Evolution of Roundabout Technology: A History-Based Literature Review

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Abstract and Introduction:
Circular intersections have become an item of interest to the American transportation community after a fifty-year absence. Over that time, the United States built few circles and published little on them. In Britain however, the technology advanced and then spread to more than twenty-five countries, eventually including the United States. On the way, each country modified the parent idea. Britain also improved on their previous methods.

In the 1980's, rumors trickled into the U.S.. In Michigan, word of “roundabouts” first arrived in 1995, and as in other states, skepticism and misunderstanding were common. Practitioners received partial information, from different countries and eras, using different assumptions, terminology, and technology. Individually, reports were confusing, because most focused on details and the host country’s needs of the moment, rather than the whole concept. So, within Michigan DOT, staffs from different areas reacted to limited information from three different countries, while the majority had never considered the notion, and no information was available locally.

To clear things up, Michigan DOT research staff requested reports on roundabouts from libraries around the U.S. and Canada. Reports were sorted and assembled by country and date of publication. (The first observation was the extent of roundabout research from the United Kingdom.) Researchers then contacted staff in Britain, Australia, and the U.S., whose recollections helped fill gaps in the written record.

A clearer picture emerged. Roundabouts developed over 100 years, in differing highway cultures, accelerating with recent breakthroughs. Viewed in this wider context, we can see that roundabout history follows a series of setbacks, flukes, decision points, and careful scientific research, as each culture followed their own direction to meet needs of the time.

The purpose of this article is to simplify and provide historic context for American highway practitioners seeing modern roundabouts for the first time. It may help explain what went on during the fifty years the U.S. was not paying attention, WHY previous researchers chose their avenue of research, and may help Americans make use of other countries’ successes and failures. The report uses American terms wherever possible, and provides a partial road map for the hundreds of readings available from countries where most roundabout development took place. The author suggests patience, study, understanding, cooperation, more roundabouts, and synthesis of all available roundabout technologies to advance a worldwide school of traffic management.

“The history of research on roundabouts shows that ‘what is going on’ is not obvious.”
Mike Brown, Retired Chief of Geometrics, London[1]

The American Branch:

Earlier, under a different name, the U.S. helped invent the roundabout. Britain picked up where we left off and changed the whole idea. American technology is now fifty-years out of date, but national pride aside, modern roundabouts wouldn't exist if they weren't partly shaped by earlier American work.

Before the Automobile

Americans often confuse Washington D.C.'s traffic circles with roundabouts. In his 1791 city plan commissioned by President Washington, Major L'Enfant placed circles at strategic points in the Washington Street network. L'Enfant designed the circles for aesthetic and military purposes; he did not anticipate cars.

Human Powered Traffic Control

Early this century, traffic control was a policeman in the middle of an intersection. Each officer directed traffic as he saw fit, or by local convention, stopping or waving traffic as needs arose. For left turns, an officer could direct left-turners in front of him, or around and behind him. In the first case the officer acted as the forerunner of the signal, stopping and starting movements in sequence. In the second case, he acted as a roundabout, with one-way traffic circling him. Either way, labor costs and danger to policemen left street officials searching for better methods.

Early Rotating Intersections:

One early American school of thought replaced the traffic cop with a marker in the center of the intersection. Traffic pioneer William Eno promoted a lighted signpost in the center of the intersection, alternatively called the "Sleeping Policeman," "Silent Policeman," or "Dummy Cop." One four-foot high version succinctly stated *"GO to the RIGHT, GO SLOWLY*."[2]

Probably because drivers knocked over the posts, one Ohio company promoted a rollover version called the "Mound." The device was a raised cast-iron disc in the center of the intersection, stamped with the instruction "KEEP to RIGHT."[3] The mound was more durable than the post, but they were less visible, and drivers may have just ignored them. Presumably for those reasons, America abandoned the dummy cop and mound in the early 1930's. High-tech versions emerged forty years later, on another continent.

A second American line of thought, the "traffic circle," required the use of central islands of various sizes and shapes, with the common characteristic of one-way roadways around them. New York, Paris, London, and Detroit built them before 1920, and circles were soon common around the U.S. Design was based on rules of thumb at first, but gradually changed as new theories of operation developed.

Weaving a Rotary:

During the 1930's, the U.S. developed a type of circle that became widespread: the "rotary." Unlike traffic circles, where streets usually intersect the circle at a 90-degree angle, traffic entered a rotary on a tangent, and merged at speed with traffic on the circular roadway. This design required the use of wide "splitter" islands, separating entering and exiting lanes on each leg. The U.S. built many rotaries during the heyday:

sixty-seven in New Jersey alone.[4] Other examples remain along old U.S-27 at US-20 in Angola, Indiana, and old US-12 in Marshall, Michigan.

Road agencies used weaving theory to explain rotary performance. Then, they assumed that capacity of a rotary related to the length of the weaving section between an entry and the next exit: the longer the weaving section, the higher the capacity. The theory reigned for decades, and Americans never abandoned it until the modern roundabout arrived. While the theory held, it led to enormous designs: one rotary in Long-Beach, California had a diameter of more than 140 meters.[5]

In large rotaries, speeds were high, and this reduced capacity because vehicles could not easily enter fast-moving traffic on short weaving sections. Rotaries also operated under the principle that entering vehicles had the right of way, and this caused them to block circulating traffic. With these two problems, O.K. Normann calculated the upper limit of rotary capacity at 3,000 vehicles per hour. The rotary is gone now, and technology has changed markedly, but this 1940's capacity misconception is still widespread in the U.S..[6]

The rotary began in the U.S. as a simple circle with no governing principles, but evolved into new designs based on weaving theory. Under that theory, and with increasing vehicle speeds, rotaries became too big. Designers had begun to appreciate the limits of the technology when American rotary construction ended on December 7, 1941.

The Rotary Extinction:

During World War II, most road construction stopped, except work critical to the war effort. Highway staff entered the military with many finding their way into the Army Corps of Engineers in Europe. There, allied troops marched past the Arc de Triumph and through the gigantic Place de l'Etoille Gyratory. Built in 1907, the Place de l'Etoille surrounds the Arc de Triumph with a twelve-leg, twelve-lane traffic circle, and a circulating roadway 38 meters wide. [7] After the war, U.S. occupation forces visiting Paris would have seen the Place de l'Etoille jammed with nearly 20,000 vehicles per hour and frequent crashes.

The German roads caught Eisenhower's attention: autobahns helped explain how the Nazi's deployed troops so quickly. On their return to the U.S., highway crews resumed construction, and the effort shifted to German-style freeways.

With this new emphasis, U.S. highway engineers applied weaving theories from rotaries to the new grade-separated highways. Road designers found that rotaries would need impossibly large and expensive layouts to provide weaving distance at freeway speeds. Also, many rotaries from the 1920's and 30's now had traffic demand beyond their capacity. In the United States, under the prevailing theory of operation, traffic speeds and volumes had passed the practical capacity that rotary technology could serve. To their credit, American practitioners understood that, so they dropped the idea. The last official reference to rotaries was in the 1965 AASHO guide, and later editions contained no reference to any circular intersection. By 1995, New Jersey DOT had destroyed thirty-seven of their sixty-seven historic rotaries and replaced them with traffic lights.

The British Roundabout Revolution:

Earlier this century, British engineers studied American highways and built circles and rotaries, calling them "roundabouts." As traffic grew after World War II, rotary technology also began to fail in the United Kingdom, but the British did not abandon it. Their postwar economy could not support highway construction on the scale of the U.S., and they had little cheap land for freeways. They also saw that roundabouts were safer than crossroads, and the British government not only built roads, but also paid for hospital care. Britain improved their existing roads and roundabouts.

Yield-at-Entry

Conventional traffic rules (nearside priority) give the right-of-way to drivers on the near, or steering wheel side -- the driver on the right in the U.S. This *"nearside priority"* convention worked at cross intersections, but at roundabout entries, it gave the right of way to vehicles entering the circle. As traffic reached a critical point, circling traffic stopped to let vehicles in, and queues in the circle blocked the upstream exits, so no one could exit the roundabout. Capacity dropped to zero as the roundabout "locked-up."[8]

In the 1950's, traffic increased and locking-up became a problem in Britain. Highway staff adapted by converting some existing roundabouts to *offside priority:* installing the recently invented "YIELD" sign at entries. Many feared it would not work: that drivers would not yield, crashes would rise, or capacity would fall. After trying the method experimentally however, yield-at-entry eliminated locking-up. Capacity also increased 10%. Vehicle delays dropped 40%, and personal injury crashes also dropped 40%. Britain made *Yield-at-Entry* universal for all roundabouts in November 1966.[9]

1960's Experimental Designs:

Continued traffic growth overloaded still more roundabouts, and adjacent development often prevented expanding the intersection. The British Road Research Laboratory (RRL) tried new designs to increase capacity without taking more land. In one 1968 field trial, F.C. Blackmore discovered that widening the entry and shrinking the central island increased capacity up to 45% within the same space.[10] Test track research confirmed that layouts with the widest entry width for each movement, particularly at the point of entry, had higher capacity.[11] Experiments also found that roundabouts needed no central island at all.

Two-Level Interchanges and Multiple Roundabouts

Another solution to traffic growth at a roundabout was grade separation, and Britain began this process in the 1960's as traffic continued to grow. Roundabouts were also selected for use as motorway interchanges. But, grade separation of large conventional roundabouts required two expensive bridges. With the new smaller designs, the British DOT could now build one bridge connecting two smaller roundabouts at ramp terminals on each side of the freeway. Single-bridge roundabout interchanges achieved capacities equal to or greater than a signalized layout, without the cost of a signal.[12]

Other field experiments involved complex multi-island layouts and extensive public information. The principle was to eliminate conflicts by separating movements into different roundabouts within one layout. To an American, aerial views of these multiple designs look odd. They look simpler from driver level. Still, many of them improved performance, and each experiment provided useful data. [13,14,15,16]

With the introduction of two roundabouts in close proximity, as at an interchange or a multiple layout, their interaction became important. Observers found that gaps created upstream decayed with time and distance to a downstream entry, thus reducing the gap available for drivers entering downstream. They also found they could correct for the effect by reducing the distance between the point where the gap is formed and the point where it is used in the system, and by increasing the capacity of the downstream entry.[17]

The End of Weaving, and Search for a New Explanation of Capacity

After Britain applied the Yield at Entry rule nationwide, they found that the new rule did not just prevent locking up and improve general performance. Yield-at-Entry changed *everything*, leaving designers with no established method to predict performance of a roundabout.

Previously, like the U.S., British highway engineers relied on weaving theory for capacity prediction. In Britain, weaving theory was based on research by J.G. Wardrop in 1955, and known as *Wardrop's Theorem*.[18] Wardrop held that weaving distance determined capacity. In 1973, after the universal Yield-at-Entry rule had been in use for several years, Ashworth and Field observed that Wardrop's Theorem no longer adequately described the performance of roundabouts. Instead, they proposed that entry capacity was in inversely related to circulating volume.[19] This central tenet is now a part of all modern roundabout capacity analysis. It is in the *interpretation* of this relationship that one roundabout culture now differs from another.

Gap Theory:

When weaving theory no longer explained the capacity of a roundabout, British researchers reviewed the literature and found the work of J.C. Tanner. In 1962, Tanner had estimated minor road entry capacity at "T"intersections, based on the availability of acceptable (or "critical") gaps on the main road. British roundabout capacity and delay studies during the early 1970's (Cooke 1973, Ashworth and Field 1973, Watson 1974[20], and Armitage and McDonald 1974[21]) centered on Tanner's 1962 research.

Basic Gap Theory:
Geometry ≡ Driver Behavior ≡ Aggregate Capacity

The basic idea behind gap theory is simple: given a certain layout, drivers will reject small gaps in traffic and enter a gap of certain minimum size, as cars move up in the queue behind them at a certain rate. If theories can correctly predict the critical gap, correctly predict how many such gaps are available, and correctly predict move-up time for vehicles in the queue, then theoretically we can sum individual driver behavior to predict total capacity, queuing, and delay. It is this apparent simplicity that gives gap theory its broad appeal.

Yet in practice, gap theory has some tricky problems at a roundabout. First, a roundabout IS geometry. Unlike a signal, roundabout performance is entirely controlled by geometry and markings. To evaluate the effect of geometric design elements, a gap theorist must reliably predict a driver's reaction to all relevant geometric parameters describing the layout. For reliable prediction, each correlation must be statistically valid, with a predictable error rate. This requires an extremely large number of observations, as analysts must measure the effect of *each* geometric factor, on *many* drivers, for different driver behaviors, over a wide range of conditions.[22]

It's also necessary to predict the driver's reaction to other traffic. This varies. When circulating flow is heavy, impatient drivers may inch forward and force a gap where none exists. Unlike a high-speed "T" intersection, gap forcing can be done fairly safely at slow roundabout speeds. Friendly drivers may also open a gap for an entering vehicle, temporarily allowing a "priority reversal." Americans can observe these behaviors at congested entrance ramps and T intersections. Conversely, when traffic is light, entering drivers may let a minimal gap go and wait for a larger one. So, minimum acceptable gap is not constant over the range of traffic flow.

In the last step of gap theory, analysts sum predictions of individual driver behavior to predict aggregate intersection performance during the analysis period. This is mathemetically simple but statistically dangerous, because aggregating results of previous estimates will compound any estimation errors.

In their 1974 evaluation of roundabouts using Tanner's gap model, Furgason and Papathanassiou[23] found that Tanner's model was an improvement over Wardrop's theorem, but concluded that:

> *"A major difficulty was experienced compared with the study of a normal T-junction. With a T-junction ... the Tanner Model gave a good description of the conflicting flows even when the gap sizes presented to the minor flow were a consequence of vehicles turning out of the main stream. However, at a mini-roundabout"* (now called a normal roundabout) *"unless a clear indication is given and can be observed it is much less obvious whether a vehicle will or will not turn out of the circulatory flow into the approach being examined. As a consequence of this it was found that vehicles could reject large gaps formed in this way but accept smaller gaps in an 'uninterrupted' major flow."*

Drivers behaved predictably in a high-speed T intersection, but because of lower speeds, critical gap in a roundabout was not a simple thing to observe. Furgason and Papathanassiou stated that it would be necessary to add variables to Tanner's model to account for lane use and exiting traffic. Therefore, they concluded that Tanner's gap model was not suitable for design optimization, because it would require considerable data not available for a proposed site. They also observed that *"all flow patterns will depend on the arrival pattern of the first approach considered*." This inferred that roundabout analysis would require simultaneous evaluation of all approaches.

Researchers could interpret Furgason and Papathanassiou's findings two ways, so they did. British researchers interpreted the results to mean that another method besides gap theory was needed to optimize roundabout designs. Australian staff interpreted it to mean that gap theory simply required more research and development. Afterwards, each country proceeded independently along these different lines of thought.

The Australian Divergence:

As British roundabout performance improved under the Yield-at-Entry rule, other countries began to take notice, and Australia began building Yield-at-Entry roundabouts in the mid-1970's.[24] Subsequent evaluations found them extremely safe compared with alternative intersections, showing 60-75% reductions in casualty crashes after conversion. [25, 26] Viewed against a background of highway fatality rates 50% higher than those of the United States,[27] the popularity of roundabouts spread rapidly down under.

Early Australian Development:

British roundabout capacity and delay theories in the early 1970's were derived from Tanner 1962 and other gap models. Also in the early 1970's, Australia required a method to predict roundabout performance, and a principal researcher had recently studied in Britain.[28] Australia used the only available formulas, British gap theories, to describe roundabouts in Australia.

Ten years later, in 1984, the Australian Road Research Board (ARRB) published a literature review.[29] By then, Australian engineers had already used gap-acceptance techniques for uncontrolled intersections for some years, and most did not want to change. ARRB researchers began efforts to advance previous gap research.[30]

Early ARRB research was carried out with little data. In 1984, Troutbeck compared the predictions of various models with the performance of a single roundabout entry, during twelve, one-hour periods.[31] From this, the author concluded that: *"there are no grounds for rejecting the gap acceptance methods of estimating the capacity at roundabouts in favor of some other method."*

This finding misstated the null and alternative hypotheses. The null hypothesis should have been: *Gap acceptance methods do not adequately predict the behavior of a roundabout*. Statistical tests should then attempt to disprove the null hypothesis, and because the results were not significant, the correct conclusion is that the null hypothesis could not be rejected. The conclusion is to accept the null hypothesis and state: *There are no grounds to accept the hypothesis that gap acceptance methods adequately predict the performance of a roundabout*. Other roundabout researchers drew a similar conclusion from the study.[32]

Since the stated purpose of the study was to evaluate capacity estimation techniques, the following statement in the concluding remarks is revealing:

> *"Since the gap acceptance techniques have been used in other Australian intersection design guides, and because these models offer a logical basis for driver behavior, it is recommended that they be continued to be used in the analysis of the performance of roundabouts."*

Thus, although the results were not conclusive, Troutbeck's 1984 study was used to justify use of gap theory for roundabout analysis throughout Australia. The ARRB did not originally select gap theory on grounds of scientific validity, but because they had already begun using it and did not want to change.

Later Australian research helped advance roundabout design. P.W. Jordan's 1985 analysis of pedestrian and bicycle crashes provides useful data.[33] Hossen and Barker's regression analysis of vehicle path curvature and through speed also provides valuable information for American practitioners.[34] This study found that a maximum path radius of 100 meters reduced 85th percentile speeds to less than 50 KPH (32 MPH).

From 1984 to 1990, Australia continued to institutionalize the roundabout: developing design manuals and advancing work on gap models. Troutbeck (1988) describes an analysis of 65 roundabout entries using Australian signs and markings, and an effort to fit a gap model to the observed data.[35] The article states that problems were found in application of Tanner's 1962 gap theory, and that Cowan's headway model was applied to attempt to reduce the error. The Cowan model divides driver behavior into two types, those who bunch together, and "free vehicles" who move up independently.

Mr. Troutbeck described an alternative model combining a series of equations to describe gap acceptance, queuing delay, geometric delay, a ratio of critical gap to follow on time as a function of circulation flow and number of entering lanes, proportion of free vehicles, and an equation to describe circulatory headway parameters.

> The result was a graphic relationship between entry capacity and circulating flow, which depicts a sharply-defined "S"Curve.

Troutbeck (1991)[36] further describes this research. He states that *"the appropriate gap acceptance theory for Australian roundabouts is discussed, using the conclusions from observed driver interactions. As a result of these interactions, all circulating streams could be assumed to act as one."* He describes the problem of quantifying the usefulness of gaps and assumptions regarding driver behavior. Troutbeck further reported complexities of driver behavior observed by video at Australian roundabouts. He confirmed previous British findings that exiting drivers had little effect on entering drivers, and that many drivers yielded to all circulating vehicles, regardless of their location on the circular roadway. He also stated that entry lanes appear to operate independently, regardless of the presence of other entering lanes.

With drivers in adjacent entry lanes assumed to act independently, Mr. Troutbeck predicted the behavior of each based on dominant and sub-dominant streams. This increased model complexity, as driver behavior in each type of stream was related to roundabout geometry, which he hypothesized as a function of inscribed cricle diameter, number of entry lanes, number of circulating lanes, and the circulating flow. A table depicts a *variable* critical gap, dependent on entry lane width, number of circulating lanes, and the circulating flow. The final figure depicts the predicted relation between entry capacity and circulating flow for one roundabout design. The graph superimposes the relation predicted by British TRRL regression research, and Troutbeck's S-curve overlaps closely. Troutbeck observes that *"This conclusion has converged the gap acceptance and empirical theories."*

This statement raises a several questions: Is this convergence based on observed field data or one example? If based on field data, then it may indicate that Australian drivers had become as adept a driving a roundabout as the British. Are the results the same for all roundabout designs? Was this convergence coincidental, or was the gap model calibrated to the TRRL data? Finally, if the central tendencies have converged, what of the models' variations? Do both models have the same standard error in their capacity estimate?

The SIDRA Model

Also in 1991, the Australian Road Research Board extended their Signalized Intersection Design and Research Aid (SIDRA) program to include the roundabout capacity theories developed by Troutbeck.[37] The program featured graphics, and a version for export to the U.S. incorporated features of the 1985 U.S. Highway Capacity Manual.

Since then, SIDRA versions 4.07 and 4.1 were released. SIDRA 4.07 and the AustRoads (1993) guide on roundabouts used the formulas developed by Troutbeck. However, the software developer states that serious problems were observed in application of SIDRA 4.07 at a number of sites. In one case, SIDRA 4.07 predict a nine-vehicle queue, while unbalanced flows and uneven lane distribution caused an actual queue 500 to 600 meters (~1950 feet) long. The 4.1 version applied more conservative capacity limits to prevent this.[38, 39]

The current SIDRA 4.1 version was released in 1995-96, and lists 50 variables and 25+ equations. The software developer states that Troutbeck's basic gap-acceptance formula and all performance models were scrapped and replaced with new equations based on analogy with traffic signals. This allows comparison with other intersection types. Regarding SIDRA 4.1, Akcelik, Chung and Besley (1996) state that *"some of the improvements are of a remedial nature, since it was not possible to carry out extensive research into the areas where shortcomings were observed*." SIDRA is currently the only model that explicitly models lane use, however lane use must be assumed for sites not yet built. It is not capable of predicting the effect of flared entry lanes, and the vendor states that SIDRA's statistical error has never been calculated.[40] SIDRA is widely advertised and marketed in the U.S. by McTrans.

The Second British Roundabout Revolution:

In 1976, at the renamed "Transport" Research Laboratory (TRL), R. L. Kimber began the most extensive (and expensive) series of experiments on roundabouts ever attempted. Millions of dollars later, they achieved the results they wanted. They completely changed the direction of British roundabout capacity and safety analysis, leading to what is sometimes called "*dynamic roundabout design*."

The reader will recall from the earlier section on gap theory that, in 1974, Furgason and Papathanassiou found that Tanner's 1962 gap model was not able to completely describe roundabout performance, and could not be used for design optimization. The British saw this as a major setback, because their main objective was to optimize roundabout design. Their purposes were to meet capacity needs, improve safety, and reduce space requirements. Without Wardrop's or Tanner's theories of capacity, no theory was available to describe roundabout performance. So, they designed a series of experiments, and assumed nothing.

The Track Experiment:

In the first capacity experiment, researchers laid out two roundabouts on the TRL test track (a large paved area) using cones and striping.[41] The first layout was an experimental control. It was never changed and operated continually to detect any daily variation.

The second roundabout was the test facility. There, researchers controlled vehicle volumes and adjusted the design to evaluate the effect of geometric changes. Drivers, often homemakers, were directed to approaches and signalled the direction to turn. Technicians maintained queues of at least five vehicles on approaches to assure they were measuring capacity. Then, minute by minute, they counted vehicles as they circulated past or entered the roundabout leg under study, until they gathered statistically valid samples.

The experiment had two components. The first evaluated the effect of geometric changes on capacity. For that, the geometric variable being studied was adjusted, and traffic was circulated through the roundabout at maximum capacity. The second component evaluated the relationship between entering flow and circulating flow. For that, staff varied circulating volumes as queues attempted to enter the roundabout. The analysis concluded that:*"..no deviation from linearity was apparent in any test: separate straight line tests* (linear regressions) *account for 90% of the variance of* Q_e (entering flow) *in most cases, with no systematic trend in the residual 10% or so."*

"..no deviation from linearity was apparent in any test"

The relationship between entry flow and crossing flow was linear. The"S"Curve predicted by gap theory did not appear. Data also showed that bunched or continuous traffic streams did not significantly affect capacity. The experiment did find significant relationships between entry capacity and circulating flow, and with the geometric variables: entry width; circulating width; diameter (ICD); and entry flare. Still, while the track experiment helped show what to look for, researchers did not use the track results to produce a formula. Instead, they waited for field data.

Debate and Verification:

During the next four years, researchers collected and tested data, while academic debate continued as to the appropriate model structure. One study by Philbrick reported field calibration work at 21 roundabout sections in the Sheffield and London areas.[42] There, data was not used when entries were not operating at capacity (i.e., without at least five cars in a queue), or when any exits were blocked. They confirmed that weaving did not explain capacity, and that the relation between entry and circulating flow was linear. They calculated passenger car units for vehicles other than cars, finding trucks equivalent to two passenger car units. Otherwise, the results were not conclusive, and additional data collection was suggested.

In a 1978 study by the University of Southampton, McDonald and Armitage compared test track data to field data they collected independently. They applied a simple gap-acceptance method combined with a *saturation flow - lost time method*.[43] This model proposed the variables: entering flow, circulating flow, lost time, and minimum circulating headway. They concluded that to make the model valid, saturation flow, lost time and headway must relate to the simple geometric factors: approach width, entry width, and flare length (at sites where the approach was flared). They concluded that "*test track results were consistent and compatible with public-road data,"* and stated that empirical relationships based on geometric factors produced consistent results for the sites studied.

In 1979, Laurence and Ashworth evaluated three recent formulas, including the interim formula then in use, a gap formula, and the TRL's current empirical track research.[44] They agreed the interim formulas were not adequate. Regarding gap theory, they stated *"even if an accurate prediction formula can be developed*" (for gap and minimum headways), "*it is still necessary for design purposes to decide suitable values for these parameters appropriate to a particular layout*." This suggests they were uncertain that research could solve the gap formula, and that even then, a formula must fully define the relation to geometry. Laurence and Ashworth suggested this might be done by using standardized roundabout layouts, or by developing empirical relationships.

Regarding development of empirical (statistical regression) relationships, they stated: *"This method is not likely to reveal the theoretical basis of observed phenomena and requires thorough verification with independent data before the results can be applied to other situations."* They cautioned against using regression formulas for prediction beyond the limits of the data, and stated that such a formula must be accurate and easy to use and understand. They added that "*this approach may be well suited to developing a design procedure, since a formula with these properties would be ideal for design purposes.*" Comparing the models with field data, they concluded that the TRRL empirical formula gave the best capacity prediction and that its basis in predicting entry capacity was more useful in design. They suggested a simple change to account for flared entries might validate the regression model for that type of roundabout.

> *"...a formula with these properties would be ideal for design purposes."*

Empirical Geometric/Capacity Regression

Given several possible approaches to estimating capacity, the TRL decided how to proceed based their objective. The objective was not to quantify the behavior of individual drivers in a roundabout, as would be required in a theoretical gap model. Behavioral relationships are intractable, they obscure the relation between geometry and capacity, and defining them is unnecessary for design. The relevant task was to find the geometry that would give the capacity and safety performance needed, within the constraints of the site. Nowhere in this task description was it necessary to model driver behavior.

Geometric Capacity Regression:
Geometric Layout ≡ Observed Capacity

Along with the test track, British researchers had another asset not available elsewhere: hundreds of roundabouts, of widely different sizes and shapes, from many years of British road construction. Together, these two unique resources gave the TRL the opportunity to measure capacity precisely, over a wide range of different roundabout designs, in both controlled tests and field conditions.

After the track experiment, the TRL and Sheffield University monitored roundabouts on public roads. Field data included four major studies, observing 500,000 vehicles during 11,500 minutes of at-capacity operation, at 86 different roundabouts. This data, coupled with results from controlled observations of 35 different track layouts, gave the information necessary to deduce direct relationships between geometry and capacity. [45, 46]

Instead of attempting to describe driver behavior, the TRRL measured the relationships between the roundabout geometry and observed capacity. Again, to assure they were in fact measuring *capacity*, data was only used if entries had queues of at least five cars.

Researchers examined the effect of many geometric variables. In order of importance, the geometric variables with the greatest influence on capacity were: entry width, flare, outside diameter, entry angle, and entry radius. They measured and discarded other variables with no discernable effect, including width of the previous entry, circulation width, and length of weaving section. They also found that entry capacity was not perfectly constant, but *varied* from minute to minute and site to site. The resulting regression formulas described entry capacity with a predictable standard error.

Queuing and Delay Research:

During the roundabout capacity research, TRRL staff also researched relationships between flow, delay, and queuing.[47,48] Kimber, Marlow, and Hollis describe theories for time-dependent queuing to predict delay and queue formation at roundabouts. They describe a basic formula, and the authors state that field calibration is ongoing.

In 1979, TRRL researchers Kimber and Hollis published a seminal report on traffic queues and delays at road junctions.[49] They discuss two methods. The first was a high-definition method based on short periods of time, (five minutes), for use in detailed design and network analysis. The second method was a low-definition method based on longer periods (an hour), for use in economic evaluation. They describe inaccuracies associated with *Steady State* and *Deterministic* theories previously used. The report proposes a simple method to approximate the growth and decay of queues and delay, without recourse to probabilistic calculations that consume expensive computer time. (This may have changed: Kimber and Hollis wrote this report in 1979, when mainframe computers were in use.)

By 1980, purpose-built yield-at-entry roundabouts became more common, and more data became available on delay. F.J. Bramwell reported a 1972 experiment, when he covered a signal with a cloth bag, and installed roundabout signs and markings without changing the curb lines.[50] Delay dropped by 75%. Two intersections in the City of Swindon showed similar results; measured travel time was reduced for all turn movements after a roundabout replaced a signal.[51] Mr. Bramwell went on to suggest development of a hybrid type of intersection, which would use the best characteristics of both signals and roundabouts.

Safety Research:

Researchers could not evaluate safety on a test track. For this, they relied on crash records from the numerous roundabouts across Britain. Again, the wide variety of roundabouts in the country offered a broad range of geometric characteristics for safety comparison.

In 1977, crash data was collected from 114 roundabouts built before 1972.[52] Analysis showed that roundabouts reduced injury crashes by 46% at sites formerly under priority control, and by 62% at formerly signalized sites. However, sites previously controlled by large-island roundabouts showed markedly increased crash rates when they reduced the size of the central island. Further research would determine why.

The most definitive work on roundabout safety to date was by the TRL and Southampton University, and reported by Maycock and Hall in 1984.[53] Data came from eighty-four roundabouts with an average of more than five years of crash data per site - a total of 431 junction years of crash data. Unlike earlier efforts, this study aimed to relate fatal and injury accidents to traffic volumes and roundabout geometry, using regression analysis. By regressing observed crashes against traffic flow and geometry, they found that different types of crashes related to different variables. Among the key variables are: traffic volumes, approach width, approach and entry path curvatures (or *deflection*), angle between arms, sight distance, the number of motorcycles, and the number of pedestrians. The result was a geometric crash prediction model: a series of equations to predict crash types and injuries based on geometry and traffic flow. The results also showed why reduction of the central island had increased crashes at large roundabouts, and they provided a method to correct the problem - *Deflection of the vehicle path*.

The result was a geometric crash prediction model.

Further safety research was reported in Kimber and Kennedy (1988),[54] and in Maher (1989).[55]

The ARCADY, ARCADY2, ARCADY3, and ARCADY4 Computer Models

With new capacity and delay formulas ready, researchers put them into an iterative computer program, tried it, and published preliminary results in 1980. A 1978 roundabout project provided data.[56] There, highway engineers had tested two different geometric layouts at the same site, and carefully measured the capacity of each layout. ARCADY researchers compared these observations to output from a roundabout balancing computer program using the TRRL's new regression formulas. Researchers stated *"the results showed close agreement."*

The first of four versions of the ARCADY (Assessment of Roundabout CApacity and DelaY) computer program debuted in 1980.[57] The 1980 version developed by Hollis, Semmens, and Denniss predicted average capacity, and average queues and delays. Capacity calculations used the TRRL regression formulas described previously. Queues and delays were based on time-dependent queuing theory described in Hollis and Kimber (1977)[58] and Kimber and Hollis (1979).

ARCADY2 was released in 1985.[59] This version incorporated new research into the capacity effects of pedestrian crossings studied by Maycock and Hall (1984). [60] It also included geometric delay research reported in McDonald, Hounsel and Kimber(1984).[61] ARCADY3 was released in 1990, incorporating recently developed crash prediction models.[62]

ARCADY4 was just released in 1996 and we have not yet seen it. However, Chard (1997)[63] expressed concern over lack of a method to correct for uneven lane use. In extreme cases, Chard states that ARCADY could overestimate entry capacity and an improper design would result. (This is the same problem noted with SIDRA 4.07 in Akcelik et al (1996).) Chard proposes a method to correct for uneven lane distribution by adding a "dummy" leg. This proposal perhaps raises as many questions as answers, and the notion is still being discussed. ARCADY is the only roundabout model that incorporates crash prediction, geometric delay, and pedestrian crossings. It is available in the U.S. from George Hoyt and Associates in Mount Vernon, Virginia.

The RODEL Program

Roundabout designer R.B. Crown announced the RODEL (ROundabout DELay) program in 1987.[64, 65] The RODEL model differs from other roundabout models in two important aspects. First, unlike ARCADY or SIDRA, it is the only roundabout model that uses observed variation in capacity to allow the user to set any statistical confidence level needed. Second, the RODEL model output provides the maximum probable queue over forty days, rather than the average queue. This increases confidence that the design will have adequate space for queuing.

The initial TRRL capacity research quantified the variance in the relationships between circulating flow and entry capacity, and in the predictive relations with geometric variables. Implicit in this variability around the regression line are factors such as uneven lane distribution, variation in headway, gap, and move-up time, entry vector, and random variation in driver behavior. The ARCADY model relies on a band surrounding the 50th percentile or regression line. By definition, the regression line means that half the time the entry capacity will be less than predicted (i.e., the design will fail), and half the time the capacity will exceed the prediction. For design purposes, a designer wants a high level of confidence that the capacity will meet requirements.

To provide this confidence, Crown designed the RODEL program to use the same capacity and delay formulas as the ARCADY model, but included the range of variability detected in the original field data. Using that variability, (usually the 85th percentile confidence band), the RODEL model allows an estimate of the entry capacity at any desired level of confidence. Thus, using RODEL, designers can set a level of confidence that the capacity will meet or exceed the desired value.

Including statistical variability in RODEL gave roundabout designers a precise level of confidence that their designs would meet the required capacity, and flexibility in how to achieve it, using geometric variables.

Dynamic Roundabout Design
Observed Capacity Distribution + Confidence Level ≡ Flexible RDBT Geometry

The developer states that the RODEL program was designed for a rapid response, and that designers need rapid response to evaluate iterative changes quickly during design. Speed is also critical in evaluating an urban network, where changes in intersection capacity will redistribute traffic flows, requiring close coordination between designers and traffic modelers. RODEL has the advantage of direct empirical relation between capacity and geometry, so the geometry output is very precise. However, statistical variance is not capable of explicitly correcting for unusual driver behavior, and designers must still exercise judgement. Mr. Crown plans a future version of RODEL to incorporate crash prediction and other improvements to make the model more versatile. He hopes to complete the first update in 1997/98.[66] RODEL is marketed in the U.S., and can be ordered from the Staffordshire County Council in the United Kingdom.[67]

Mini-Roundabouts

Pioneering research by Mr. Frank Blackmore in the 1960's led to a remarkable traffic control device - the mini roundabout. As reported earlier, Mr. Blackmore then discovered that roundabouts needed no central island at all. When he proposed building such an intersection, authorities told him absolutely not to build one.

The mini-roundabout may be the most cost-effective intersection control ever discovered.

In 1989, Walker and Pittam reported on safety performance of 1,600 mini roundabouts in Britain.[68] These included roundabouts with a central island less than 4 meters in diameter, mounded versions, and those with no raised island. They found that, per intersection, mini roundabouts had only 50% as many injuries as signals. Given this safety, and coupled with their low delay and cheap construction cost, the mini roundabout may be the most cost-effective intersection type yet developed. Strangely, with some modernization, the mini is very similar in concept to Ohio's "mound" from the 1920's. Walker and Pittam projected that Britain would have more than 2,500 mini roundabouts by 1995.

Spirals, Signals, Markings, and Pedestrian Crossings

Roundabout research has continued in recent years, with a closer focus on details of design and operation. Most British roundabouts do not have lane markings in the circular roadway. They tried concentric lanes, but they were found to have no safety significance.[69] South African engineer Allan Walker has advocated use of spiral lane markings to channelize drivers in large roundabouts.[70] This principle is currently in use at high-capacity roundabouts in Coventry England [71] and Edinborough Scotland.[72] One in Edinborough, a signalized and grade-separated spiral design called "Gogar," carries 70,000 vehicles per day.

Signalized roundabouts are also a major area of recent research. Evaluating a newly signalized roundabout entry in Sheffield, Shawely, Li, and Ashworth (1991) found signalization could improve peak-hour operations, and that it was an effective way to make use of platoons arriving from upstream signals.[73] Peak hour signals have become more common in recent years, and some purpose designed "signabouts" have combined the peak-period control advantages of signals with the inherent safety of roundabouts.[74, 75, 76] Roundabout signals can operate with short cycle lengths or may be actuated by queues. Signalized entries also improve the safety of cyclists, with results showing a 66% reduction in bike injuries at roundabouts with one or more entries signalized full time.[77]

Roundabout signs and markings are recent areas of research, and some are unknown in the U.S. Dashed "YIELD LINES" are standard at roundabout entries. Chevron signs are common on the central island, and the town of Oxford built black-on-white chevrons into the central island by using black and white concrete blocks, sloping toward the center of the island.[78] Block chevrons are durable and visible, and the British DOT endorsed them for nationwide use. Another common treatment is the blue-on-white plastic bollard placed on the splitter island. The stubby bollard is lit from beneath and highly visible, with an arrow directing traffic toward the roundabout entry.

Pedestrian crossings influence roundabout operation, and Britain has four types: Unmarked, Zebra, Pelican, and Toucan. Zebra (striped) crossings influence entry and exit capacity, depending on the number of pedestrians. Marlow and Maycock (1982) described the capacity effects of zebra crossings, and the ARCADY program contains these formulas. Pelican (pedestrian light controlled) crossings serve heavier pedestrian flows, and Hunt and Jabbar (1995) examined their effect on roundabout entry capacity.[79] They suggested that signal time for vehicles should be set to assure it does not reduce roundabout entry capacity. A "Toucan" crossing means bikes TOO CAN cross here. British transport agencies use these at extremely large roundabouts where bicycles are particularly vulnerable.[80]

Unmarked crossings are the most common in Britain and the U.S. Pedestrian injuries are much less likely at a roundabout than at a crossroads, because of the reduced speed and refuge island. Left turning vehicles are most dangerous to pedestrians,[81] and no left turns take place at a roundabout. However, because roundabouts are new in the U.S., pedestrians may not know how to cross at first. A British treatment reported by Tan and Zeeger (1995)[82] may be of use: simply paint the words "LOOK LEFT" and "LOOK RIGHT" on the pavement in front of the pedestrian. This simple guidance tells the pedestrian all he must do to cross a roundabout entry safely. American researchers tested similar treatments at pedestrian crossings, and found more pedestrians scanned for approaching vehicles.[83]

Roundabout Evolution Reaches the United States

A few Americans found out about the new roundabouts in the 1970's and 80's, and tried to persuade U.S. highway agencies to build them. In Maryland, Kenneth Todd attempted for years to persuade the Maryland DOT to try one, and publicized the safety potential.[84] In California, Leif Ourston did the same with CalTrans, and established a firm to promote roundabouts in the U.S.. Efforts focused on explaining to Americans what a roundabout is, the operational benefits of yield-at-entry, the safety benefits of deflection, and the capacity benefits of flared entry designs. He also stresses the cost savings possible by increasing intersection capacity and keeping roads narrow.[85, 86]

The Ojai Fiasco:

The first report of a proposed modern roundabout in the U.S. was in the City of Ojai California in 1988. There, CalTrans proposed a roundabout at the three-leg intersection of state highways 33 and 150. A 1988 article by Maas widely publicized the proposal.[87,88] The article was favorable to roundabouts, however, it stated that Caltrans was going to *"TEST"* the concept in Ojai. The actual proposal was a simple three-leg design, but the Maas article depicted a multiple or "ring-junction" design, rare even in England, and incorrectly stated that "*Traffic circles like this one in England are common sites in Europe*."

Understandably, some Ojai citizens took exception to being the subject of a government "test."[89] Although other countries tested roundabouts for many years and documented their safety, fear of the unknown took hold, a public outcry followed, and CalTrans backed out of the Ojai roundabout proposal.[90] CalTrans has since built successful roundabouts in Long Beach and Santa Barbara, but this early episode still provides a useful lesson in roundabout public relations.

The First US Roundabouts: Summerlin, Nevada - 1990

North of Las Vegas, Howard Hughes properties planned a new city, Summerlin, on the late Howard Hughes' Nevada estate. They planned America's first two modern roundabouts for the town center. The design team of Ourston, Sprague, and O'Brien laid out two high-capacity roundabouts at opposite sides of a large ring road surrounding the town center.[91] To allow for future traffic growth, they designed the two roundabouts with capacities of 6,000 and 3,000 vehicles per hour. Current volumes are still low, and the previous vacant land offers no "before" condition on which to base a judgment, but the publicity captured the attention of planners and engineers around the U.S.[92]

Maryland Dares Lisbon - 1993

The Maryland State Highway Administration (MSHA) Project Planning Division took an interest in roundabouts about the same time, but they had difficulty getting their engineering staff to take the idea seriously.[93] However, the MSHA decided by 1991 to build a roundabout. They produced a videotape to explain to lay people what roundabouts are, how they work, and what they can do. Then they went to Lisbon.

Maryland's' first roundabout site was the intersection of MD-144 and MD-94 in Lisbon. The two-way-stop-controlled rural crossroad had a history of serious injury accidents, and local citizens demanded a signal, but the intersection did not meet signal warrants. Instead, the MSHA proposed a roundabout. They also offered to remove it afterwards if citizens did not like it. After installation, the local government overwhelmingly approved it, and the MSHA made it permanent. With complete before and after crash data, crashes are down 70%, injury crashes are down more than 90%, and measured delay is less than a signal.[94] This early success has led to about eight more roundabouts in Maryland, and the Maryland State Highway Administration has accepted roundabouts as a standard intersection type.

U.S. States go in Different Directions:

In 1993, word had still not reached most state highway agencies. In the same issue of AASHTO Quarterly, two articles on the same page describe demolition of New Jersey traffic circles, and proposed construction of a new roundabout in Maryland.[95] In 1994, California converted a traffic circle to a roundabout, lifting it from level of service "F" to "A" while carrying 5,000 vehicles per hour and reducing crashes 44%.[96] Still, in 1995, the Midwest had still not heard of the new technology: Michigan was completely in the dark, and Wisconsin DOT had just built a brand new 1940's rotary design.[97]

Keck Circle, Montpelier Vermont, 1995

In Montpelier, information on roundabouts and traffic calming interested citizens in neighborhood meetings, and this led to Vermont's first roundabout in 1995.[98] The small (34-meter) three-leg roundabout is adjacent to an elementary school. This roundabout probably has the highest pedestrian volume in the U.S.; hundreds of children and adults cross the approaches daily. Crossings are marked on the pavement. The Vermont Agency of Transportation (VAOT) reports that total delay is now less than ½ the previous level, and they detected no significant changes in traffic patterns. Police reported only two minor fender-benders in the first year.[99]

One pedestrian injury crash occurred since the VAOT study. However, vehicle speed was low and the pedestrian was not seriously hurt.[100] We may attribute the cause to driver and pedestrian inattention, as neither saw the other. For practitioners however, this first pedestrian accident at a U.S. roundabout is of particular interest. The pedestrian may not have understood how to cross a roundabout entry, or the marked crosswalk may have fooled her into thinking it was safe to enter the road. Designers should consider pedestrian crossings carefully.

Vail Colorado - 1995

In 1995, Vail Colorado built the U.S.' first modern roundabout interchange. The previous interchange had become overloaded, and an estimate had been prepared to correct it using signals. Because the underpass had only two lanes, queue storage for the signals would have required widening the bridge, with an estimated cost of $14.4 million.[101] Using a two-roundabout layout with flared entries and continuous flow, designers increased capacity of the existing underpass.[102] The total cost of the roundabout conversion project was $2.8 Million, saving almost $12 million over the signal alternative. To date, crashes are down, and injury crashes are down by 60% at last word. ITE Journal printed an inverted photo of the interchange on the cover of their April 1996 issue.

Avon Colorado - 1997

The 1995 Vail roundabout interchange project proved so successful that Avon, the next town west on Interstate-70, decided to convert their entire town to roundabouts. Citizens voted 2-1 in favor of increasing their taxes to pay for five high-capacity roundabouts, from Interstate-70 through the center of town. This project is under construction in 1997.

Preliminary U.S. Research

In 1991, Leong, Mazurek and List published a study of roundabout capacity analysis procedures.[103] They stated that gap acceptance capacity models were susceptible to error from inaccurate estimation of critical gap. They added that the geometry-based formulas have proven simpler and more useful, but that minimal gap and headway are important because they influence capacity.

Now, however, Troutbeck's finding that British and Australian capacity experience are virtually identical suggests this is less of an issue. He showed that, in time, the same geometry provided identical capacity, in diverse countries on opposite sides of the globe.

In 1992, an ITE Technical Council Committee published an informational report on the use of roundabouts and summarized it in ITE Journal.[104, 105] The survey reported on 1,881 circular intersections in the U.S. and other countries, including 340 American circles, thirty-eight of which gave entering vehicles priority over circulating vehicles. The study concluded that American circle designs had not worked well, and recommended that North American traffic engineers develop a better understanding of roundabouts.

Flannery and Datta (1996) reported on observations at four small U.S. roundabouts.[106]

Statements in the report appear to misstate British roundabout capacity methods, perhaps due to the difficulty of finding British research laboratory reports in the United States. The study evaluated gap acceptance at the subject sites, with the stated reason that other U.S. researchers had also done so. The study found little variation in gap acceptance behavior at the subject sites.

In a follow-up study, Flannery and Datta (1997) reported that Australian SR-45 recommendations differed by a much as 1.6 seconds (46%) from observed critical gap at U.S. roundabouts. Follow-up time differed by a maximum of 0.4 seconds (20%). Again, this was based on only four sites, so the data should be used cautiously. However, the study concluded that the roundabouts operated with little delay, and appear to have great potential as an alternative to sign and signal-controlled intersections.

Bared, Prosser and Tan Esse (1997)[107] provided a concise and balanced synthesis of some international and domestic practices regarding roundabouts. They discuss French, British, Australian, Dutch, and German practice, and include many useful design suggestions, along with descriptive diagrams.

Recent U.S. Safety Research:
The Autumn 1995 issue of Public Roads included a widely- read U.S. report on roundabout safety, and it later appeared on the internet.[108] One country after another reported dramatic reductions in crashes after construction of roundabouts. Flannery and Datta (1996) analyzed crash records from six U.S. roundabouts converted from another form of control.[109] Although the data set was very small, the findings were significant: roundabout conversion reduced crashes from an average of 3.75 per year, to an average of one per year: a crash reduction of 73%. The reduction was statistically significant at a 99% level of confidence.

To estimate safety using a larger data set, Ourston (1996) compared crash records of signalized crossroads, T intersections, and roundabouts. Through comparison of California, British, Australian, and Norwegian data, he estimated that roundabout construction should result in 50% fewer crashes than a signalized cross intersection.[110]

Slabosky (1997) reviewed the literature to estimate likely roundabout crash reductions for specific intersection conditions.[111] The findings suggested safety improvement from roundabout installation was probably superior to improving an existing signal, installation of a warranted signal, or installation of an unwarranted signal. The only comparable safety treatment was installation of median crossovers and indirect turns.

Status of the U.S. Roundabout Revolution:
Roundabout popularity is increasing rapidly. America built its first in 1990, and in early 1997, about twenty-five roundabouts operate in California, Colorado, Florida, Nevada,

Maryland, Michigan, South Carolina, Texas, and Vermont. Road agencies plan about ten more for construction in 1997, and the state DOT's of Maine, New York, Illinois, Iowa, Florida, Vermont, Kansas, Michigan, Wyoming, and California are in various stages of research or implementation. Other states are probably also active.

Roundabouts have also created major interest on the national level. The Transportation Research Board (TRB) has commissioned a study of current U.S. roundabout design practice. Also, the TRB Committee on Highway Capacity and Quality of Service, (which includes an Australian roundabout software marketer), prepared a 1997 update to the U.S. Highway Capacity Manual (HCM). The HCM Chapter 10 on unsignalized intersections now includes a short section on small roundabouts, using gap theory. The Federal Highway Administration is also engaged in a multi-million dollar effort to enable the NETSIM program to animate a roundabout.

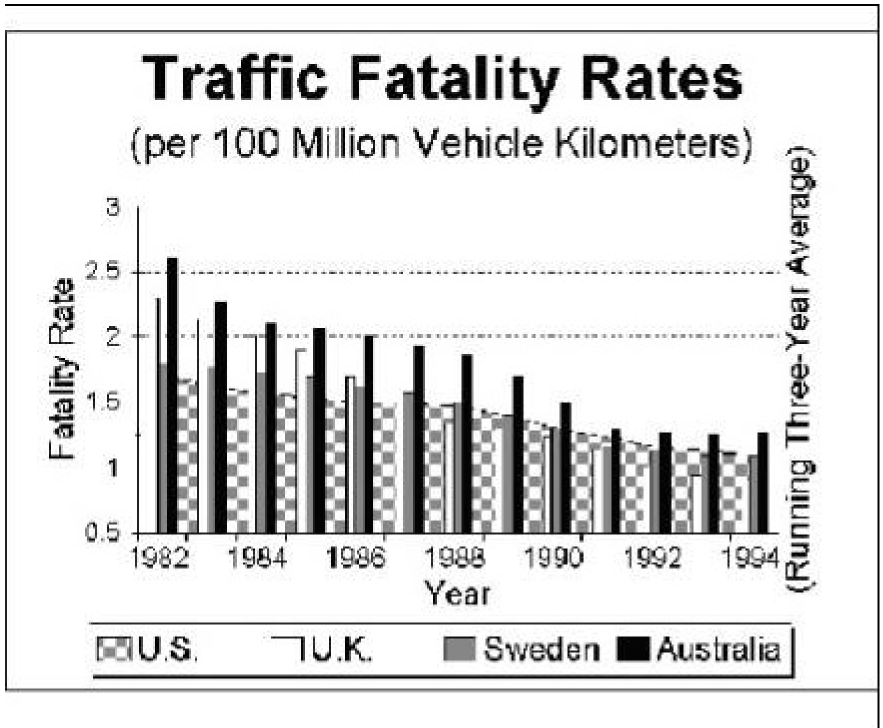
A Collision of Technologies:

In the U.S., Australian and British roundabout technologies collided with earlier U.S. rotary experience, and these three perspectives have formed camps - each arguing the rightness of their cause. On the east coast, Australian roundabout designer Michael Wallwork promotes Australian-style roundabouts in Florida, and Australian software marketer Rahmi Akcelik has promoted SIDRA widely in the U.S. transportation community. On the west coast, the British-trained California firm of Ourston and Doctors use British design technology for high capacity roundabouts and interchanges. In the skeptic camp, adherents to old American technology fail to grasp the importance of recent design advances. Many cling to theoretical capacity limits from the 1940's, or oppose the notion of roundabouts altogether.

The US camp is based on a misunderstanding that will fade with education. However, the British-Australian, Empirical-Behavioral debate is deeper and more theoretical, and many arguments have been made as to the relative effectiveness of each method. One debate concerns relative safety, but no data exists to show that either is safer, and no comparative safety study has ever been done. Crash reductions have been compared, but the question remains "Reduction from what prior condition, and at what volume? International crash comparisons suffer from differing data collection, so data is very difficult to interpret.

Few disagree about the term "fatality" however, and travel data is available for most countries. Graphing this data shows that three countries using roundabouts have dramatically reduced their fatality rates in recent years. Australia and Sweden have begun using roundabouts more recently than Britain, and both countries show a steep decline in traffic fatalities.

Comparison of national fatality rates over time reveals that, measured in fatalities per distance traveled, the United States no longer has the safest highways. Stating *why* other countries have begun to pass the United States is not possible. Nevertheless, it is interesting to observe that the United Kingdom has fatality and injury rates 20% lower than the United States. They also make extensive use of roundabout intersections and avoid signalized cross intersections where possible. If the United States matched British crash rates, 8,000 fewer Americans would die in crashes each year, and one-half million of our 2.4 million annual injuries would never take place.



Another common accusation between Australian and British roundabout adherents is that one method produces more accurate capacity, queuing, and delay predictions than the other. However, no comparative study has ever evaluated these performance measures at roundabouts operating at capacity. Neither has anyone measured and compared their capabilities to predict performance at roundabout not yet built.

Some claim that one method is more compatible with U.S. driving conditions. With little U.S. roundabout experience, we cannot yet know what U.S. conditions are, except that they vary.

New roundabouts will be designed to meet a twenty year traffic forecast. American drivers have had little opportunity to practice driving in a roundabout, so we cannot expect them to perform as well now as they will after twenty years of practice. The question is, how will American's drive roundabouts twenty years from now, when volumes reach design capacity? In twenty years, can Americans learn to drive roundabouts as well as the British? For that answer, it would be necessary to predict U.S. driver behavior at roundabouts 20 years in the future. Australian capacity research suggests that after twenty years of experience, Australian drivers have achieved capacities as high as British drivers. Americans probably can too, but we will not know with certainty until the year 2017.

The Future of Roundabout Evolution

More roundabouts are certainly on the way. Americans love technology, and the new roundabout technology will peak our interest as soon as we all notice it. Normal roundabouts will become fairly common.

Very soon, Americans will appreciate the extremely low cost, low delay, and remarkable safety of mini roundabouts. We have not yet built the first American mini, but their cost-effectiveness is too good to pass up. These will appear soon and spread rapidly. They will gradually outnumber all other types of circular intersections in this country.

In the future, a computerized, regression-based, capacity-safety-terrain-cost non-linear programming function may be possible. This would optimize based on traffic flow, terrain and site constraints, as well as safety and construction cost, allowing true design optimization. British researchers have come close to a two-objective nonlinear programming solution to roundabout design. Some preliminary efforts have been made toward that.[112]

Also, improved data availability from many countries may enable new insights and modeling potential, enabling near-perfect animation and simulation of roundabouts and other components of a virtual road network. These efforts are still crude, but improving, and data from more U.S. sites will improve accuracy.

As the U. S. comes on line, we will add considerable financial resources and technical expertise to roundabout efforts. We have the most to gain from this, because the U.S. has the most cars, and so has the most roundabouts to build. If the United States follows the French example, we may eventually build 4,800 roundabouts per year in order to to cope with growing traffic demand. This would add tremendously to the world technological base, as thousands of Americans researchers and designers tackle problems at various sites.

Conclusion

Now, roundabouts seem radical and revolutionary from the U.S. perspective, because for fifty years we were not paying attention, and it caught up to us all at once. The “revolution” was really a slow “evolution” as hundreds of researchers and practitioners worked for fifty years in other countries. “Roundabout” is now series of mature technologies ready for use: the relationships between geometry, capacity, and safety are well established.

Here, misconception, preconception and fear have interfered with our acceptance of this technology. We have been quick to assume our own expertise on the topic, quick to jump at the first method we see, and quick to prescribe “guidance” when we really know so little. The North American continent now has a total of 23 modern roundabouts, and most are less than three years old, so we have virtually no data. For capacity and safety experience, we must rely on the experience of other countries, and we should use all of the help we can get, so we do not reinvent the roundabout.

Recommendations for American Practitioners.

1. Eliminate Bias. The first step is to eliminate preconceptions so learning can begin.

2. Study. The FHWA TRansportation Information System (TRIS) database lists more than 300 articles relating to roundabouts. These include all major research by the British Transportation Research Laboratory, the Australian Road Research Board, and other countries. Sources listed at the end of this article are a good start. The U.S. should use the experience of every country, and ask their experts for advice.

3. Build More Roundabouts. Roundabouts are as safe or safer than any other at-grade intersection. Flared designs can increase the capacity of approaching roads, and available capacity and design software and manuals will help us do it correctly. By building more roundabouts, the U.S. can gain the experience necessary to use the technology to improve safety, reduce costs, and improve service to the public.

4. Collect and Analyze Data. Many roundabout projects have not been well documented. We should record the before-and-after conditions at every American roundabout site for the benefit of other practitioners. Records should include speed studies, delay studies, traffic and turn counts, complete crash data, and precise descriptions of the layouts before and after installation. We can only evaluate the effect on flow, diversion, speed, delay, safety, and cost if we have complete data.

5. Work to Build Syntheses. Division between practitioners and theorists adhering to different methods hinders technological advancement. Greater understanding is needed. Through international and inter-professional cooperation, adherents to signal, freeway, and all roundabout technologies can find ways to integrate these for the betterment of roads worldwide. With the internet, global cooperation can take place in an instant.

Disclaimer. The views expressed in this article are those of the author and do not necessarily reflect the views of the State of Michigan or the Michigan Department of Transportation.

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GLOSSARY OF TERMS

The following terms may help Americans interpret British and Australian reports:

Conventional Roundabout: British term for large circular intersections built before the universal Yield-at-Entry (Offside priority) rule. A rotary.

Dual Carriageway: The British equivalent to *Divided Highway*.

Gyratory: Derived from French, and used in the United Kingdom to describe a one way circulation system with land uses in the central island area.

Mini-Roundabout: 1. A roundabout with a central island less than 4 meters in diameter or pavement markings, but with other features of a roundabout remaining. In early British descriptions, sometimes called a "micro". 2. In earlier writings, mini sometimes refers to a roundabout with a central island diameter less than 1/3 that of the inscribed circle. Later references call this a *normal* roundabout.

Multiple Roundabout: A system of two or more normal or mini roundabouts with short connecting roads between them.

Nearside Priority: Standard traffic rule in which drivers on the near side (traffic on the right in the U.S.) have priority.

Normal Roundabout: The British term for a smaller roundabout with a central island, developed after the Yield-at Entry rule in 1966.

Offside Priority: 1. Right-of-way rules in which drivers on the off side (in the circle or on the left in U.S.) have priority. 2. Yield-at-Entry

Ring Junction: 1. A British term for large conventional roundabout retrofitted with two-way traffic and mini or normal roundabouts at each entry. 2. Three or more roundabouts connected by two-way road between them.

Roundabout: 1. The British-English generic equivalent term for "Traffic Circle." 2. Applied in the United States to mean several intersection technologies developed after Britain adopted the universal Yield-at-Entry rule in 1966.

Rotary: 1. A generic term for circular intersection used in some parts of the United States. 2. A special form of intersection, often very large, where vehicles merge with a circulating roadway at speed and weave into and out of the circular roadway.

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