Modern Rotaries: A Transportation Systems Management Alternative

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Although many rotaries, large and small, were constructed in the United States before World War II, they have received little attention in American literature in recent years. The present paper describes British developments in this field. In Britain, where rotaries (or "roundabouts") are a common form of intersection control, the capacity of large, conventional rotaries has been increased by 20-50 percent by reducing the size of the center island and enlarging the space available at the point of entry into the circulatory roadway. Rotaries need not be large to achieve high capacity. Small designs have been developed that generally have operating and safety characteristics superior to those of conventional alternatives, particularly when their geometry is devised to reduce approach speed and facilitate gap acceptance. At previously signalized intersections, capacity increases of 5-30 percent were obtained. Three-leg (T and Y) rotaries gave the best results for safety and capacity. Pedestrian and other fatal and injury accidents decreased substantially at sites converted from other forms of control, though an increase in property-damage-only incidents was observed at several locations. However, except at three-leg sites, fatal and injury accidents almost doubled after the center islands of conventional rotaries were reduced in size. Considerable savings in right-of-way acquisition and construction costs can be obtained on arterials, where the need for additional lanes to increase road capacity is greatly reduced by the use of rotaries. Rotaries can also reduce cost and land take when used as alternatives to, or in conjunction with, grade separation. The rotary concept can be employed in a grid of one-way streets, where blocks form rectangular center islands.

The cure for many traffic congestion problems is seen in the construction of wider roads. Yet it would often be more economical to increase the capacity of critical intersections rather than to widen a road in its entire length. The present constraints on government expenditure, the growing public resistance to large-scale highway construction, the energy crisis, and the problem of air pollution have given added impetus to the search for simple, inexpensive, and readily available techniques that relieve traffic congestion, increase street capacity, and make best use of existing facilities.

It was recognized many years ago that a rotary could be designed to have a capacity equal to that of the intersecting roads. In the United States, little work has been done in this field. The purpose of the present article is to acquaint the reader with developments in Britain, where small rotaries have been built with operational and safety characteristics that are superior to conventional alternatives.

A rotary has been described as a series of T-intersections at which a number of streets join a one-way circulatory roadway (1). For its successful operation, it is essential that entering drivers are advised by a right-of-way rule or a yield sign to give precedence to those within the rotary.

In the United States, rotaries have been unpopular because of the large area required and the low capacity of their weaving sections. The American Association of State Highway Officials (AASHO) used to recommend rotaries for complex intersections of five legs or more, as well as for intersections that would otherwise require multiphase signal control, but considered their capacity limited to about 3000 vehicles/h (2), though traffic circles in the United States were reported to handle 5000 and 7600 vehicles/h (3, 4). Fairly high design speeds and the concept that the length of a weaving section contributed materially to its capacity led to large layouts, where time gained by the higher speed is lost on longer travel distance. In practice, observed mean speed is about 24-28 km/h (15-17.5 mph) on urban rotaries (5, 6), so that the slow-down, as well as the extra distance traveled, contribute to what is called the "geometric delay".

However, small rotaries in the form of "dummy cops", "mushrooms", and small traffic circles were used extensively 50 and 60 years ago (7-9). The dummy cop was a trestle or stone column, often illuminated, that stood in the center of an intersection. The mushroom, also called a bumper or button, consisted of an iron disc about 45 cm (18 in) in diameter and 15 cm (6 in) high; some contained an electric light and others were fitted with reflectors. Small traffic circles were pioneered by early traffic engineers, notably William Phelps Eno (7, 8), George Guy Kelcey (9, 10), and Theodore M. Matson (11). These circles entered the literature under the heading of "channelized intersections", but in the United States they have not been researched and developed as intensively as they have been more recently in Britain.

MODERN ROTARIES IN BRITAIN

In Britain, rotaries are called "roundabouts" and are widely used for intersection control, particularly in rural areas, where signal control is rare. In an effort to overcome the disadvantages inherent in conventional, large rotaries—size, cost, low capacity, and extra travel distance—the Road Research Laboratory [now called the Transport and Road Research Laboratory (TRRL)], on the initiative of Frank C. Blackmore, made an intensive study of the design and application of smaller layouts specifically built for high capacity at low speed. Experiments conducted first on test tracks and later on public roads showed that a reduction in the size of the center island and an increase in the entry width could raise the capacity of large rotaries by 20 percent (12) and in some cases by 50 percent (13, 14). In terms of road-user costs, some conversions paid for themselves within 5-10 weeks (14). When very small center islands were installed, such layouts provided greater capacity than signals at sites previously considered too restricted for rotaries (15). In the first public road experiment, at Peterborough, Huntingdonshire, the replacement of signals by a "mini-roundabout" with a center island of 3 m (10 ft) in an inscribed circle of 29 m (95 ft) raised the saturation capacity of a T-intersection from 3700 to 4700 vehicles/h (16). A 20 percent capacity increase to 3300 vehicles/h was obtained at Longbenton (Figure 1) after signals were replaced by a center island of 2.5-m (8-ft) diameter in an inscribed circle that had been enlarged from 22 m (72 ft) to 24 m (79 ft) (15).

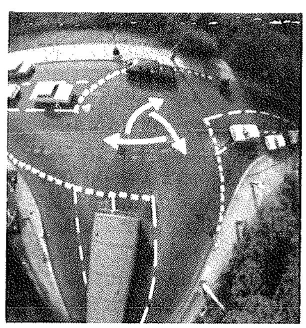
In its smallest form, the center island is made crossable by vehicles and, finally, reduced to zero, with the rotary principle indicated by circular markings in paint or thermoplastic. In this form, a rotary might be visualized as a three- or four-way yield to the left (in countries where traffic drives on the right, or to the right in those where traffic drives on the left), a technique commonly referred to as "offside priority".

A film by TRRL shows the operation of a rotary that has a zero center island in an inscribed diameter of 17 m (58 ft) at a previously signalized T-intersection in South Benfleet, Essex (Figure 2). Saturation capacity rose from 1800 to 2400 vehicles/h. Peak-hour queues were reduced from 2 km ($1\frac{1}{4}$ miles) to 50 m (165 ft) (15).

Over the last 10 years, the use of mini-roundabouts with center islands of 4 m (13 ft) or less and other offside-priority rotaries that have center islands of up to about one-third of the inscribed diameter has spread widely in Great Britain. They are employed to increase the capacity of existing large, conventional rotaries or as control where the intersection of a major and minor road had become dangerous or caused excessive delays, as turn and speed control in residential areas, and for new intersections. Where they replaced signals, they increased capacity by 5-30 percent and significantly reduced peak and off-peak delays, as well as the number of stops. A variety of at-grade rotary layouts is shown in Figure 3a-f.

Figure 1. Mini-roundabout at Longbenton, Newcastle-upon-Tyne.

Figure 2. Fish-eye view of a zero roundabout, Benfleet, Essex.



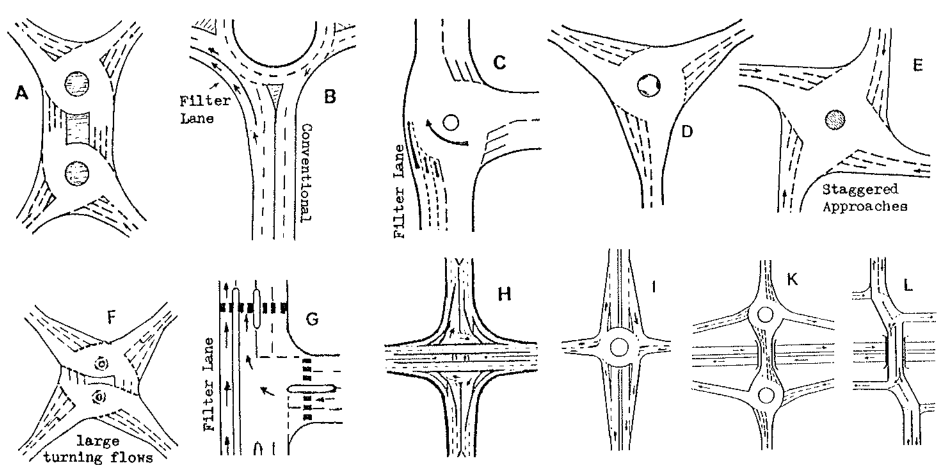
The operation of three-leg rotaries has been found to be safer, easier, and more reliable than that of others. The Y-intersection is the most satisfactory layout; it usually gives good visibility and a natural slow-down effect, which recommends it for new and redesigned sites (17). At some four-leg sites it has been found an advantage in capacity, safety, or convenience to change the intersection into a pair of adjacent three-leg rotaries (18) (Figure 3a). This feature can obviate the reconstruction of two offset "dog-leg" T-intersections into a single straight-through layout, a solution often proposed for signalized intersection improvements.

Rotaries eliminate the need for left-turn prohibitions (where traffic drives on the right), and they require no median to accommodate left-turn lanes. Unlike signals, they are immune to equipment failure and need little maintenance and no operating expenditures. They have a further advantage that is important to the resident, the taxpayer, and the environmentalist: they greatly reduce the need for highway widening. To raise capacity and accommodate the movement of high-volume platoons, signalized arterials are often widened to six or eight lanes. By contrast, the capacity of an offside-priority rotary is not affected by the width of the approach roads (19) but depends on the number of vehicles able to accept each suitable gap. In principle, if space permits, a rotary's capacity can be increased until it reaches or exceeds that of the approach roads, a feature recognized in the United States in the 1930s (20). It is usually less expensive and less controversial to enlarge a congested intersection than to build additional lanes where right-of-way acquisition would affect numerous adjoining properties (21).

From this it is apparent that the conversion of an existing six- or eight-lane signalized arterial to rotary control would, without detriment to total traffic flow, free the curb lanes for the exclusive use of buses, carpools, bicycles, or parking, provided all traffic may use the entire intersection area and its immediate approaches and exits (22).

In the United States, the widespread use of larger cars is likely to result in capacity at all types of intersections about 20 percent lower than that in Britain, where rotaries have been built to handle 5000-6000 or more vehicles an hour. Marble Arch, in London,

Figure 3. Various intersection and interchange layouts (traffic drives on left; not to scale).



though not designed as a high-capacity rotary but as a one-way system with a 16-m (52-ft) roadway, carries 8600 vehicles/h in the peak hour. Hyde Park Corner, a one-way system with an 18-m (56-ft) roadway, handles more than 10 000 vehicles/h in the peak hour, as well as 2000 through an underpass.

Scott Circle, in Washington, D.C., which had a circulatory roadway of 22 m (72 ft) prior to its reconstruction, carried 7600 vehicles/h (4) before it was fitted with signals in 1926.

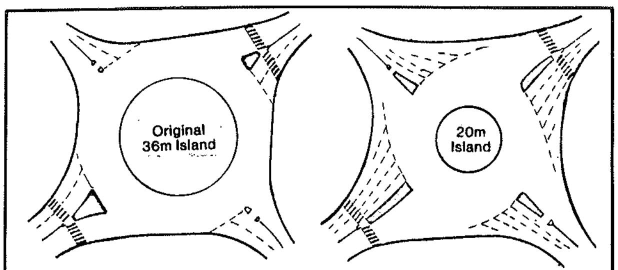
In Paris, the Place de l'Etoile, where 12 streets converge on a roadway 38 m (125 ft) wide, was reported in 1956 to handle close to 20 000 vehicles/h (23), in spite of a rule that gives right-of-way to entering drivers and thereby prevents exploitation of a rotary's full potential.

IMPROVING ROTARY PERFORMANCE

Principles of modern offside-priority rotary design are shown in Figure 4 [adapted from Blackmore and Marlow (24)]. Since a rotary operates on gap acacceptance, measures that facilitate the gap-acceptance task are beneficial in reducing delay and increasing capacity.

A higher rate of vehicle discharge is obtained when an approach is flared into a wider entry, with the yield line brought forward into the inscribed circle. By adding more entry lanes, output from one approach can be raised independently of the output from others and

Figure 4. Design principles for offside-priority rotaries (traffic drives on left).



Design Principles for Offside Priority Roundabouts:
1. Smaller center island to allow greater circulation width and entry width.
2. Yield line moved forward to increase entry width.
3. Greater number of narrower entry lanes in a given width.
4. Yield line left open near curb to encourage filtering.
5. Curb adjustment and narrower deflection islands to allow larger entry flare.

the effect of an unbalanced flow can be countered. Conversion from a conventional one to this type of rotary brings a fundamental change in operational characteristics. As can be seen in Figure 4, no proper weaving sections remain, and traffic no longer weaves. Depending on a driver's initial position at the yield line, the path selected and the size of the rotary, the vehicle's trajectory varies from an intersecting movement at right angles to merging at an acute angle.

Where drivers are reluctant to spread out into the wider entrances provided, they should be encouraged to do so by means of education (24), by a more gradual flare (25), and through initial police supervision of a newly installed rotary.

On entering a rotary, a driver should select a path, proceed along it at an even pace, and not cut in front of another vehicle but drop behind it. Correct use of turn signals, switched on shortly before the exit, helps others to make efficient use of gaps. Bicycle riders are served best if they keep to the outer curb lane and treat the rotary as a succession of T-intersections, at each outlet signaling their intention to turn off or continue ahead.

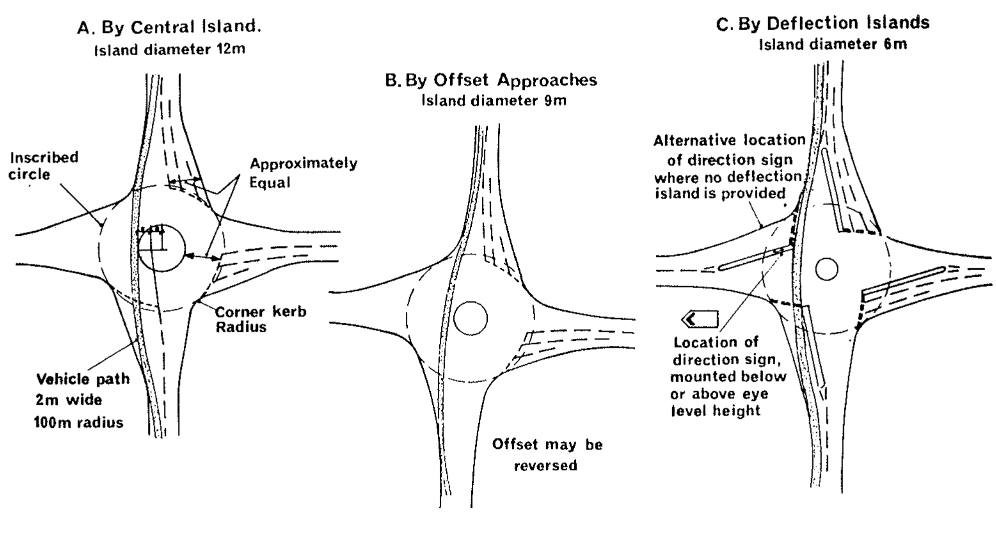
The slow-down necessary at the approaches to a rotary can be assisted by a deflection of the entry lanes (Figure 5) (17) or by a staggered road alignment (Figure 3e). These methods help to eliminate the visual impression that a fast, continuous road lies ahead. They give a gyratory effect with an acute angle of entry and thereby allow drivers to adjust their speed to that of the circulating stream. Entry gaps as short as 3 s have been found acceptable, and even 2 s in ideal conditions (1, 26). Deflection islands should be narrow, so that they do not restrict entry width, yet wide enough [about 1.2 m (4 ft)] to provide a refuge for pedestrians.

Advance warning signs, illuminated yield signs, flashing beacons, chevron boards, and other devices should be employed where necessary to counter excessive approach speed.

"Filter" lanes, provided to give unimpeded movement to drivers who are taking the first exit, have added considerably to the output from an individual approach road (24, 27) (Figure 3b). A yield line kept open ended near the curb has given a similar effect (24, 25) (Figures 3c and 4). At conventional T-intersections, through vehicles can likewise be separated from turning traffic if they are channeled into a filter lane that is indicated by a curb, barrier, or pavement markings (22, 28) (Figure 3g).

The maneuver of slowing down for a rotary and

Figure 5. Alternative methods of providing vehicle-path deflection (diameter of inscribed circle = 32 m; traffic drives on left).



accelerating back to normal travel speed imposes a certain delay that, depending on the speed differential, amounts to about 2-10 s. Since it occurs all day, this delay should be taken into account in cost-effectiveness studies, as well as the extra time a driver takes to negotiate all but the smallest rotaries.

PEDESTRIANS

Rotary control appears to bring considerable benefits to both pedestrian and vehicle safety. This can be attributed to a smooth flow and to comparatively simple decisions made at low speed. Crosswalks, placed two to three car lengths away from the yield line across the throat of the entry flare and divided by a center refuge (Figure 4), allow the driver to deal with pedestrian and vehicular conflicts in separate stages. Likewise, the refuge allows pedestrians to deal separately with vehicles from opposite directions. Where necessary, additional "stepping-stone" refuges can help pedestrians to cross one traffic lane at a time. At high-volume locations, guardrails have been provided. Pedestrians at rotaries generally have to walk a longer distance, but their average delay has been found to be less than that at signals (19). Antiskid surfaces are often used at crosswalk approaches, as are zigzag pavement markings, to indicate a parking and passing prohibition (29).

SAFETY

U.S. literature has mentioned the comparatively good safety record of rotaries; accidents are usually of a minor nature and involve property damage only (PDO) (2, 5). Probably the first before-and-after accident study at a rotary was conducted in Los Angeles in 1922. The installation of a traffic circle with a 37-m (120-ft) inscribed diameter and a center island of 12 m (40 ft) at Western Avenue and Wilshire Boulevard, reportedly capable of handling 5000 vehicles/h, reduced accidents by half and the cost of property damage by 75 percent (3). Published studies in the United States are rare, but those in Britain indicate that rotaries have a better safety record than major-minor road intersections or signals and that safety increases with the size of the center island.

Manning considered that rotaries tend to have at least 25 percent fewer accidents than signals (30). Garwood and Tanner found a reduction of 83 percent in fatal and serious injury accidents at three sites where rotaries had replaced signals and an overall reduction in injury accidents of 56 percent (31). A 10-year study by H. C. Smith compared 12 signalized intersections and 12 rotaries that had similar traffic volumes and found the rate of injury accidents at signals twice as high and the rate of pedestrian injuries three times as high (32).

A study by TRRL recorded personal injury accidents before and after installation of small rotaries at 150 locations. Since the number of accidents at any one site was small and the before and after periods were not always of the same duration for any site, the analysis was performed according to a method devised by Tanner (33) that uses the British national average for a control. Site conversions varied from simple, low-cost markings to expensive changes in design, so that the result could only be a measure of the composite effect averaged over the various sites. British national accident statistics include fatal and injury accidents only; they do not list PDO collisions, which do not have to be reported to the police.

In 48- and 64-km/h (30- and 40-mph) speed-limit zones, 88 sites previously operating as major-minor road intersections showed a decrease of 34 percent in slight injury accidents and of 46 percent in serious injury and fatal accidents; three-leg sites with raised center islands performed best. At 13 sites previously signalized, serious injury and fatal accidents were reduced by 62 percent and all injuries by 31 percent. However, when the center islands of 31 conventional rotaries were reduced in size, the reverse trend occurred except at three-leg sites, and the accident total was almost doubled, thus testifying to the inherent safety of conventional layouts. In higher-speed-limit zones, the study included no signalized intersections but otherwise endorsed the above results (34).

In Newcastle-upon-Tyne, a city that pioneered mini-roundabouts, pedestrian accidents were halved, according to a study that covered 22 years of mini-roundabout operation (35), even though traffic at all sites increased.

A before-and-after study at 38 locations where rotaries had replaced major-minor road intersections was conducted in the greater London area. The total number of injury accidents fell by 39 percent, fatal plus serious injury accidents by 64 percent, wet-road accidents by 51 percent, overall pedestrian accidents by 46 percent, fatal plus serious pedestrian injury accidents by 70 percent, and accidents involving two-wheeled vehicles by 18 percent. There was no change in the total number of rear-end collisions. Again, the larger rotaries performed best—overall accident reduction of 52 percent. At sites with curbless center islands, total accident reduction was only 23 percent; these sites showed an increase of 60 percent in rear-end collisions and of 7 percent in accidents involving two-wheeled vehicles (36).

Despite the general reduction in injury accidents and their severity, more sideswipes and other PDO incidents have been observed at several sites (14, 19, 37); this is attributed to a higher level of activity at high-capacity rotaries. To allow a true assessment of the effect of a change in traffic control devices, it would be useful if studies included every incident, the traffic volumes, and accidents within the neighboring roadnet. For example, an increase in accidents at an intersection that handles more traffic after the changeover may be accompanied by less congestion and fewer collisions on the approaches and on residential streets through which commuters had previously made a detour. Unfortunately, today's reporting and record-compiling methods rarely allow such full analysis.

THE ROTARY AND THE RESIDENT

Citizens often clamor for stop signs to discourage the use of residential streets by commuters and to control speeding. The Manual on Uniform Traffic Control Devices (38) advises that stop signs should not be used for speed control. The signs have been found ineffective and even counterproductive for that purpose (39).

Small rotaries have been installed to control speeding in residential areas in Seattle (40) and San Francisco (41). They are also used for that purpose in some of Britain's more than 30 New Towns, which rely on limited access and grade separation for their traffic control within the primary road system and, at the more important at-grade intersections within the secondary system, almost exclusively on rotaries. Rotaries are said to have a more attractive appearance and to create a more pleasant environment than signals, with their profusion of lights and the disconcerting effect of stop-start movement and the noisy revving of engines (42). Because delays are shorter than at signals, motorists have less incentive to filter through residential side

Figure 6. Rotaries in a one-way grid (traffic drives on right).

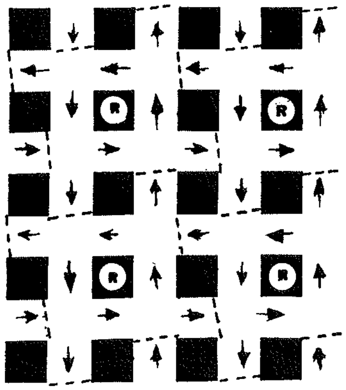
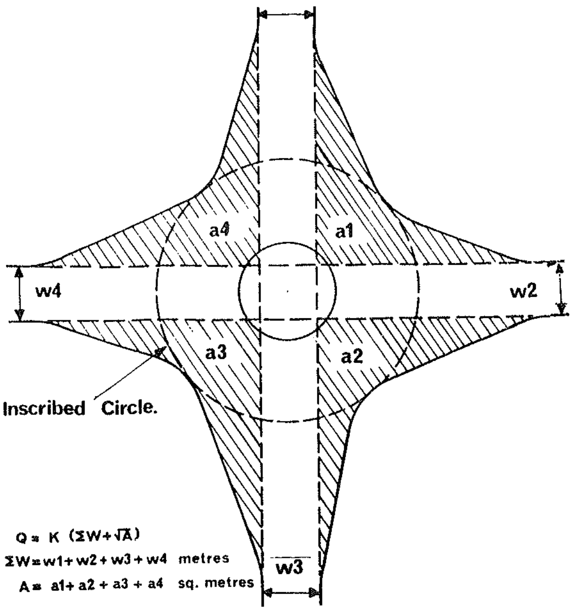


Figure 7. Calculation of capacity.



streets (32). Flowers, trees, and greenery can be planted on the center island. As evidenced in Washington, D.C., by Scott Circle, Grant Circle, and many others, they can embellish the civic scene by serving as convenient emplacements for the graven images of warriors and politicians.

ONE-WAY GRIDS

The engineer in search of the least restrictive form of traffic control for a system of one-way streets may wish to follow in the footsteps of Pratt (43) and Malcher (44), who recognized in the late 1920s that a grid of one-way streets forms a series of rotaries. The AASHO Blue Book (2) likewise states that parts of an existing street system may be designated as the one-way road of a rotary. In a one-way grid, every second block forms the center island of a rectangular rotary, with the surrounding streets representing the circulatory roadway (Figure 6). Yield signs can be installed in such a manner that, when traveling along the entire length of a street, a driver yields to traffic on the left at every second intersection; at the intervening intersection those on his or her right yield. Great flexibility can be obtained in such a system when the right-of-way on a street is reversed to permit entry into a heavy traffic stream from a street carrying very low volumes, or when the direction of a one-way street is reversed to meet different capacity requirements. Since a block also represents a median, pedestrians can move within a one-way grid in the same way as at other rotaries, with additional intermediate refuges acting as an aid to crossing high-volume vehicle streams.

GRADE SEPARATION AND THE ROTARY

The rotary has been called a compromise between a signalized intersection and grade separation and recommended where the limitations imposed by cost and space prevented construction of the latter (45, pp. 9-12). Today's inflation and the growing resistance of the public to large-scale highway construction projects may make the high-capacity rotary at comparatively low cost a more widely accepted alternative to grade separation. Cost as well as a shortage of land may prohibit the construction of a conventional cloverleaf interchange where a two- or three-level rotary design would reduce cost and space requirements to a minimum (Figure 3h, i). At diamond interchanges, two small or zero-center rotaries linked by a single bridge (Figure 3k, l) have been recommended for economy in place of the conventional two-bridge, single rotary (17). This construction can be employed to relieve or eliminate the problem that often exists at signalized diamond interchanges where traffic backs up along the exit ramp onto the freeway.

CAPACITY CALCULATION

From road experiments, TRRL developed the following formula for calculating the capacity of offside-priority rotaries with small center islands (Figure 7) (17):

$$Q = K(\Sigma W + \sqrt{A}) \tag{1}$$

where

- Q = practical capacity (vehicles/h);
- K = efficiency constant of 70 for three-leg intersections, 50 for four-leg intersections, and 45 for five-leg intersections (for rotaries whose center islands are less than 4 m (13 ft) in diameter, a reduction of 10 percent should be made);
- ΣW = sum of basic widths (not half-widths) of all intersecting roads (m); and
- A = area added to the intersection by the flared approaches and exits (m^2).

TRRL has now adopted a new procedure that assesses capacity on an entry-by-entry basis in terms of entry geometry (25, 46).

Accurate results have been obtained by the rule-of-thumb formula (19)

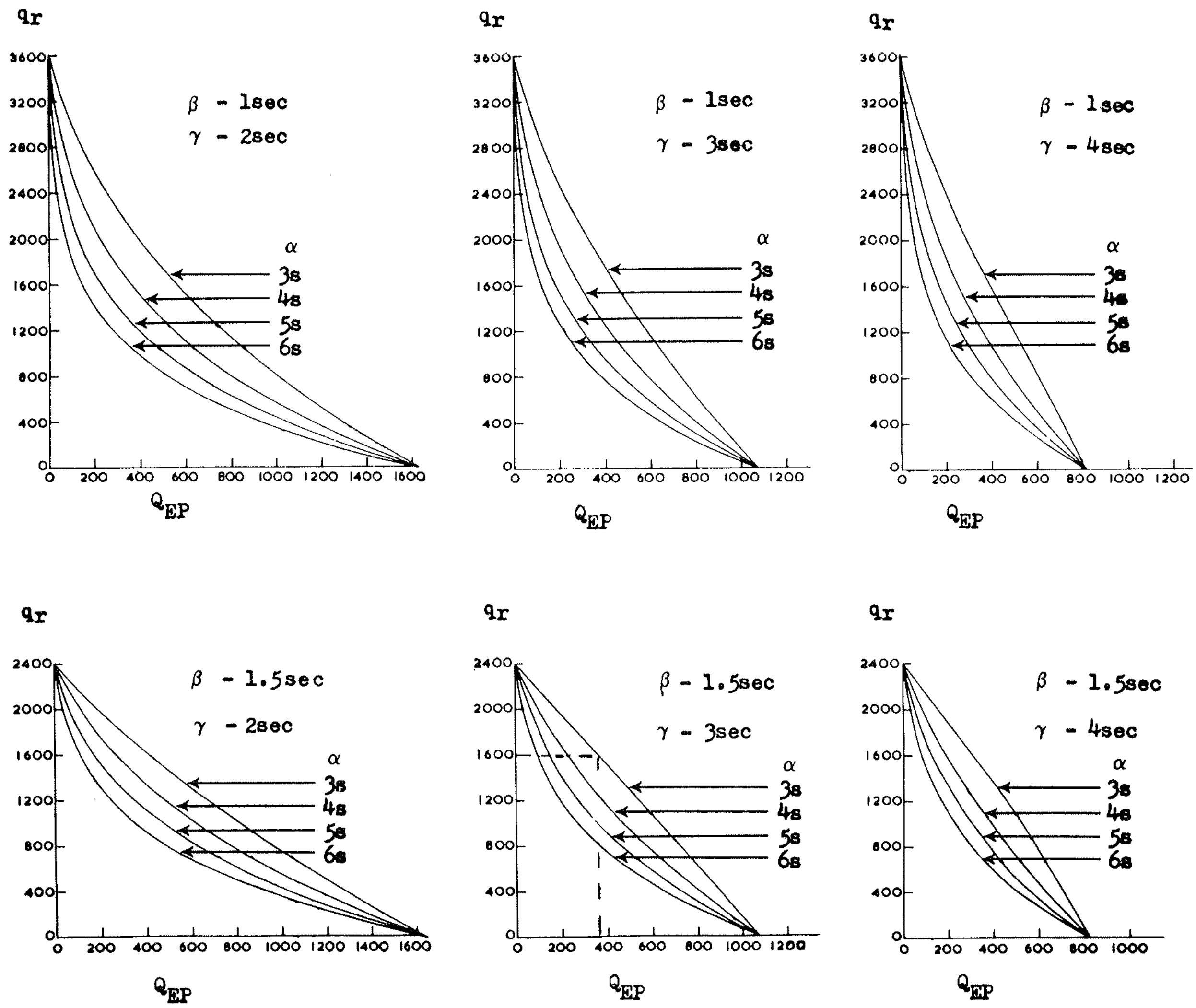
$$Q = KD \tag{2}$$

where

- Q = saturation capacity (passenger vehicles/h),
- K = 150 for three-leg intersections and 140 for four-leg intersections, and
- D = diameter of the inscribed circle (m); for an oval intersection, D is the mean of the major and minor axes.

For design purposes, the flows should not be more

Figure 8. Bennett's design graphs.



Bennett's design graphs, based on Tanner's formula $Q_{EP} = \dfrac{q_r(1-\beta q_r)}{e^{q_r(\alpha-\beta)}(1-e^{q_r\gamma})}$

than 85 percent of the volumes calculated from these formulas.

R. F. Bennett (1) considered each approach as an entry into a T-intersection. By modifying Tanner's formula (47), he developed the graphs shown in Figure 8, where $\overline{Q}_{EP}$ is the practical entry flow per lane from the approach leg (passenger vehicles/h), q_r is the circulatory flow per 7.5 m (24 ft) of roadway passing the entry, β is the minimum headway on the rotary, α is the minimum gap acceptable to entering drivers, and γ is the move-up time of vehicles in the entering queue. Suggested values for α, β, and γ are as follows:

1. $\alpha = 3$ s for level urban approaches, 4 s for level rural or uphill urban approaches, and 5 s for uphill rural approaches.
2. $\beta = 1$-1.5 s (for peak flows, 1 s gives more realistic results).
3. $\gamma = 2$ s for a downhill approach, 3 s for a level approach, and 4 s for an uphill approach.

For example, if there is a level approach to an urban rotary that has a circulatory flow (q_r) of 1600 vehicles/h and values of $\alpha = 3$, $\beta = 1.5$, and $\gamma = 3$, then the entry flow per lane of 350 vehicles/h can be read from the fifth graph in Figure 8. Therefore, if the entry flow is 850 vehicles/h, three entry lanes will be required.

SUMMARY

In Britain, the capacity of large, conventional rotaries has been raised by reducing the size of the center island and increasing the entry width to give a higher rate of vehicle discharge. Small rotaries have been developed to overcome the drawbacks of large layouts. The simpler designs in the form of T- and Y-intersections gave the best performance for safety and capacity. The rotary principle can also be applied to a grid of one-way streets, where a block forms the center island of a rectangular rotary. The following benefits (in comparison with conventional alternatives) can be obtained:

1. Stops and delay are drastically reduced.
2. Capacity within the existing intersection area is raised by 5-30 percent.
3. Space permitting, an intersection and its immediate approaches and exits can be enlarged to handle more traffic, without a need to widen the streets along

their entire length; the need for six- and eight-lane arterials is greatly reduced.

4. On existing six- and eight-lane highways, exclusive lanes for buses, carpools, or bicycles can be operated without detriment to overall traffic performance.

5. There is no left-turn prohibition (in countries where traffic drives on the right, or right-turn prohibition where traffic drives on the left), and no median is needed to accommodate left-turners (or right-turners, respectively).

6. Compensation is made for unbalanced flows.

7. There are low maintenance costs, no operating costs, and no equipment failures.

8. Rotaries are aesthetically pleasing, give smoother flow, and have lower noise levels.

9. There is less incentive for commuters to filter through residential areas.

10. Safety is increased, and road-user decisions are simpler.

11. Signal-free operation of one-way streets is possible.

12. Less land is taken and there are lower construction costs at interchanges.

ACKNOWLEDGMENT

Permission from the County Surveyors' Society, TRRL, and the Institution of Highway Engineers to reproduce illustrations from their literature is gratefully acknowledged.

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Discussion

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I think we all, to some extent, share the author's concern about the phasing out of existing rotary intersections and the lack of interest in constructing new rotaries in this country. I think we can agree with his assessment of their many advantages. As a recent brief article on traffic circles in Transportation Research News (48) noted,

> In view of their many apparent advantages, it would seem logical that traffic circles would continue to be universally popular. The need for expensive and complicated conventional traffic control devices may be reduced or even eliminated. The graceful lines of circles would seem aesthetically preferable to the angularity of typical at-grade intersections and their control hardware clutter. The continuous flow of vehicles through a circle provides a quieter and cleaner environment than the stopping and starting actions associated with conventional intersections.

The most recent U.S. publication in Todd's references is Policy on Geometric Design of Rural Highways, published in 1965 (2), which lists advantages similar to those mentioned above.

The way in which they are described, however, is not strongly persuasive. For example, the statement "there is little speed reduction and no delay from stopping" applies only to low volume levels. It is further stated that accidents "are of minor nature" but, in the United States, accidents have been a concern at rotaries, not because of their severity but because of their frequency.

The reasons for the demise of rotaries in the United States are probably best summarized in the listing of disadvantages in the AASHO Manual:

1. "A rotary can accommodate no more traffic than a properly designed channelized layout. In some cases, rotaries have been eliminated and replaced with a channelized intersection, resulting in better operation." This statement by AASHO is contrary to the assertion in Todd's paper that a rotary can be "called a compromise between a signalized intersection and a grade separation."

2. "A rotary does not operate satisfactorily when, on roads of four or more lanes, the traffic volumes on two or more intersecting legs approach capacity at the same time." This is an extension of the capacity limitation found in U.S. experience. When capacities of approaches to rotaries are exceeded, there is no way to adjust the capacity of each approach to reflect traffic demand volumes. As a result, disproportionate backups are generated on the leg or legs that have the highest demands.

3. "Rotaries require more right-of-way and roadway, and generally cost more, than other at-grade intersections. Access must be controlled for a rotary to function properly. This control may be difficult to obtain when approach highways or streets do not also have access control." These characteristics practically eliminate the consideration of replacing existing high-volume intersections with rotaries.

4. "Rotaries are not directly suitable for conditions that require the crossings of large movements of pedestrians. Orderly flow of vehicles is interrupted where this requirement must be met and it is frequantly necessary for rotaries to be operated with traffic signal controls. This, however, violates the rotary concept of continuous movement." This statement seems very logical—that pedestrians (or bicycles) would find it difficult to cross continuously moving vehicles in several traffic lanes. Yet, Todd states that "Rotary control appears to bring considerable benefits to both pedestrian and vehicle safety" and "Pedestrians at rotaries generally have to walk a longer distance, but their average delay has been found to be less than that at signals."

5. "Rotaries are not readily adapted to high-speed roads. They must be extremely large to provide the proper weaving lengths between intersection legs. Large rotaries add additional travel mileage, particularly for left-turning vehicles. This characteristic should be weighed against delays likely to occur at alternate channelized layouts. For safety and proper operation, particularly of those not familiar with the layout, numerous signs clearly visible both day and night are essential. Signing which avoids confusion on the part of drivers, however, is difficult of attainment." One of the many problems for users of rotaries, particularly strangers, is disorientation. As a result, care must be taken so that sufficient signing and marking is supplied to properly guide motorists; yet oversigning, which would produce confusion, must be avoided. In this regard, it is interesting to note that signing and marking recommendations for rotaries are not commonly found in current federal or state manuals of uniform traffic control devices.

6. "Lighting is desirable and landscaping of the extensive unpaved areas is required. The cost of these items should be weighed against installations required for alternate channelized designs. . . . Rotaries are not readily adaptable to stage development. Attempts at stage development generally result in some over-design when measured by immediate traffic needs."

In light of these many disadvantages, the generating of new enthusiasm for rotary retention or construction in the United States appears difficult, if not impossible. The most discouraging advice, however, appears in the report of the Committee on Urban Street Design of the Institute of Transportation Engineers (ITE). The report, Guidelines for Urban Major Street Design, is described as "a proposed recommended practice"; it is in the final stages of review and approval by ITE's Technical Council and Board of Direction. Rotary intersections are mentioned on only one page of this very large report: "rotary intersections are not recommended.... Rotaries are undesirable because of the high number of weaving movements that must be accommodated in a short distance."

It would appear that the handwriting has been on the wall for quite a few years. Todd's paper is based on extensive references from both the United States and overseas. The latter, however, are mostly from Great Britain, where rotaries have been uniquely successful. Those from this country, on the other hand, are principally from the years prior to 1940, and their applicability to present conditions can be questioned.

Since at least the 1960s, however, U.S. engineers on the state and local levels and consultants have been working to produce good operation in existing rotaries and, based on their experience, have recommended that new rotaries should not be constructed. In the face of these facts, a resurgence of interest in rotaries in this country would seem extremely unlikely.

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Although the New Jersey Department of Transportation is not constructing any new circles on its highway system, we do have approximately 60 circles on our system, most of them built in the 1920s and 1930s. No one is advocating building any more. Therefore, insofar as our highway system is concerned, the basic problem is not how to design new traffic circles but what is the best approach to improve the operation of those we have.

Todd states that, in some instances, traffic circles have been used to replace traffic signals. This is just opposite to our practice. We have reconstructed a number of circles by cutting through them and signalizing the resulting intersections. We have found that such a technique results in a smoother flow, with less congestion and few accidents. At circles that have no more than four approaches and large enough radii to handle the storage of turning vehicles, this approach has worked very well.

We have had no experience with reducing the size of the circle, as Todd mentioned. We believe that the basic problem lies not in the size of the circle or even in the shape of the circle (for in New Jersey we have many "circles" that vary in shape from ellipsoid to ovoid) but in the conflicts generated between overly aggressive and overly timid drivers. Our observations lead us to believe that, if this conflict can be resolved or ameliorated, the flow through the circle will improve.

Therefore, our latest approach has been to try to improve flow into the circle by installing traffic signals on one or more of the approaches 100 m (300 ft) or more in advance of the circle in order to meter the flow into the circle. Since this approach used no additional right-of-way, it does not disturb the land use adjacent to the circle, nor does it involve lengthy and complicated construction.

Since traffic circles in our state tend to be the preferred locations for gasoline stations, shopping centers, and diners, the last item is not a minor one. We have at present one circle that has five approach roadways, all signalized, with detectors in both the approach roadways and the circle proper, wired into a computer installed in a trailer inside the circle. Studies now under way at that location, Ellisburg Circle, show that we can achieve total hourly volumes in excess of 4000 vehicles/h but that above 4400 vehicles/h the flow tends to become unstable and "lockups" occur beyond that point.

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Todd's paper is an enlightening account of the design and operation of rotary intersections in Great Britain. Normally the subject would draw little interest in the United States.

The rotary as a real traffic carrier has been written off and, for the most part, considered a relic in modern transportation engineering practice in the United States. Of course, the rotary may have its place for local or distributor-type traffic at low volumes for aesthetic or architectural purposes and occasionally for maintaining low speed levels in residential communities. Such minor use, however, is incidental, since this discussion focuses on situations where the ability and necessity to handle traffic is of primary concern.

Although this paper at first glance may not seem relevant, it does command interest and perhaps some analysis because of the unusually optimistic and highly favorable account presented in terms of increased capacity, operational efficiency, safety, and a multitude of other advantages attributed to the use of rotaries in Great Britain. The troublesome aspect of this review is that nearly every performance level or characteristic cited as an attribute and an advantage for the British situation is considered a failure and a disadvantage for the American condition.

According to our experience in the United States, it is hard to conceive that rotaries could improve safety, lessen delays, and reduce pedestrian-vehicular hazards. What is really difficult to comprehend is that "mini-roundabouts" with center islands less than 4 m (13 ft) in diameter have become popular in Great Britain during the past 10 years. Their advantage is that the capacity has been increased 50 percent by means of reducing the size of the center island (of previous designs) and increasing the entry width.

Although it is assumed that such design and attendant performance could not be achieved and certainly would not be attempted in the United States, we must recognize that Todd's presentation draws on actual experience and research, and it consequently deserves proper attention. There must be an explanation for such diversity in design application and operational experience.

The decline in the use of rotary intersections in the United States, which began some 30 or 35 years ago, is supported by specific and valid reasons. Also the adherence to the rotary, or roundabout, in Great Britain to the present time—and its increased use in recent years—is also fully understandable. The claims of functional advantages or disadvantages, or operational efficiency or inefficiency, as the case may be, can be fully comprehended and explained if they are properly analyzed.

Let us first consider the course that the United States pursued in its highway development and what goals were to be achieved in traffic operations: increase in capacity; increase in speed, followed by improvement in safety; and a desire to maintain higher levels of service. The willingness to make changes, coupled with available administrative, engineering, and budgetary resources, during a period of intensive improvement programs, provided the means to convert rotaries to other forms of intersections. Although it was only part of the total improvement programs, the replacement of the rotary was a step toward the goals designed to improve operations.

Contrary to highway development and programming of improvement in the United States, the approach in Great Britain during the past several decades was apparently to maintain the operation of its existing roundabouts and to continue to provide new facilities as they were considered appropriate. Such perseverance in the use of the rotary-type intersection has encouraged the engineer to experiment and improve its operation and, in the process, to justify its existence. At the same time, the driving public has continued to acclimate and grow with the use of rotary configurations. The incentive to maintain their existence and to improve their operation has apparently produced the results Todd reported.

The obvious question that cannot be avoided is, Should we in the United States return to building rotaries, or should rotaries in Great Britain be replaced with the more conventional intersection configurations and controls? The obvious answer is that each country will, and perhaps should, continue its present practice. If each considers it has a degree of success with its approach, and there is a reasonable explanation on the part of each, the discussion can thus be appropriately concluded. However, it is difficult to brush this issue off by implying that practice and drivers are sufficiently different in each country that the same design may work well in one and not in the other.

It may be true that the education, orientation, attitude, and tolerance of drivers may differ from area to area, but an issue so major cannot be so simply explained away. It is therefore appropriate to look at the problem from a much broader point of view in an attempt to obtain a better explanation.

I believe the main issues in the question before us have to do with philosophy, human factors, and the broad principles of system configuration. It is here that the real differences may be found. Although the following is stated in the light of U.S. perspective and reasoning, the points made would appear to have universal application, although emphasis and values may differ.

1. Philosophy: What degree of serviceability, quality of operation, or level of service for the driver are considered appropriate? What allowances for comfort, convenience, freedom to maneuver, and speed of operation—as policy—are provided and adhered to in design and operations? This refers not just to an intersection point but to a linear facility or a network of facilities. Another philosophical approach to design and operation is to make it "simple," "direct," "uniform," "easy to follow and maneuver," and with "least possible points of conflict."

2. Human factors: As an extension of the service-level considerations, there are further operational aspects relating to the driver. This concerns the more in-depth characteristics of driver behavior and the reasons behind it. In addition to his or her physiological characteristics, the driver's psychological and emotional makeup play a significant role in how to design the facility and its operation. For this reason, the number and complexity of tasks the driver must perform should be kept to a minimum.

3. Principle of system configuration: An important feature of highway facilities, essential for optimum operation, is the principle of nonoverlapping routes. A major effort to eliminate overlapping routes has been evident in recent years. The principle applies to a single intersection or to a length of highway and its interconnections. Accordingly, improvements and corrections to the system are continually eliminating staggered intersections, rotaries, cloverleaf interchanges, other forms of intersections and interchanges that have weaving sections, and direct overlappings of routes in which two roadways join on one roadway and (after some distance) separate as independent roadways.

These three points embody the reasons for not using rotaries in the United States. The mini-roundabout described by Todd would probably receive an even less enthusiastic response. It would seem that introducing the mini-roundabout would be somewhat akin to reverting back to intersections without control. There is evidence that, at heavily traveled intersections, approximately as much traffic can be handled without signal control as with it if properly regimented traffic proceeds intermittently. Although this has been demonstrated, its application would not be accepted here, nor would the larger rotary, which presents the driver with a multitude of overlapping tasks, worries, and harassments during periods of heavy flow.

It is problematical to what extent these principles, philosophy, or policies would apply or have any bearing on design and operation of rotaries in other countries. Certainly the differences are not in the number of vehicles measured, accidents reported, or left turns (or right turns) accommodated, but in human factors aspects and in quality and uniformity of operation. The standard by which operational quality and driver satisfaction is measured, coupled with other local characteristics, determines the success or failure of a certain design.

Author's Closure

I would like to thank the discussants for their stimulating comments. I agree that many rotaries in the United States do not perform as well as they should. Their decline, in spite of so many advantages, is perhaps due to a lack of effort to eliminate their many disadvantages. It was said long ago that "the failure to function well should not be attributed to the fact that they are traffic circles, but to the fact that many of the most fundamental requirements for successful operation are lacking" (49). The reasons for this failure may be worth looking into more closely.

Built long before the automobile arrived, the earliest rotaries in the United States were an architectural feature, not a traffic control device. The outer curbline of many runs concentric with the center island rather than in the opposite direction. The resulting tight entry-curb radii slow the entering vehicles excessively and force them to swing out into the circulatory roadway, leaving dead pavement areas. Nevertheless, these rotaries do handle traffic moving at low speeds. Their proper operation was most severely impeded in the days when streetcars were present.

As the use of rotaries spread into rural areas in the 1920s, speeds below 40 km/h (25 mph) were found unsatisfactory in conjunction with highway speeds of 64 km/h (40 mph) or more. Design speeds of not less than 40 km/h were recommended, and the minimum radius required for the design speed determined the size of a rotary. To avoid excessive dimensions, the maximum recommended design speed was 64 km/h.

The designs provided that entering vehicles should merge and then weave with circulating traffic; the larger the weaving volume, the longer the weaving section had to be (50, p. 13). It led to the belief that rotaries had to be very large to handle heavy traffic and that the capacity of existing layouts could only be raised by enlarging the inscribed diameter or by cutting a road through the center.

When urbanization spread and brought more traffic, rotaries that had primarily been built to speed requirements were found to lack capacity. Many had been built with two-lane approaches merging into a two-lane circulatory roadway. Two heavy streams of traffic, each on two lanes, cannot be expected to merge successfully into two lanes on any type of road.

A rotary does not function properly when drivers within the circle tend to yield to fast traffic approaching on what seems to them a major road; some center islands had even been shaped to keep speed fairly high along the busier road. A rotary functions worse still where the basic yield-to-the-right rule gives the right-of-way to entering drivers. This prevents vehicles within the rotary from leaving and causes traffic to lock. I am told it happens frequently in New Jersey, but the American literature does not seem to be aware of the problem. We should remember that by the early 1930s, the heyday of the rotary, all states had adopted the yield-to-the-right rule. (Stop or yield signs placed at the entries will cure the locking by reversing the right-of-way, but the stop sign violates the principle of continuous movement and the yield sign did not appear on the scene until 1951, long after the rotary had fallen out of favor.) A similar problem existed in Britain, where no legally defined right-of-way was in force until 1966, when legislation was introduced that required entering drivers to yield. This cured the locking, but many signals that had been put up to overcome it were never removed. In the United States, some jurisdictions (Delaware, Massachusetts, Maine, New York, North Carolina, Rhode Island, Virginia, and the District of Columbia) have adopted similar laws, beginning in 1952.

Hagenauer's comments rely largely on quotations from the 1965 AASHO Blue Book (2), whose section on rotaries is almost a verbatim copy of that in the 1954 edition. The 1954 edition, in turn, gave an abridged version of A Policy on Rotary Intersections (50), published in 1942. Hence, the comments are based on experience with large layouts of pre-1942 design that have design speeds of 40-64 km/h (25-40 mph), many of which are beset with the problems just outlined. Smaller rotaries that have design speeds below 40 km/h were specifically excluded from consideration in the 1942 publication, which said (p. 1),

> According to definition, even a center post at a street intersection produces rotary traffic flow, but a rotary is more commonly considered to have a central area or island of some size. In this discussion, the name rotary is applied only to those layouts in which the radius of any portion of the central island is at least 75 feet [23 m]. Rotary intersection layouts with small central islands of radii less than 75 feet require speed reduction to less than 25 mph [40 km/h].

A radius of 23 m (75 ft) plus a 7-m (24-ft) circulatory roadway would give an inscribed circle diameter of 60 m (198 ft) as the minimum size AASHO considered. In Britain, a modern roundabout of that size would be expected to handle about 6000 vehicles/h.

"A [section] length below 100 feet [30 m] resolves weaving movements into typical at-grade crossings," stated the 1965 AASHO Blue Book (p. 482). These rotaries have no weaving sections, and traffic does not weave—it intersects. In consequence, the passage quoted from the ITE report that "rotaries are undesirable because of the high number of weaving movements that must be accommodated within a short distance" should not be applied to a type of rotary that has no weaving sections.

"Where the distance [between adjacent entrances and exits] is so small that vehicles cross at an oblique angle without weaving, the intersection is not classed as a rotary but rather as a channelized intersection" (51, p. 514). The performance of this type of intersection has never been evaluated in the United States, and conclusions drawn from experience with large layouts of pre-1942 design, all of them operating under the yield-to-the-right rule until the early 1950s and many until this day, cannot simply be transferred to a type of rotary that was developed for the express purpose of overcoming the disadvantages previously encountered, a type that occupies far less space, is not designed for speed but for capacity, and lends itself to stage development far better than any other type of intersection.

As to the accident frequency mentioned by Hagenauer, in spite of much effort no data have been found that allow a comparison of unsignalized rotaries with other forms of control in the United States. Any information from readers would be welcome. Rotaries have been blamed for accidents that were, in fact, due to inadequate signposting, a lack of advance warning, a slippery pavement, or poor design. If more PDO collisions do occur, which is quite possible, they should be set off against any reduction in the more serious accidents, as well as reductions in accidents and operating costs due to less congestion and fewer stops in the road network as a whole.

In regard to Nolan's remarks on signalizing rotaries, this has also been done in Britain. A more positive solution would be to raise the output at the critical entry point by geometric changes, but this is not always possible. Signals are likely to increase overall delay, particularly if they are kept in operation during hours when the problem they were put up to cure does not occur. Several methods other than stop-go signals (for instance, pedestrian movements or peak-hour police control) could be used to generate gaps in a predominant traffic stream at a rotary or elsewhere, but their description is beyond the scope of this paper.

The timid, or defensive, driver will always reduce capacity at unsignalized intersections when he or she rejects the shorter gaps. At a rotary, this is minimized when more entry lanes are provided that other drivers can use while the timid driver is hesitating. Defensive drivers also reduce capacity at signals by leaving longer headways. It is the aggressive driver within the rotary who reduces capacity; he or she intimidates others into rejecting short gaps. Although it has often been shown that drivers accept shorter gaps in faster traffic, there are sound reasons to believe that an enforced speed reduction to about 25 km/h (16 mph) can raise gap acceptance—and capacity—at rotaries and elsewhere.

A road has been cut through the center of several circles in the Washington, D.C., area. The circle then no longer operates on the rotary principle, which requires that all entering drivers yield. It functions in a manner similar to two jug handles and needs signals.

Finally, like Leisch, I am interested in the philosophy of traffic control. Since the profession has for 50 years advocated the use, wherever possible, of controls less restrictive than signals (52, p. 13; 53, pp. 322-323), I do not think that anyone would wish to recommend signals (with more stops, delay, queueing, and congestion) in order to achieve better operational quality and greater driver satisfaction.

For the design engineer, the difference in philosophy is perhaps whether to build for speed or to build for capacity. A philosophy developed for the construction of high-speed roads in the days when money was plentiful is not necessarily the most suitable for treating bottlenecks in times of severe inflation. But this paper does not deal with philosophy. It confines itself to describing the potential of modern rotaries, and the reader can decide according to his or her own philosophy what to do with the information. Nevertheless, when a highway department proposes the widening of a road, the elimination of a street jog, or the construction of an interchange, it would be expected to submit other feasible, prudent, and less harmful alternatives, together with its own recommendations and reservations. The fact that past and present design standards do not deal adequately with rotaries should not deprive the public of the benefits of a highly cost-effective TSM alternative.

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Publication of this paper sponsored by Committee on Operational Effects of Geometrics.

NOTICE

This paper was previously published in the ITE Journal (July 1979), without the three discussions and author's closure that accompany this version of the paper.

Highway Guide Signs: A Framework for Design and Evaluation

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Inadequate guide-sign design and location practices are responsible for a great number of instances of inefficient and potentially hazardous traffic operations within the highway system. Many of these deficiencies are rooted in inadequate highway system planning. The great majority of these locations, however, have operational problems that are directly related to the failure to coordinate guide-sign design and functional design as part of the highway development process. A framework for the coordination of guide-sign design with functional design is proposed and illustrated; emphasis is on the guide-sign development, design, and evaluation tasks. A computer program to plot perspectives was modified to provide the means of accurately depicting proposed guide signs within the perspective of a highway facility from the position of the driver's eye. The view presented by the perspective provides the designer with the third dimension—the view of the sign from the road. Shifts in vertical, lateral, and longitudinal sign position can be studied accurately by using the perspective as a tool. Examples were taken from two existing highway locations and provide the means for evaluating the suggested guide-sign design procedure for both existing and proposed guide-sign installations. Recommendations for further research and development are aimed at the reduction of the manual aspects of the procedure, thereby providing the designer with maximum incentive for investigation of alternatives, graphic details, and variations thereof.

Highway design philosophy, procedures, tools, and techniques have undergone rapid change in response to a recognized need for safe, efficient, environmentally acceptable, and economic highway facilities (1-5). The major objective of these studies, taken together, is directed toward the provision of a highway facility on paper that clearly satisfies recognized needs before construction and before the facility is put into operation.

Until recently, the driver and the driving task have been largely neglected by highway engineers; the driver has been obscured by gross statistical descriptions contained in design manuals, handbooks, and policies under the label of "driver and traffic characteristics." Since current research in human factors engineering, as applied to the driver and the driving task, are gaining more acceptance among highway engineers, attitudes are changing in the designers' approach to planning and design of new facilities and in refurbishment of obsolete highways. This attitude can be described as an awareness and concern for the driver and for facility operation; it incorporates a design philosophy that attempts to include the driver.

The need for recognition of new tools and techniques for design by the designer is absolutely necessary in order for him or her to deal effectively with obvious past deficiencies (obvious after the facility is put into operation). Why should accident experience or inefficient traffic operations be the prime motive for change and evolution of design procedures?

An important component of the design process is the design of the formal communications system for a high-