necessary values were read and supplied to the field forces on construction

The outer edge of pavement was plotted on the same profile and as can be seen by the dash line on Figure 8, visualization of the cross slopes at all points, including the terminals, was not difficult. Of course the plotted outer edge is not to true length but this has no effect on the result.

Sometimes a ramp takes off on a horizontal curve in a direction opposite to the curve of the through road. In such case the cross slope on the ramp should be opposite that on the through road. This results in a ridge over which all ramp

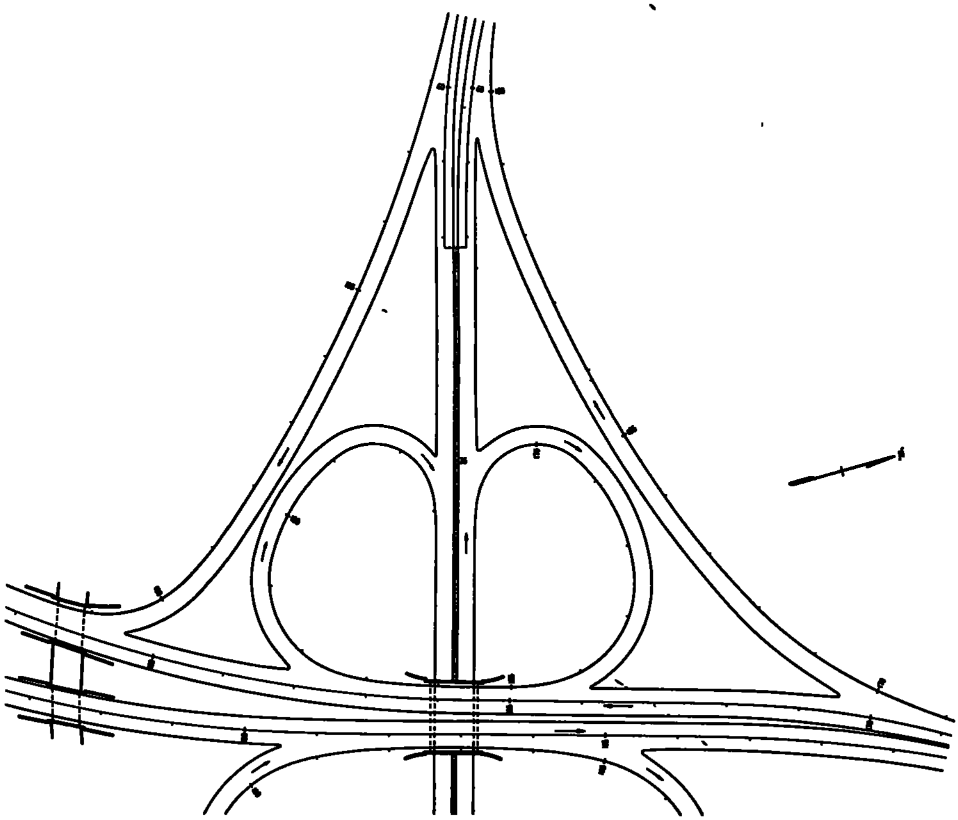

Figure 7. Plan of Ramps

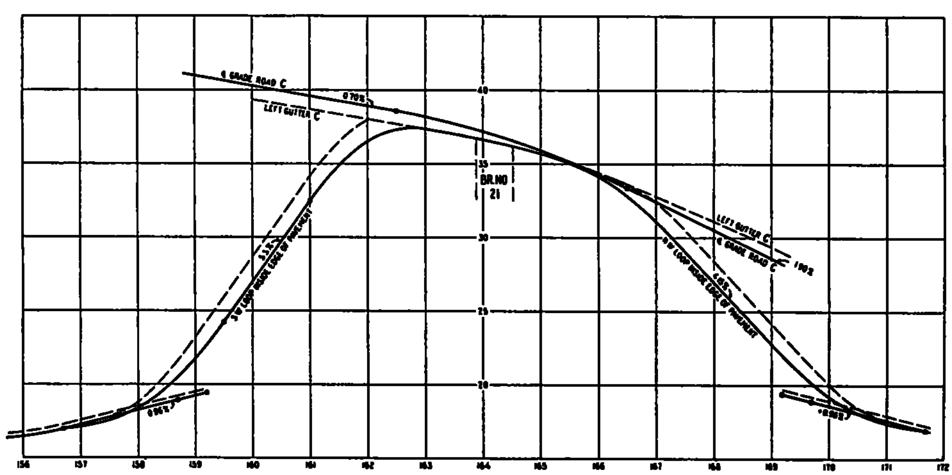

Figure 8. Profiles of Ramps

traffic has to roll. This problem is similar to that encountered at the entrances and exits of rotaries and is discussed in "A Policy on Rotary Intersections." [12] As recommended therein the algebraic differences of the cross slopes in such cases were kept to within 0.05 or 0.06.

In some cases where a cross slope on the ramp terminal was opposite in direction to that on the through road, it was necessary to make the cross slope of the outer lane of the through road less than the middle or inner lane to keep the algebraic difference of the cross slopes to the recommended figure. This is logical since it can be expected that vehicles on the outer lane will be traveling slower than vehicles on the middle or inner lane. In some cases the terminals of the ramps connected to an added lane devoted to speed-change and maneuvering space as previously described. The added lane in one case was designed to a lesser cross slope than the through traffic lanes. In another case the cross slope of the added lane was made opposite in direction to that of a superelevated through traffic lane, placing the ridge between the added lane and the adjacent through traffic lane rather than at the right edge of the added lane.

The flexibility of design when using a spline on profiles is unlimited, and if the reader feels that the refinements described are not justified he should ride and see the ramps and their terminals and then realize that the work involved was nominal. For the concrete pavements and concrete bases the design force laid out the joints and on all pavements gave elevations every 25 ft., or closer when necessary, at each edge of traffic lane, scaling all elevations from large scale splined profiles. The field forces located the base line or inner edge of pavement, taped across and set each elevation without being required to compute any profiles.

[12] "A Policy on Rotary Intersections" by the Special Committee on Administrative Design Policies, A.A.S.H.O., 1942.

DESIGN DETAILS

Several details of geometric design that tend to aid drivers in making proper maneuvers were incorporated in the Network. Most of them have been suggested at different times and several have been used before by various State highway departments.

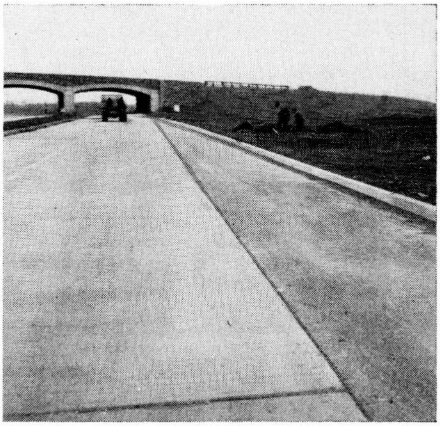

Figure 9. A Through Road With Inner Two Lanes of Concrete Surface, Outer Lane a Bituminous Surface With 6-In. Curbs.

Contrasting Pavements

The through traffic lanes were concrete and all speed-change lanes and interchange roads were bituminous pavements. It was thought that sufficient contrast in color and surface texture would result to subconsciously inform drivers when they leave the through lanes. Unfortunately war measures dictated that carbon black be used in the concrete pavements to reduce visibility from the air. As a result the contrast in color is not so great as originally intended. For the same reason white cement for high visibility curbs was also deemed undesirable. Figure 9 shows a section of road with concrete surface, bituminous surface and curbs. It was also thought that contrast in surface texture might be obtained by using a primary course of hot asphaltic concrete and, after initial rolling, spreading a surface course of $\frac{1}{2}$-in. chips at the rate of 10 to 15 lb. per sq. yd. and rolling it into the primary course while still hot. This method was not very effective in providing a surface texture of sufficient contrast to warn drivers. In fact recent casual observations on driving over several types of bituminous surfaces indicated that except for open surface macadam pavements the contrast between the surface textures of concrete pavements and high type bituminous pavements is not sufficient to materially affect driver behavior.

On the roads which did not have a continuous added lane of bituminous pavement a strip of "Durax" (small granite block) paving about a foot wide was used along the right edge of the through traffic lane between the concrete surface and the bituminous surface where interchange traffic leaves the through traffic lane. Ordinarily this strip was not used where ramp traffic merges with through traffic because it is desirable that entering traffic make use of every break in the through traffic stream to enter the through traffic lane and the granite block strip might act as a deterrent. Sometimes a granite block strip was carried through a merging area because it could not be terminated conveniently.

Noses Facing Traffic

Where a one-way road forks or separates into two one-way roads additional pavement width should be provided for maneuvering and the nose should be so located as to provide added length for the driver who changes his mind or discovers that he is heading toward the wrong road. Also, it should be obvious to a driver that he is approaching an island. Such warning is provided primarily by signs which are attention compelling, have good target value and are visible and readable at considerable distances both day and night. Additional warning aids are double curbs with reflectors incorporated in them, as shown in Figure 10, and a tapered rounded approach to the curbed nose, contrasting in color and texture as described in "A Policy of Intersections at Grade." [13] The area clear of the through traffic lanes is made of a coarse surface texture and while it may be flush with the surfaces of the adjacent through traffic lanes it is preferable to raise it gradually as the nose

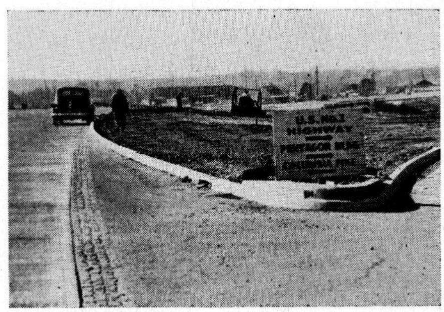

Figure 10. Double Curb With Reflector Units at Turnoff Nose Showing Nose Offset Taper and Granite Block Strip Along the Right Edge of the Through Road. The Sign is Temporary.

is approached. In the Network several of these nose approaches were made of granite block pavement, constructed flush with the adjacent pavement at the edges and raised to 2 in. above the pavement at the curb nose. Approach noses were constructed on a radius of 2 ft.-6 in. minimum and the face of curb at the side of the nose was kept at least 2 ft. from the edge of the through traffic lane.

Where a ramp leaves a speed-change lane the nose separating ramp and through road is vulnerable to being hit by vehicles

[13] See chapter entitled "Islands and Channels" in "A Policy on Intersections at Grade" by the Special Committee on Administrative Design Policies, A.A.S.H.O., 1940.

which encroach on the speed-change area and then must swing back onto the through traffic lane. In such cases the nose should be kept a considerable distance from the edge of the through traffic lane, perhaps a distance nearly equal to the width of the speed-change lane, and the edge gradually tapered so that vehicles can return to the through traffic lane. One of these approach noses with offset and taper is shown in Figure 10.

Where two one-way roads meet and traffic merges the design of the nose presents no problem. The traffic lanes are carried through without widening and curbs if used are carried to a point or nearly a point. One foot radius was standard for such noses on the Network.

Lighting

It is planned to light all roads as soon as the strategic material situation eases sufficiently to make available the necessary underground cable, transformers, lighting units, etc. Under-pavement ducts have been provided for such future installation.

In the general layout it was deemed desirable to keep lighting standards consistently to the right of traffic as an aid to drivers and as a safety measure in that vehicles forced to pull off the road on the left where they are apt to be driven at highest speed might have sufficient time to regain control if not confronted with lighting standards close to the pavement. For the most part it is practicable to hold to this rule but where the roads are more than three lanes wide, as at the mixing roads and at widened pavements for speed-change at ramp terminals, the distribution of light over the pavement is unsatisfactorily spotty unless the lighting standards are located and staggered on both sides of the road.

Some of the grade separation structures are so wide that the undercrossing is long enough to require lights in the abutment walls. The widest bridges are: No. 1, 185 ft. wide and No. 10, 140 ft. wide. It was thought at first that these undercrossings would require 24-hour lighting on circuits separate from those of the normal highway lighting. In fact thought was given to providing a much higher intensity of illumination during the day than at night as a safety measure to counteract somewhat the effects of sunlight beyond the structures. The bridges are completed and thus far only ducts have been installed. It now is evident that these refinements are unnecessary, the daylight even under bridge No. 1 being sufficient for all practical purposes. Apparently in considering lighting for grade separations distinction should be made between those undercrossings in which the approaches dip down sharply as at many railroad grade separations in level country and those in which the lower road is on long sweeping open alinements and profiles as in the Network.

Signs

It appears to be almost axiomatic that an improvement of any magnitude has in itself the seeds of further complications which require additional so-called improvements. In the case of the Network the complication is the difficulty of signing the roads to aid in directing to the proper destinations the relatively small percentage of drivers who are timid, easily confused, or strange to the area. The direct roads and interchanges used by the great percentage of drivers present no serious problem in this regard because the turnoffs, which properly may be termed bends or swings, are natural and in the general direction desired but the inner loop ramps at the clover leafs are confusing to many drivers, especially those not familiar with the type.

The signing of a network of roads with as many interchanges as closely spaced as on this Network is a problem of major importance, especially since the distances between points of ingress and egress are insufficient to provide the time intervals for drivers of fast-moving vehicles for perception, reading, deciding and starting of the proper maneuvers. The design of signs for the Network is worth a separate paper, possibly for next year's meeting of the Board, after the signs have been installed and an opportunity had for observations of compliance and other types of driver behavior. The signs are to be illuminated when road lighting becomes available. In the meantime they will be reflectorized. The size of signs and letters

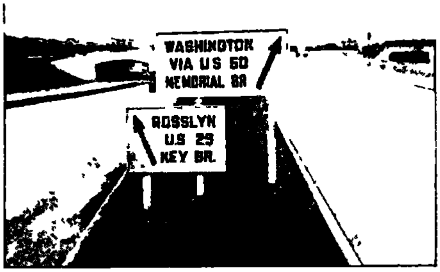

Figure 11. Typical Dual Sign at Road Fork

will be related to the speed and in some cases overhead signs will be necessary. Signs at a typical interchange road are shown in Figure 11.

Planting

Plans for planting were prepared by landscape architects and checked by the design engineers. Flat areas were covered with topsoil and seeded to grass Native-type ground cover was used on the steeper slopes to prevent erosion and keep maintenance costs to a minimum. A low growing ground cover was used at the noses facing traffic as a further aid in directing drivers to veer to the right or left Such direction is effected by giving the driver a sense of a barrier ahead for which purpose the vines or shrubs should be fairly high, say 3 ft. or more, but since signs must be located back of the ground cover it must not hide them. It is felt that the combination of a double reflectorized curb as heretofore described, low growing ground cover and the signs will reduce to a minimum the number of drivers who mount the curb at these approach island points.

Trees are potential hazards to vehicles which leave the traveled way in emergencies. It is hoped that the liberal standards used in design and the fact that all the pavements have curbs will tend to eliminate this type of accident. Nevertheless it was deemed desirable to minimize as much as possible the potential hazard of trees adjacent to the roadway To this end no tree is to be planted within 15 ft. of the edge of pavement on through roads or interchanges between through roads. Planting was designed so as not to interfere with sight distance. In addition thought was given to the psychologic effect of trees on drivers. Trees were so located and arranged that the direction of through roads and the points of turnoff were made evident on the subconscious mind of the driver encouraging him to make the proper turn. Trees were not used where it was thought they might be hazardous or encourage wrong driver behavior. Unfortunately no hard and fast rules based on controlled observations were available and judgment was the major guide. At ramp terminals where vehicles enter through roads all trees were kept well back of the point of entrance to insure a clear view of approaching merging traffic Closer grouping of trees was used on the right side of traffic at terminals where vehicles leave through roads. But it was felt that after a driver completes the maneuver of leaving the through road and is on his way on the ramp he should be given a clear view across to the point of entrance to the next through road Any considerable number of trees may act as a psychologic screen encouraging some drivers to hesitate. An occasional high growing tree was used on the theory that drivers can look past the trunk but it is a moot question as to how many trees or what arrangement will have the effect of a deterrent to a clear view.

All planting adjacent to through roads and ramps consisted of informal groupings; there were no regularly arranged or formal planting groups.

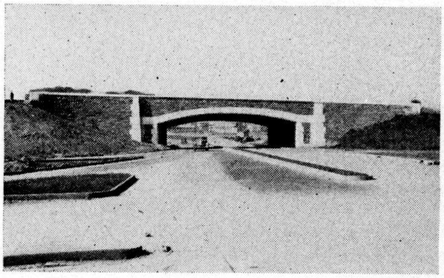

Figure 12. Bridge 7, a Single Span Rigid Frame Structure

safety on an overcrossing. Clearances at structures have been discussed elsewhere.

Structures should be pleasing to the traveling public and some thought and effort always should be exerted with this end in mind. Additional cost is not necessarily involved. The Network is part of the permanent road system of the nation's capital in close proximity to the national cemetery, the parks along the Potomac and public buildings of outstanding excellence. Some additional cost to satisfy the amenities, therefore, was fully justified and all but 6 of the 21 bridges were faced with stone. The office of Paul P. Cret was retained to assist in the architectural design of the structures. While bridges should be pleasing they should not force themselves on the eyes and minds of drivers as they pass through or over them. It is desirable therefore to keep structures as simple as possible, relying upon form and outline rather than ornament for

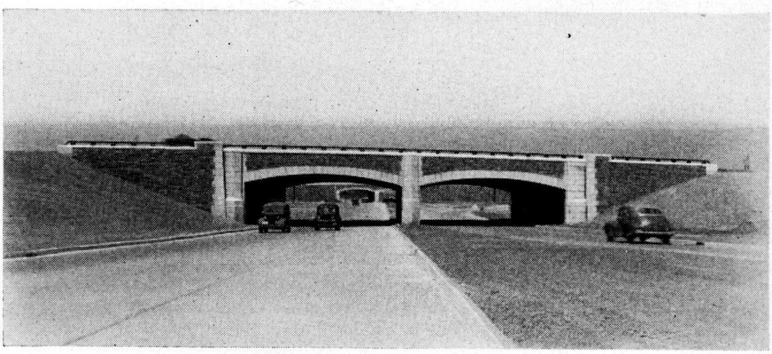

Figure 13. Bridge 10, a Double Span Rigid Frame Structure

GRADE SEPARATION STRUCTURES

The type of structure best suited for grade separations from the standpoint of traffic behavior is one that will give drivers as little sense of restriction as possible. To this end clearances, particularly lateral clearances, should be as great as practicable. Drivers should be given a sense of openness through an undercrossing and a feeling of liberal width yet a sense of

architectural excellence. Bridges of the rigid frame or continuous type with curved soffits appeared to be most appropriate. Figure 12, a photograph of bridge No. 7 and Figure 13 of bridge No. 10 show typical bridges of the rigid frame type.

On overcrossings parapets should be as low as possible to enable passengers to look over the side and yet present an appearance of strength. A satisfactory parapet is one which is solid, 15 to 18 in. high and mounted with an open rail. A parapet of this type is shown in Figure 13. The wood railing will be replaced by metal

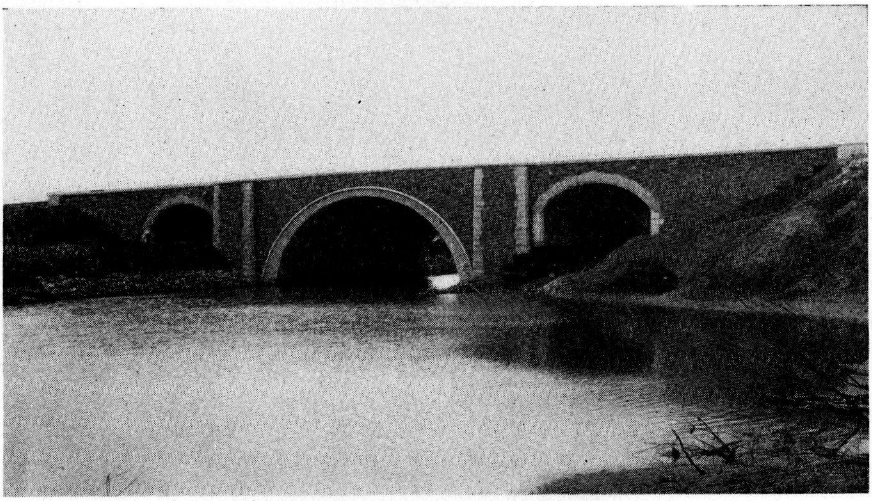

Figure 14. Bridge 3, Spans for Boundary Channel and Two Service Roads

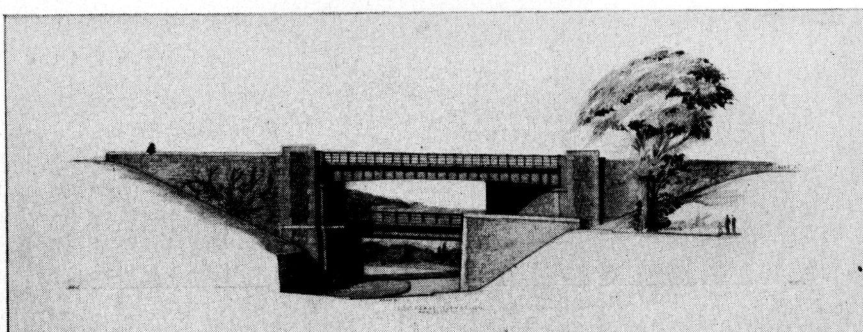

Figure 15. Three-Level Bridge, No. 13

after the war. Bridge 3, shown in Figure 14, spans Boundary channel and two service roads.

An interesting structure is Bridge 13, a triple decker and not yet completed. It is shown in Figure 15, a reproduction of an architectural rendering.

CONCLUSIONS

Since this paper is not on research in the usual sense conclusions based on carefully controlled tests or observations are not in order. It is, rather, a description of the problems met in developing a network of express type of roads in a metropolitan area, how they were solved and to what extent research of the past was applied on a practical problem of appreciable magnitude. Only the geometric phases of design have been discussed, the important structural and construction problems being worthy of separate papers. Some general conclusions are indicated

Design should proceed on the basis of one-way roads and liberal use should be made of spline alinements and profiles instead of hard and fast tangents and curves.

Heavy interchange traffic streams should be provided with directional paths in preference to the customary inner loop of a clover leaf grade separation

Where an express highway is crossed by closely spaced important routes, a condition common to metropolitan areas, it may not be practicable to provide the distances between points of ingress and egress considered desirable for high speed operation of the through express road.

The high value of right of way in metropolitan areas will be one factor against providing ramps which can be driven at a speed considered desirable in relation to the assumed design speed of the through express road. Other factors are the extra travel distance and additional maintenance involved in large radius inner loop ramps.

Based on the experience of this and other networks of express highways the opinion may be hazarded that in metropolitan areas the saving in time of travel and cost of operation by construction of networks such as this is considerable and well beyond comparable savings effected by most other types of highway and street improvements. This is so even where the crowded conditions of metropolitan areas impose design restrictions which will make it necessary to keep the actual speed of travel lower than on the open road. Therefore it is felt that in metropolitan areas traffic of high volume with varied origins and destinations can best be served by express types of one-way highways with all interference from cross traffic eliminated by separation of grades, all access limited to carefully designed points of ingress and egress and directional paths provided for the major traffic streams. The demand for this type of facility is bound to increase as the driving public becomes acquainted with its many desirable features and administrative officials become courageous enough to satisfy their wants.