Unconventional Arterial Intersection Design, Management and Operations Strategies

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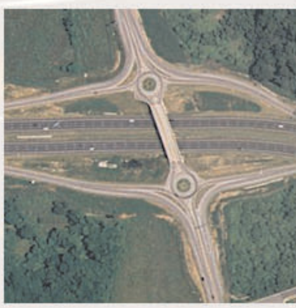

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FOREWORD

This monograph describes a wide variety of "unconventional" intersection design, operation and management principles, and explores the role that they can have in improving operational efficiency on arterial roadways.

In many urban and suburban areas across the United States, principal arterial roadways are unable to adequately serve increasing travel demand, particularly along highly developed corridors. Long-distance trip efficiency is lost, even at off-peak hours, as motorists suffer stop-and-go traffic conditions between intersections. Of the many potential operational control factors on the arterial, the congestion experienced at signalized intersections can have the greatest impact on arterial travel efficiency.

Unconventional intersection designs share common principles in emphasizing through-movements along the arterial, eliminating some signal phases, and reducing and separating conflict points to improve operations, efficiency and safety at intersections and potentially along the whole of the arterial. Unconventional designs also offer the potential for lower costs and reduced environmental impacts, particularly when compared to traditional widenings or converting at-grade intersections to interchanges. As transportation agencies and communities seek long-term solutions to arterial congestion, there is new and greater continuing interest in unconventional intersection design as potential congestion and growth management solutions. However, to date, there is no authoritative reference for professionals that addresses a range of unconventional design, operation and management principles.

This monograph was developed to serve as such a reference, to present a menu of unconventional at-grade and grade-separated intersection designs with potential to improve certain types of high-volume arterial intersections. Chapter 1 examines the current need for new approaches to reducing intersection congestion, and identifies deficiencies in current conventional intersection design, operation and management practice at high-capacity intersections. Chapter 2 explains unconventional intersection design, operations and management principles in detail. Chapters 3-5 present unconventional intersection and interchange designs used regionally or in isolation throughout the US, as well as newer research into unconventional designs yet to be implemented. Chapter 6 examines implementation issues, including building public awareness, motorist acceptance, use of operations analysis software, and potential design impacts and benefits.

ACKNOWLEDGMENTS

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Several individuals contributed to this research work as project technical mentors or peer review team members. Many thanks to these individuals for their efforts in making this as broad and thorough a research effort as possible.

Technical Mentorship Team

Hal Kassoff serves as Parsons Brinckerhoff's Highway Program Area Manager and was formerly Director of Planning and Preliminary Engineering and then Administrator for the Maryland State Highway Administration. Hal's wealth of public and private sector transportation planning and design experience combined with his contributions to the concept of "sustainable highways" made his mentorship and review of this research invaluable.

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Tracey Nixon, AICP, is a transportation planner in Parsons Brinckerhoff's Indianapolis office. Tracey has worked on a number of highway and transit studies throughout the US, writing environmental documents and preparing informational materials for the public. Tracey provided invaluable technical edits for this monograph and brought an experienced planners' perspective to this topic.

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Michigan Department of Transportation
Minnesota Department of Transportation
Mississippi Department of Transportation
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Nebraska Department of Roads
Nevada Department of Transportation
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1.0 NEED FOR ARTERIAL INTERSECTION INNOVATION

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1.1 INTRODUCTION

"Traffic congestion is such a problem that engineers and researchers across the country are making it their personal missions to find innovations that will enhance traffic flow, ultimately leading to alleviation of congestion." – Joseph Baerd and Evangelos Kaiser in a Public Roads article on innovative highway design concepts.

Traffic engineers, community planners, elected officials, business owners and the motorist public desire efficient, safe and reliable travel on urban and suburban surface arterials. Finding appropriate approaches to reduce arterial traffic congestion and improve mobility is an important task in many cities and communities, but is complicated by fiscal constraints and the increasing demands being made on the current highway system. Over the past decades, construction of new transportation infrastructure in the US has not kept pace with the growth in national demand for vehicle miles of travel, which has expanded from 916 billion annual miles of travel in 1970 to 1.5 *trillion* in 2002 (1). Several decades of automobile trip growth, driven by population growth, shrinking household sizes, growth in automobile ownership, and the spreading of new, low-density residential developments farther and farther away from traditional employment and shopping centers, have resulted in record congestion and delay rates in many US urban and suburban centers, with little hope of sustainable periods of improvement. Funding sources for new highway construction are in decline and/or facing increasing competition from other infrastructure needs.

Traditional planning and engineering approaches to mitigating arterial traffic congestion include adding lanes, upgrading arterial intersections to interchanges, and building bypasses. These approaches are often expensive and disruptive, and face new and difficult challenges ahead:

- Adding new roadway capacity by widening existing roadways is becoming increasingly difficult and costly due to concerns about environmental impacts and to restrictions on the availability of right-of-way, including urban and suburban infill.
- Current transportation funding will face increased competition from other projects needed to replace and maintain an aging US infrastructure system, as well as a new class of transportation projects created by the need for increased homeland security.
- Lack of proper planning and/or an inability to integrate land use with the transportation system have left many developed areas with high levels of current and/or expected congestion, even when the full planned roadway network is built out.

While conventional transportation solutions to congestion on freeways and other classes of roads can and do provide necessary and useful improvements, they are at times insufficient to achieve a total solution:

- Good parallel streets to create one-way pairs rarely exist outside downtown areas.
- Intelligent transportation system (ITS) strategies are important in dealing with non-recurring disruptions, but require continual monitoring and maintenance and can be less effective at over-capacity intersections. Most of the recent ITS studies and applications have focused on freeway facilities and their interfaces with surface arterials, but have largely overlooked the arterial corridors themselves.

- High occupancy vehicle (HOV) and other managed lane concepts intended to preserve corridor mobility are increasingly common on freeways in urban areas but have not been widely applied to surface arterials.
- Commuter rail and bus rapid transit (BRT) services are a growing market in many urban centers that can provide commuter options in congested highway corridors; however, transit services generally do not improve the movement of goods and services dependent on surface street system delivery.

One of the last untapped and largely overlooked sources of adding highway capacity involves intersection improvements on surface arterials, where capacity is largely limited by signalized intersections and where design innovation has been severely lacking. Poor intersection planning and operations of signals along many major arterials in the US have resulted in sluggish, slow, and stop-and-go traffic conditions on facilities designed to be carriers of large volumes of higher-speed through-traffic.

Exhibit 1: Urban and Suburban Arterial Congestion

Major intersections on multi-lane urban and suburban principal arterial corridors are most often controlled by multi-phase signal control. As discussed in later sections, these multi-phase signalized intersections are often the single limiting capacity factor for the entire arterial corridor, causing delays and congestion during peak commuter periods. Current multi-phase signalization strategies are limited in effectiveness by the number of conflicting phases to be processed and often fail to balance the capacity of major intersections with those of minor signalized (or unsignalized) intersections between. Current systems planning, design and operations efforts rarely attach importance to the interaction between intersection design and the arterial segments and access points in between.

1.1.1 Unconventional Intersection Design

There is a class of arterial intersection design concepts called "unconventional" designs that attempt to increase arterial intersection capacity by reducing the impacts of turning movements at major intersections through various intersection design and operations and management control. Unconventional designs are increasingly providing the creativity needed to close the gap between what is required and what is possible under "conventional" approaches. There are at least a dozen unique designs that make up the unconventional design class, many of which are used in regional or isolated portions of the US. There are also unconventional designs used in other parts of the world yet to be constructed in the US, as well as a host of designs researched and simulation tested but not yet implemented. These designs are presented in detail in Chapters 3, 4 and 5.

Unconventional arterial intersection design, operation and management strategies share several principles, including:

- Design and operations emphasis is on through-traffic movements along the arterial
- A reduction in the number of signal phases (e.g., left-turn arrow phases) at major cross street intersections and increased green time allotment to arterial through movements
- A reduction in the number of intersection conflict points and separation of the conflict points that remain

These principles are discussed in more detail in Chapter 2.

The intent of this monograph is to serve as a guide to aid transportation practitioners in addressing one of the most pressing urban mobility problems: congestion at major signalized intersections. Objectives of this monograph are to: 1) increase the awareness of current unconventional intersection designs and other operational and management strategies, 2) summarize current and past research on unconventional design, operational experiences, costs, and safety performance, and 3) provide references and resources for specific designs of interest for further in-depth study.

1.1.2 Survey

In an effort to develop an understanding of state agency experience with unconventional design, operations and management within the US, a survey was sent to all 50 state highway agencies, with 30 states responding. Survey respondents were typically senior traffic operations, signals or congestion management engineers or managers with the state agency. Survey question topics included state experience with specific unconventional designs (specific designs used, design and signing details, accident experience, public perception), traffic operations policies (signal phasing/warrants, cycle lengths, turning prohibitions), analysis tools and resources used, and reasons states would consider or reject unconventional design.

The goal of the survey was to learn how important and to what extent unconventional high-volume intersection design is practiced in each state, as well as understand design issues, signal standards and traffic laws particular to each state. Questions asked in the survey included:

- What unconventional designs are currently being used?
- What are the state agency's experiences with specific unconventional intersection designs?
- Have accident rates declined or increased after project implementation?
- How were new unconventional designs introduced to the public?

Follow-up telephone interviews and/or field visits were conducted depending on each state's level of experience with unconventional design and the presence of designs in the field.

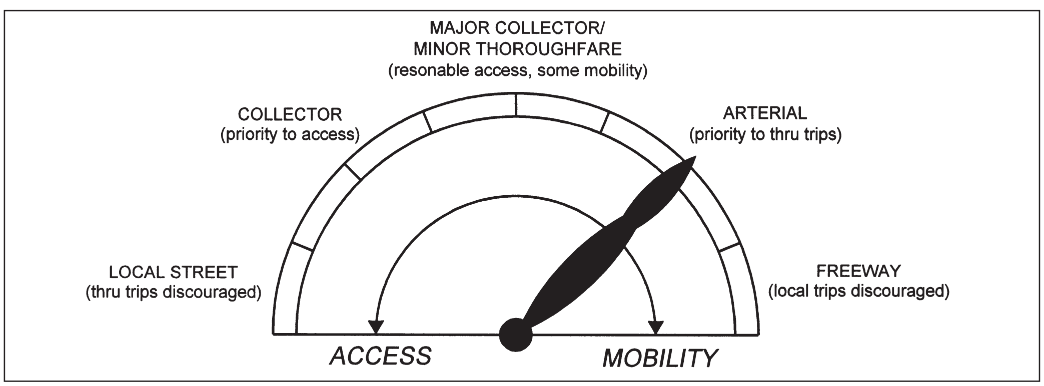
The survey form and a summary of the survey results are included in the appendices of this monograph.

1.2 IMPORTANCE OF THE ARTERIAL SYSTEM

1.2.1 System Mobility

Roadway systems in the US and many other industrialized nations are built within a hierarchy structure of classifications to deliver both mobility and access to effectively move people and goods. At one end of the spectrum, freeways, expressways and principal arterials are focused towards providing optimal mobility for longer trips at higher speeds. At the other end, local roads and streets focus on access to places of business and residence. The spectrum also includes major and minor thoroughfares and collector roadways that transition between mobility and access needs.

Exhibit 2: Mobility to Access Scale



The American Association of State Highway and Transportation Officials (AASHTO) Policy on Geometric Design of Highways and Streets (often referred to as the engineer's "bible" of roadway design) presents a systematic approach to roadway network planning to provide balance between the mobility and access needs of a transportation system. In that approach, the objective of a roadway defined as a "principal arterial" is to provide the greatest surface street mobility with limited or provisional access to adjacent land use. Where restriction of local access is not practical, special designs that include access management and some form of median control at minimum are desirable. Measures should be in place to vigorously protect the ability of the arterial to function at an optimal, predetermined level of service (2).

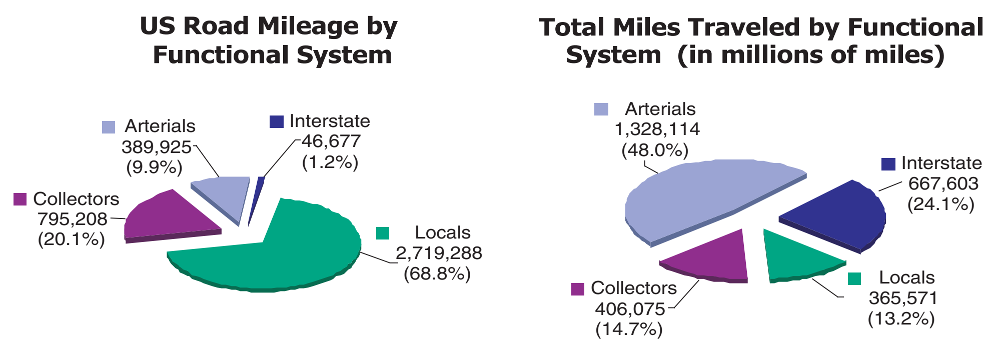
A well-designed urban and suburban principal arterial system serves major centers of activity and handles the highest surface (non-freeway) traffic volumes and the longest trip desires. Typically, the principal arterial system carries most of the trips entering and leaving urban areas, most of the through-movements bypassing a central business district, and most intra-urban and intercity bus routes. Ideally, principal arterials have full or partial access control, and service to adjacent land use is subordinate to the mobility needs of the arterial. Spacing of principal arterials vary from less than one mile in established central business districts to greater than five miles in less developed urban fringe areas. A high-quality regional arterial system may also circumvent the need for additional freeway lane miles, which carry much greater social, environmental and capital costs than arterials. A well operating arterial can also divert shorter trip lengths from the freeway system and reduce entrance and exit operations, allowing freeways to better serve the longest trip lengths (3).

The urban and/or suburban minor arterial typically accommodates trips of moderate length at a greater level of access control compared to collector or local roadways. Their objective is to distribute travel to smaller geographic areas, providing intercommunity continuity with the principal arterial system but not to the level of integrating with residential neighborhoods or local streets.

1.2.2 System Trip Mileage

The principal arterial system accounts for less than 10 percent of the total US highway and street system mileage, but carries nearly one-half of the total US vehicle miles traveled (VMT) on all roadways. Only the interstate system has a greater miles traveled to road mileage ratio.

Exhibit 3: US Miles of Roadway and Miles Traveled by Functional Class



a) US Miles of Roadway by Functional Class

b) Total Annual Miles Traveled by Functional Class (In millions of miles)

Source: Office of Highway Policy Information (Year 2000 statistics)

1.3 CURRENT US SYSTEM PERFORMANCE

1.3.1 Traffic Congestion

While growth in congestion is obvious to most drivers in the US, several organizations track how congestion is rising in urban and suburban areas. The Texas Transportation Institute's (TTI) annual Urban Mobility Study documents the performance of transportation systems in 75 urban areas, tracking historical trends in traffic congestion. The 2001 Urban Mobility Study findings include:

- The "time penalty" for making rush-hour trips is greater, rising from 16 hours per year in 1982 to 62 hours per year in 2000.
- The period of time each day that travelers might encounter traffic congestion has increased from 4.5 hours in 1982 to 7.0 hours in 2000.
- In 2000, an average peak period trip required 51 percent more time than the same trip under non-peak, non-congested conditions.
- There is a growing need to improve system reliability, which plays an important part in reducing congestion.

1.3.2 Declining Infrastructure

State highway agencies are facing an increasing burden to repair and maintain their existing, aging highway system, reducing initiatives and funding sources for new road construction. State and local governments devoted a larger share of their capital spending to the preservation of their existing roads and bridges in 2000 (52%) than in 1997 (47.6%). This also marked the first time in history that total capital spending on maintenance and repairs exceeded the 50 percent mark.

Since the year 2000, capital investment dollars have decreased compared to prior years' investment levels, as federal, state and local budgets have been tightened due to economic factors and increased homeland security costs. While expenditures for highway projects that improve security and the movement of goods may increase to meet homeland security needs, a significant increase in highway spending at any level of government is unlikely.

1.3.3 Opportunities for Design Innovation

Historically, federal and state highway agencies have focused more attention on building and maintaining roads and less attention on providing higher or optimal levels of service on the existing road systems. With increasing congestion, the expense and difficulties inherent in building new highway facilities, and the need for reliable and sustainable highways, this emphasis is beginning to change. Highway officials are realizing that operations strategies can make a major difference in how highway systems perform, influencing the reliability, mobility, security and safety of highway use. A reliable, predictable transportation system is particularly important when travelers place a high value on time and where transported goods are relied upon in tightly scheduled manufacturing and distribution systems. Recurring congestion and poor traffic control can increase travel time and add to the cost of travel and goods.

As discussed in later sections, unconventional arterial intersection design and operations management have been shown to improve operational efficiency on the arterial system.

1.4 CONVENTIONAL INTERSECTION DESIGN DEFICIENCIES

1.4.1 What Is "Conventional" Intersection Design?

Conventional intersection design is best described as the meeting of two streets where through, right and left turn movements are made directly at the intersection and under signal control. At higher-volume intersections, the signal control often has multiple phases and a pre-set or actuated (demand-responsive) pattern of service that orchestrates conflicting movements under differing signal phases. Conventional intersections may have single or multiple turning bays to store traffic to minimize the blockage of through-traffic lanes, and the curb radii are often greater to allow for more efficient and truck-friendly right turn movements. The vast majority of arterial intersections built in the US are of conventional design.

At lower traffic volumes, conventional intersections typically operate safely and efficiently and provide adequate access to adjacent development. As traffic volumes rise, congestion levels increase rapidly, and access to adjacent land (particularly to land parcels in the four quadrants immediately adjacent to the intersection) becomes difficult to maintain without sacrificing mobility and/or safety. Traffic engineers have tweaked traditional intersection capacity using actuated signals (traffic signals that change their timing or add/eliminate phases in response to detected traffic levels), coordinated signal systems, phase overlaps, multiple left-turn lanes and other conventional measures. Access management treatments such as median barriers or turn restrictions can improve flow and safety at the intersection, but such are often met with opposition by local businesses that rely on "easy access."

1.4.2 Conventional Intersection Capacity Constraints

"Ever since the traffic signal was invented in 1914, many a motorist has cursed while waiting for a red light. But try as they may, traffic engineers have been hard pressed to devise a better way to regulate the growing gridlock at intersections." – Orange County news article, December 1989.

Signalized arterial intersections are often congested in urban and suburban areas during peak periods, resulting in a decrease in overall arterial throughput efficiency. **In the vast majority of cases, the single, most limiting capacity factor in overall arterial performance is signalized intersection operations**. Current signalization and traffic management strategies are limited in effectiveness and often fail to balance the capacity of major intersections with the capacity of the arterial between signalized intersections.

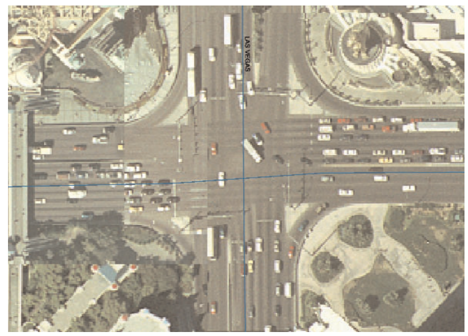
A vast majority of US arterial roadways provide direct movements in all directions (left, through and right) at major intersections. Where high through or left turn volume demand or safety issues warrant intersection improvements, the arterial intersection is typically improved by adding turn lanes and/or protected left turn phases to manage intersecting volumes. While conventional intersection improvements are prudent and serve public mobility and safety interests, there is a direct trade-off in system performance and mobility.

Multiple Left-Turn Lanes

At busy intersections, left turn volumes can become too great to be processed by a single left turn lane and dual turn lanes are needed. As demand for left turns grows, these turning lanes might need to be lengthened as well. Only a handful of agencies in the US use *triple* left turn lanes as a solution to left-turning capacity. Providing additional storage capacity for turning vehicles requires additional right-of-way at intersections, which can be costly and create unwanted environmental impacts, including restricting access to adjacent land uses.

Exhibit 4: Intersection Multiple Left-Turn Lanes

Dual lefts at Charlotte, NC intersection.



Triple lefts at Las Vegas, NV intersection.

There is no hard and fast rule as to when dual left lanes are required, although many highway agencies use a figure of 300 peak-hour, left-turning vehicles as a general guideline. Nearly all highway agencies require dual left turn lanes to be signalized under a protected phase due to sight distance requirements.

1.4.3 Protected Left-Turn Phasing

Demand for Protected Phases

Left turn demand is often a key stimulus for intersection improvements. When through movements at an intersection become close to saturation for multiple conflicting movements, permissive left turns can quickly produce excessive delays. When the ability to make a left turn on a permissive phase at a signalized intersection is limited by through vehicles conflict, left-turn capacity can be less than 100 vehicles per hour. Significant left-turn queuing may also impact through movements if the left turn bay is short and queued turning vehicles block through lanes. Drivers may also take greater risks by turning in smaller gaps in opposing traffic or run the red light at the end of the clearance phase.

Phasing Warrants

Federal, state and city transportation agencies often differ on when protected left turn phasing is warranted. Many state highway agencies have established warrant criteria for implementing protected left turn phasing in recognition of the difficulty to process left turns during permissive and clearance phases only. Two of the most common measurements for determining when protected left-turn phasing is appropriate are safety and volumes. Other variables to consider include: number of lanes, speed, average daily traffic (ADT), number of left turns, geometry, sight distance, level of service and effect on arterial progression. Note that since removal of a left turn phase is rarely recommended, the overall need for a left turn phase should be thoroughly considered and defensibly justified.

Exhibit 5: Left-Turn Queuing

Volume warrant criteria are most often measured by multiplying hourly traffic movements, either for all intersecting roadways or the highest thru and left turn movements. Safety warrants are established based on a pattern of accident history at a particular intersection. **Exhibit 6** provides a sample of the safety and volume warrants methodologies used as collected in the survey of State and City Departments of Transportation (as described in Chapter 1). Note that many of the responding agencies require multiple or combinations of warrants to be established before authorizing protected left-turn phasing.

Exhibit 6: Typical Warrant Criteria for Left-Turn Protected Phasing

Delay or Volume Criteria
Product of left turns (vphpl) x opposing thru (vphpl) > 50,000 for 3 or more hours
Product of left turns (vph) x opposing thru (vph) > 100,000
Left turn > 300 vph
Left turn vph x opposing thru > 100,000 on 4-lane facility, > 50,000 on two-lane facility
Left turn vph x opposing thru > 50,000 (2-ln); > 150,000 (4-ln); > 225,000 (6-ln)
Two vehicle hours of delay occurs in peak hour; average delay > 35 seconds per vehicle
Left turn peak volume > 2 vehicles/cycle/approach still waiting at the end of green
Safety Criteria
More than 5 correctable accident types in 12 months
Number of lanes opposing left turns > 3
Number of observed traffic conflicts > 48 in 11 hours
Prevailing through speed is > 50 mph
More than 14 total conflicts of 10 left turn conflicts observed in peak hour
Dual left turn pockets
Use of permissive/protected phasing results in unacceptable crash rate
Sight distance limitations for opposing traffic due to geometry or opposing left-turn vehicles
Notes: vph=vehicles per hour, vphpl = vehicles per hour per lane

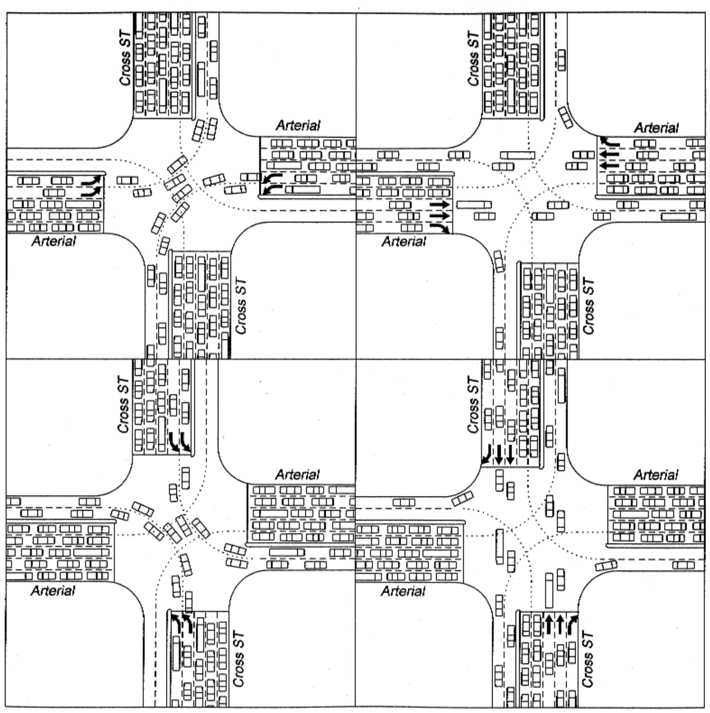
Multi-Phase Signal Inefficiencies

"They (protected left turns) have to get a slice of the signal pie. By taking left turns out of the main signal, you're basically splitting up the pie between two movements….as opposed to as many as six or eight movements." - Engineer Michael Bruce in an interview on intersection design innovation.

Much of the vehicle delay incurred at high-volume arterial intersections is caused by left turn demand. Protected left turn phases can significantly improve left turn movement capacity and substantially reduce left turn or "T-bone" type accidents on high-volume facilities. However, by protecting left turn movements, additional clearance phases (yellow plus all red) must be added between signalized movements, thus reducing the available green time for through movement phases.

Exhibit 7: Multi-Phase Signal Control

(a) (b)



(c) (d)

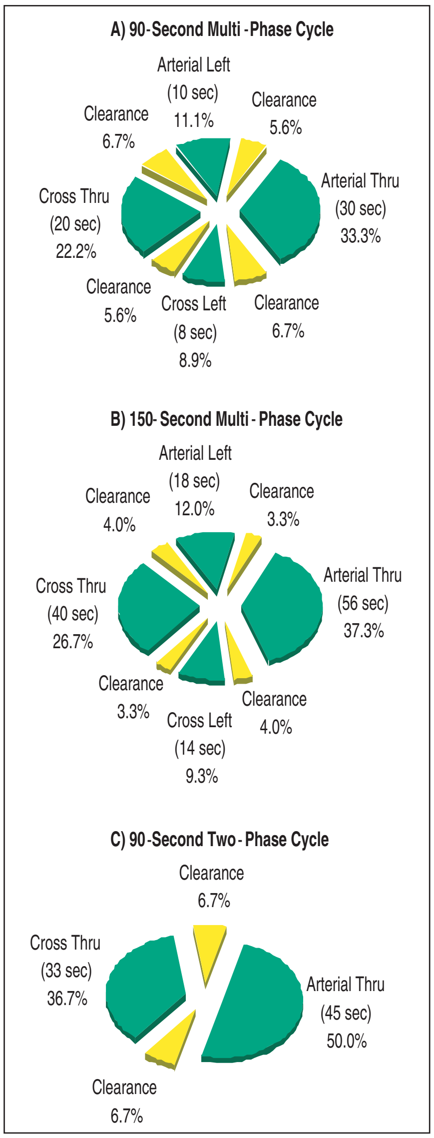
Arterial intersection signalization strategies often include four distinct traffic movements: (a) arterial left-turn movements, (b) arterial through-movements, (c) the cross street left-turn movements and (d) cross street through-movements. The order in which these phases are served may vary by state and/or demand acculturation and may overlap with other phases of lesser demand; however, each phase must be served independently of all others, resulting in a minimum of four clearance phases (yellow plus all red) in each full signal cycle.

Additional clearance phases also increase intersection "start-up lost time," the time it takes stopped vehicles to achieve optimal flow rate through the intersection. The Highway Capacity Manual (2000) estimates this time to be 1.0 to 2.0 seconds for each signal phase based on measured studies and research projects. To compensate for the introduction of additional lost times in each signal cycle, traffic engineers are typically forced to lengthen the full signal cycle to provide adequate green times for each phase served and to reduce the percent lost time per cycle. Clearance and start-up lost times are fixed for each signal phase; therefore, a greater cycle length reduces the percentage of lost time over a given cycle length.

The Highway Capacity Manual also reports that vehicle headways (measured in studies to be between 1.8 and 2.4 seconds, equating to flow rates of 2,000 to 1,500 vphpl) may *increase* with longer green phases, with green phases longer than 40 to 50 seconds proportionately less efficient than in shorter phases (4). This may be attributed to a cumulative loss in driver reaction time in longer queues or other side friction factors between the signal and back of queue.

As an example of the clearance phase time savings, **Exhibit 8** compares three signal cycle phasing patterns, the first two with multi-phase signals (protected left turn phasing for all approaches) and the last one with simple two-phase operations. All clearance phases are assumed to include four and five seconds of yellow time (for left turns and through movements respectively) and one second of all-red clearance time.

Exhibit 8: Phase Allocation Comparison



A) A 90-second multi-phase cycle requires a fixed total of 22 seconds in intersection clearance time per cycle, or 24.4 percent of the total cycle length.

B) The same fixed 22 seconds of intersection clearance in a 150-second multi-phase cycle is 13.3 percent of the total cycle length, increasing throughput capacity of a saturated intersection. Measured over a one-hour period, the time savings is substantial: the 90-second cycle requires 800 seconds of the hour for clearance time, while the 150-second cycle needs only 480 seconds, leaving five minutes of additional time for intersection throughput.

However, while increasing cycle length does reduce clearance interval impacts and extends the green time allotment to certain or all movements, longer cycle lengths typically result in longer queue lengths, greater storage requirements and less flexibility to respond to sudden changes in demand.

C) When protected lefts are removed and the intersection operates under a two-phase signal, the percentage of green time for through arterial and cross street movements is substantially increased. However, travel time and delays are not equally reduced, because many unconventional designs cause left-turning vehicles to travel through the intersection twice.

There are practical limitations to the cycle length that can be used. A vehicle that arrives at the intersection just as its movement turns red must wait through the entire cycle length until it receives green again, incurring three minutes of stopped delay in a 180-second cycle. The Highway Capacity Manual (HCM) level of service (LOS) standards would classify that vehicle's progress at LOS F despite not missing a cycle length.

Long cycle lengths at major intersections may also adversely impact other signalized intersections on the arterial that do not require long cycle lengths. Further, establishing signal progression on an arterial that balances major and minor intersection capacity needs becomes more difficult under long cycle lengths.

1.4.4 Signal Maintenance

Improving traffic signal timing and coordination, particularly along corridors of closely spaced signals, can be a low-cost improvement with significant operations benefits. However, there are limitations to the level of improvement gained, and implementation and maintenance of signal systems can be costly.

Because highway priorities are typically focused on construction and maintenance of facilities, traffic monitoring and control devices are often out of service due to lack of maintenance. It is often difficult to persuade political leaders to allocate sufficient funds for signal maintenance if that means fewer funds going to new highways. Signal maintenance often must compete with other highway maintenance needs – fixing potholes and guardrails, re-painting pavement markings, etc.

In a review of North Carolina's traffic signal operations (noted as typical compared to other state highway agencies), it was reported that (5):

- It is estimated that one-third of North Carolina's traffic signals are not working properly at any one given time, most involving improper outdated timings.
- In the city of Raleigh, 14 percent of all intersections with traffic sensing detectors were malfunctioning; the city of Durham reported a similar 17 percent failure rate.
- The biggest signal maintenance problem, both state and nationwide, is improper timing of isolated signals and coordinated signal systems along a corridor.

An Institute of Transportation Engineers (ITE) survey reported that over 50 percent of the 174 national highway agency survey respondents identified traffic monitoring detector problems/issues as the biggest challenge in operating signal systems (6). The same survey found that only one-quarter of respondent agencies retimed system signals within the past 4 years and about half of those (12 percent) said they retime signals only as needed - ever (e.g., for new development or intersection improvements).

A good signal system alone should not be looked at as an exclusive solution to optimize travel along a corridor, as detectors and system communication malfunctions may reduce operational efficiency. In unconventional intersection design/operations/management, signal systems should instead be viewed as a tool to enhance good intersection design and management strategies, as many unconventional designs rely on good operations management and depend less on actuation, thus operations are less susceptible to problems from detector failures.

SUMMARY

Traffic congestion continues to be problematic for many communities across the US, and can be particularly severe and visible at major arterial intersections. Arterials, among all surface roadways, serve an important function in travel mobility and should be designed and managed to maintain the highest levels of capacity and the lowest levels of stop delay. New roadway capacity is increasingly difficult to construct, with increasing concerns about environmental and social/economic costs, and competition for funding from the maintenance and replacement needs of an aging infrastructure system. There are opportunities for innovation in intersection design focused on improving intersection capacity at major arterial intersections. These innovations can overcome design and operational deficiencies at signalized intersections of conventional design, including multi-phase signal inefficiencies, storage bay requirements and reliance on traffic detection and actuation.

2.0 UNCONVENTIONAL DESIGN, OPERATIONS AND MANAGEMENT PRINCIPLES

2.0 UNCONVENTIONAL DESIGN, OPERATIONS AND MANAGEMENT PRINCIPLES

Unconventional arterial intersection design, operation and management strategies have three primary principles:

1. The **design and operations emphasis is on through-vehicle movements**. In the hierarchy of roadway functionality, serving through-vehicles is the main purpose of the arterial functional class (7). This includes minimizing stopped delay for through-movements on the arterial at the risk of inducing larger delay and/or travel time penalties to left-turn and cross street movements.
2. The intersection **design and operations allow for a reduction in the number of signal phases**, particularly at the main intersection crossing. Most unconventional intersection designs reduce the intersection signal control to simple two-phase operations. As a result of the reduction in signal phases, the intersection cycle length can often be reduced, as well as time lost to clearance phases.
3. Unconventional designs typically **reduce the number of conflict points at intersections and separate conflict points that remain**. A reduction in conflict points typically leads to fewer accidents (particularly the types of greater severity) and a simpler decision process for motorists entering main travel flows.

While the unconventional designs presented in this monograph may have potential benefits on collector or minor arterial roadways - those either functioning as thoroughfares or having special needs for increased mobility - the design innovations are focused on arterial roadways, designed to carry large traffic volumes over greater distances with limited direct access to adjacent development.

2.1 EMPHASIS ON THROUGH-MOVEMENTS

Highways with comparable traffic volumes are constructed to the same design criteria and provide identical levels of service although there may be considerable difference in the functions they serve (2). Arterials are expected to provide a high degree of mobility for the longer trip length and should provide higher operating speed and level of service. Because service to adjacent land uses is not their major function, some degree of access control is desirable to enhance mobility. A systematic approach to design should consider the overall purpose that the roadway is intended to serve. Access should be most restrictive when the principal function of the road is to provide higher speed, carry higher volumes and/or serve longer-distance travel.

A major benefit of proper intersection design and operations is preserving the functional integrity of high-speed, high-capacity facilities. By unlocking congestion at major signalized intersections, operations along the entire arterial corridor are improved dramatically. If at a congested intersection, average throughput delay can be reduced by one-quarter, for example, from one minute average delay to 45 seconds, that 15-second timesavings multiplied by the number of congested intersections along a particular corridor (and further multiplied by thousands or tens of thousands of vehicles daily), can result in substantial overall reductions in delay, congestion and user costs.

Providing direct access from the arterial to collector and local roadways and roadside development businesses, favors that access over the mobility needs of large volumes of through-traffic. While easy access to businesses can be important, such access should be weighed against needs of other users of the road. Many state laws require *reasonable* access to abutting property, but this does not necessarily mean *direct* access. The interstate system is protected by this principle, as interchanges are granted based on greater public good and an Interchange Justification Report is federally mandated to ensure so. While arterial access is not as tightly controlled by most highway agencies, certainly some constraints on local and/or private access seems reasonable on the highway class only one step below freeway systems.

2.1.1 Left-Turn Treatment

Ideally, the capacity of an intersection should match vehicular travel pattern demand and left turns should not be simply prohibited except where a reasonable alternative routing is available. In general, fewer, less-concentrated left turns result in better processing of conflicting intersection demands. It is better to have numerous locations of low-volume left turns than to concentrate left turns at one single intersection.

2.1.2 Separation of Turning Volumes from Through Movements

Turning vehicles typically slow down before making their turn. Where turning vehicles are removed from the through lanes of traffic, traffic speed is better maintained. This is precisely the reason for right and left turn storage bays and tapers at intersection approaches. In addition to maintaining speed, roadway capacity is preserved and accident potential is reduced. Many unconventional designs use medians, separate roadways and other channelizing features to increase the separation of left turn vehicles from through-traffic, thus improving safety and geometrics.

KRAMER'S CONCEPT OF AN IDEAL SUBURBAN ARTERIAL

In a paper that serves as a classic on the proper design and operation of a suburban arterial (8), Richard Kramer enumerates two design principles that he recommends are *essential* to be adopted and followed at *all* intersections of a suburban arterial with collector roads and private driveways. Kramer purports that, in addition to standard AASHTO, FHWA, and other applicable design and operations criteria, highway agencies should establish...... “an absolute minimum percentage of green time that will be displayed to arterial thru traffic.” Crossing or entering traffic at signalized access points are to work within the confines of the remaining percent of cycle time allocated to those movements. If they cannot, excessive cross street delays are to be tolerated or a full or partial grade separation is to be built. Locations where movements are permitted to cross both directions of the arterial at grade *must be pre-determined before construction*, and signal cycle lengths must be pre-established for critical at-grade intersections. Proper signal spacing should dominate all other design considerations and be in harmony with the pre-determined cycle length. Kramer’s second principle proposes that the arterial design should prohibit direct left turns at cross street intersections and driveways, by using raised or wide median barriers, where an acceptable level of service cannot otherwise be achieved by conventional design measures.

The great significance of Kramer's concept is that it provides a design philosophy for an entire class of facilities (which he called “Superstreets”). He predicted that this class of Superstreet facilities will be of greater importance as cities and communities continue decentralization (relative to a historic urban central business district focus) of employment and other activities into "megacenters" throughout suburbs and outlying areas, in effect giving rise to sets of interrelated small cities linked by arterial facilities.

2.2 REDUCTION IN SIGNAL PHASES

"Within the realm of signalized intersections, no greater efficiency can be attained than that provided by a two phase signal." - Craig Miller on the reasons for considering unconventional design in a recent ITE publication.

When traffic signals on an arterial are poorly spaced and/or poorly coordinated, arterial capacity, safety and speeds are compromised. Progression is most readily achieved when the spacing of signals is appropriate and the available green time for the arterial through-volumes is maximized.

Unconventional arterial intersection design, operations and management principles focus on separating left turn movements either away from the intersection, or otherwise out of conflict with arterial through-movements. Left-turn conflicts often limit capacity and cause many of the operational and safety problems at arterial intersections. Re-routing left turns usually allows a reduction in the number of signal phases from four to two, which results in decreased delay for through-traffic and promotes progression along the arterial. As discussed in chapter one, multi-phase signals minimize the availability for through-traffic phases and impede progression. A two-phase signal has more time available in its cycle for through-vehicle progression both on the arterial and on the cross street. Two-phase signals also allow for shorter cycle lengths and opportunities for progression in both directions will in most cases increase with shorter cycles.

2.3 REDUCTION IN CONFLICT POINTS

Unconventional designs also share a deliberate reduction in the number and severity of intersection conflict points, which is typically a major factor in intersection operational safety. A reduction in conflict points usually means fewer potential threats to drivers, which promotes safety. Many of the unconventional intersection design alternatives reduce the number of conflict points by rerouting some left turns.

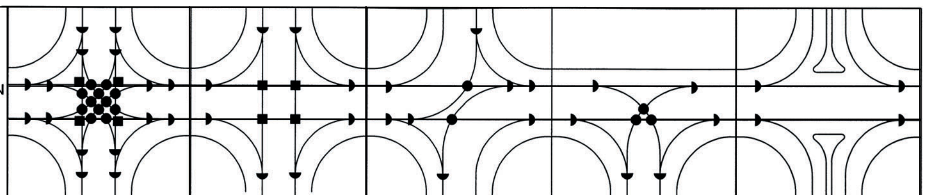
As the number of potential conflict points at an intersection increases, so does the average rate of traffic crashes. Four-leg intersections have the most potential points of conflict. As shown in **Exhibit 9**, there are 32 conflict points (16 major and 16 minor) at a simple four-leg intersection; an intersection that permits only through and right turn movements reduces the number of conflict points to eight, while a right-in, right-out driveway has no major and two minor conflicts. Eliminating crossing conflict points that have the highest accident potential can reduce the severity and potentially the number of intersection-related accidents.

Positive access management techniques can reduce the number of conflict points at intersections and at access points in between. Median barriers along an arterial limit and separate conflict points by controlling locations for left turns. Directional median openings provide greater safety and controlled access with fewer conflict points. When medians are used for the full length of a corridor, all uncontrolled driveway accesses become right-in and right-out only, with just two conflict points.

This reduction of conflict points most often translates into improved safety. Over the past quarter-century, many studies have documented a reduction in the number of traffic accidents (including fatal, injury and property damage crashes) on roadways that have applied good access management principles. For example:

- Studies in Colorado and Florida have shown a 50 percent reduced crash rate on access-managed roads.
- In Georgia, installing medians with protected left turn lanes decreased crashes by 25 percent. Similar measures in New Jersey reduced crashes by 45 percent.
- A 1988 Michigan study showed 50 percent fewer crashes on four- or six-lane divided highways compared to similar undivided four- and six-lane roads.

Exhibit 9: Intersection Vehicular Conflict Points



INTERSECTION CONFLICTS/ TYPE	FULL ACCESS	NO LEFT TURN	3/4 ACCESS	FULL ACCESS T	RIGHT IN/OUT
CROSSING (MAJOR)	4	4	0	0	0
TURNING (MAJOR)	12	0	2	3	0
DIVERGE (MINOR)	16	8	8	6	4
TOTAL	32	12	10	9	4
RIGHT IN/ RIGHT OUT (PER MILLION ENTERING VEH)	0.4	N/A	0.2	0.3	0.1

Source: Adapted from the Minnesota Department of Transportation Traffic Manual Handbook

In a three-year study of accidents on Michigan state highways, nearly 68 percent of all crashes were access-related, having occurred at intersections or driveways. More than 33,000 crashes were recorded as driveway-related, accounting for 69 fatalities and nearly 13,900 injuries. The estimated average annual cost associated with these driveway-related crashes was more than $220 million (9). The study concluded that better access management could improve motorist safety and reduce crash-related injuries and automobile repair expenses.

2.3.1 Separating Conflict Points

Separation of conflict points can also reduce traffic conflicts. Effective means of separating conflict points include sufficient driveway spacing and corner clearance at the critical approach areas of intersections. Another means is physically separating by distance an opposing movement (such as redirected left turn lanes) or improving opposing-movement visibility so motorists can safely concentrate on other conflict points. The goal is to reduce visual distractions for entering vehicles, which increases traffic safety. Greater separation distance also gives motorists a longer reaction time. Higher-speed traffic requires greater driveway separation. A single driveway can meet the access needs of multiple businesses along an arterial where a frontage road is used.

2.3.2 Access Management

Many of the unconventional intersection designs presented in this monograph can enhance the ability to manage access along the entire arterial corridor, not just at intersections. The goal of access management is to achieve a safe and efficient flow of traffic (in terms of safety, throughput and speed) along a roadway while preserving reasonable access to abutting properties. A variety of techniques are available for achieving access management control, including design considerations such as medians and control islands prohibiting turning movements, consolidation actions such as sharing driveway access and use of service roads, and signal control and coordination such as minimum intersection spacing requirements, phase limits and system coordination. Access management and unconventional intersection design share these common principles and can be woven together if considered in the planning stage. Access management must be consistently and effectively built into the geometric design of the arterial to reduce congestion.

2.3.3 Pedestrian Crossings

Many unconventional designs separate pedestrian crossings into two-stage crossings that are narrower and/or cross one direction of the arterial at a time. Crossing a single direction of a roadway, as with downtown one-way street systems, is safer for pedestrians because they only need to focus on crossing one direction and do not need to be aware of as many traffic movements. Other benefits to pedestrians result from the use of two-phase signals:

- Two-phase signals typically have shorter overall cycle lengths than multi-phase intersections and therefore the pedestrian does not have to wait as long to receive a crossing phase.
- Two-phase signals typically have more green time allotted as a percentage to the through movement (and thereby the pedestrian crossings) than at multi-phase signals.
- In some unconventional designs, pedestrian movements do not conflict with permissive or protected left-turning vehicles (the left turn movement is not allowed at the intersection).

SUMMARY

Unconventional arterial intersection design, operations and management concepts share three primary principles. First, the design and operations favor through-movements along the arterial - even at the expense of left turn and cross street movements - to provide maximum efficiency and level of service for longer trip movements on the arterial. Second, the designs minimize the number of intersection signal phases (usually to two) by re-routing or diverting left turn movements, thus eliminating signal clearance-time inefficiencies and increasing arterial progression opportunities. Lastly, the unconventional intersection designs remove or separate vehicular and pedestrian conflict points and manage access on the arterial, in most cases improving safety.

3.0 ARTERIAL SYSTEM AT-GRADE INTERSECTIONS

3.0 ARTERIAL SYSTEM AT-GRADE INTERSECTIONS

The unconventional arterial intersection designs presented in this chapter are a subset of at-grade designs that are best suited for implementation as a system of intersections along an arterial corridor, with successive intersections of like design. While several of the intersection designs presented here can be applied in isolation, these designs derive their maximum benefit from systematic applications. Isolated applications may have additional signing and motorist expectancy considerations. At-grade designs that are better suited for isolated intersections are presented in Chapter 4.

When constructed as part of a regional or system corridor, these designs have a greater potential for increased arterial efficiency as they manage operations at large intersections as well as the minor or driveway intersections between. Several of these at-grade system intersection design concepts have been used successfully for many years, while others have been implemented only in part or are still in the research stages.

3.1 MEDIAN U-TURN CROSSOVER

3.1.1 Evolution of Design

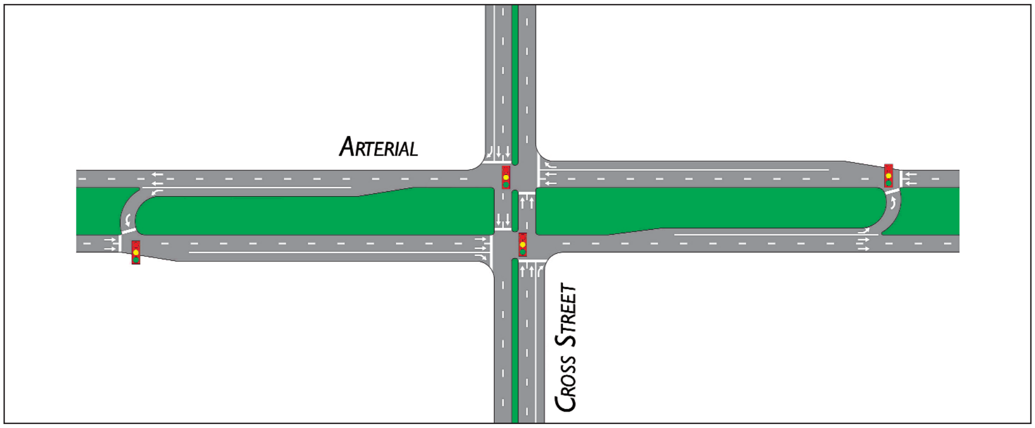
Michigan Department of Transportation (MDOT) is the most prominent user of the Median U-Turn Crossover design in the US, with over 1,000 miles in service, and continues to include them as a preferred management and operations strategy on its primary arterial system. Prominent Median U-Turn corridor examples include long stretches of US 24 (Telegraph Road) and Woodward Avenue in southeastern Michigan; a few more recent partial or designs with similar concepts have appeared in Florida, Maryland and New Mexico, and the design has been considered in planning studies in Illinois and South Carolina.

MDOT first introduced the Median U-Turn Crossover design in the 1960s. Several rural highway corridors had been preserved via policies as early as the 1920s that provided large rights-of-way for wide medians to establish future "super highways." Rural (later suburban) multi-lane highways with bi-directional openings in wide medians were gradually built up in these corridors. By the 1960s, many corridors were largely urbanized and experiencing capacity problems at intersections and at bi-directional crossover locations, largely due to interlocking left turns (10).

Exhibit 10: Interlocking Left Turns at Bi-Directional Medians

To address this concern, engineers devised the Median U-Turn concept, also known as "Michigan U-Turns" or "Michigan Lefts" that converted the bi-directional median openings to one-way crossovers within the wide median. All left-turning traffic was required to use the directional crossovers, both at intersections and at mid-block locations. In urbanized areas, back-to-back crossovers were implemented with an approximate frequency of 1/8-mile spacing to serve numerous development accesses without undue travel time and distance.

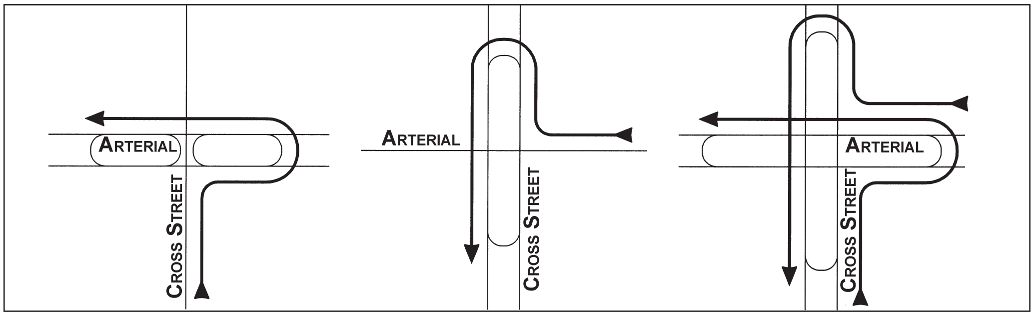
Exhibit 11: Median U-Turn Crossover Design



3.1.2 Description of Operations

The Median U-Turn design greatly simplifies major intersection signal operations. Direct left turn movements are prohibited at the major intersections, therefore creating a simple two-phase signal control, alternating between arterial and cross street through and right turn movements. Left turn movements are made indirectly, using directional left turn crossovers immediately up and downstream of the crossroad intersection. For example, a left-turning vehicle from the crossroad first turns right onto the arterial, makes a U-Turn on the arterial using the first directional U-Turn crossover and passes back through the cross street intersection. A left-turning vehicle from the arterial crosses through the cross street intersection, makes a U-Turn on the arterial at the first U-Turn crossover and turns right at the crossroad. All left turns at a Median U-Turn intersection pass through the intersection twice, as both a through then a right turn movement.

Exhibit 12: Median U-Turn Design Variations



A. *Inclusion of a stop-controlled directional crossover immediately prior to a main intersection. This may improve land access, eliminating the need for some development-bound vehicles to travel through the intersection twice. Creates increased safety concerns where U-Turns conflict with a high cross street right-turn volume.*

B. *Placement of the directional crossovers on the cross street to minimize arterial median width and ROW requirements. This "isolated" intersection treatment is best suited where drivers are familiar with the Median U-Turn concept. Placing U-Turn crossovers in the median of long stretches of arterial corridors greatly improves route continuity, driver expectation and greater access controls between major intersections.*

C. *Placement of directional crossovers on both the arterial and the cross street increases left turn capacity. This is the case where two Median U-Turn arterials intersect. It can also be the case when high left turn volumes are present on both roadways that may otherwise overburden U-Turn crossovers on the arterial alone.*

Exhibit 13: Four Corners, Maryland

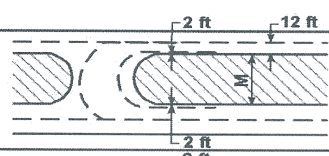
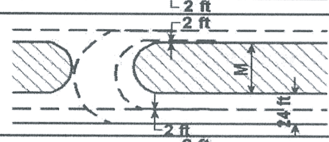
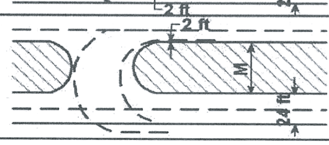
Aspects of the Median U-Turn design can be seen at this MD 193 intersection with US 29 in northern Washington, DC. MD 193 splits into two one-way roadways with U-Turn crossovers at both ends. Direct left turns are prohibited at the main MD 193/ US 29 intersection; rather they are made indirectly using the U-Turn crossovers. Aerial by AirPhotoUSA, 2003.

3.1.3 Design and Operational Considerations

Deciding the appropriate distance from a major crossroad intersection to the first U-Turn crossover opportunity is a trade-off between providing a sufficient U-Turn storage bay length (to minimize spillback potential) and keeping the left-turning path length short (to minimize travel time). The first designs in the 1960s had a spacing of 300 feet between the intersection and first U-Turn crossovers; however, this spacing was found to be inadequate for U-Turn storage. Engineering evaluation and design iterations over the years have led to MDOT and AASHTO design guidelines on locating U-Turn crossover locations. AASHTO proposes an optimal spacing of 500 feet from the major intersection, while Michigan design standards propose 660-foot spacing plus or minus 100 feet.

Desired median widths depend on the design vehicle (specifically the vehicle U-Turn radii requirements) and the number of lanes on the arterial. The AASHTO design guide presents criteria for selecting a median width for a Median U-Turn crossover. For a large semi-trailer combination design vehicle (called a "WB-50" for its assumed wheel-base length of 50 feet), AASHTO recommends a minimum median width of 59 feet (excluding U-Turn bay width) on a four-lane arterial. The recommended minimum width is reduced for a six-lane arterial to 49 feet. A narrower median is possible with a smaller design vehicle, or by providing a paved turning basin beyond the edge line. Spacing of the median crossovers along the arterial depends largely on the land use along the arterial, though the Michigan Roadway Design Manual recommends spacing of no less than 1/8 mile between back-to-back U-Turn crossovers.

Exhibit 14: AASHTO Median Width Design Standards

TYPE OF MANEUVER		M - MIN. WIDTH OF MEDIAN (ft) FOR DESIGN VEHICLE						
		P	WB-40	SU	BUS	WB-50	WB-60	TDT
		LENGTH OF DESIGN VEHICLE (ft)						
		19	50	30	40	55	65	118
INNER LANE TO INNER LANE		30	61	63	63	71	71	101
INNER LANE TO OUTER LANE		18	49	51	51	59	59	89
INNER LANE TO SHOULDER		8	39	41	41	49	49	79

Source: A Policy on Geometric Design of Highways and Streets, 4th Edition, Copyright 2001, AASHTO, Washington, DC. Used by permission.

Signing is particularly important for safe and efficient operations of the median U-Turn design. After several early signing design iterations, the most common and widely accepted signing is the “fishhook” design (left) used at the main intersections and at major crossover locations. Other regulatory signing requirements are typical of any median highway design.

Exhibit 15: Median U-Turn Signing and Pedestrian Crosswalks

A slightly longer clearance phase must be provided on the cross street because of the wider median width. The signals crossing each direction of the arterial should be staggered by a second or two between the near and far-side signals crossing the arterial (depending on the median width) so as not to confuse drivers with a stopping distance dilemma.

3.1.4 Studies and Research

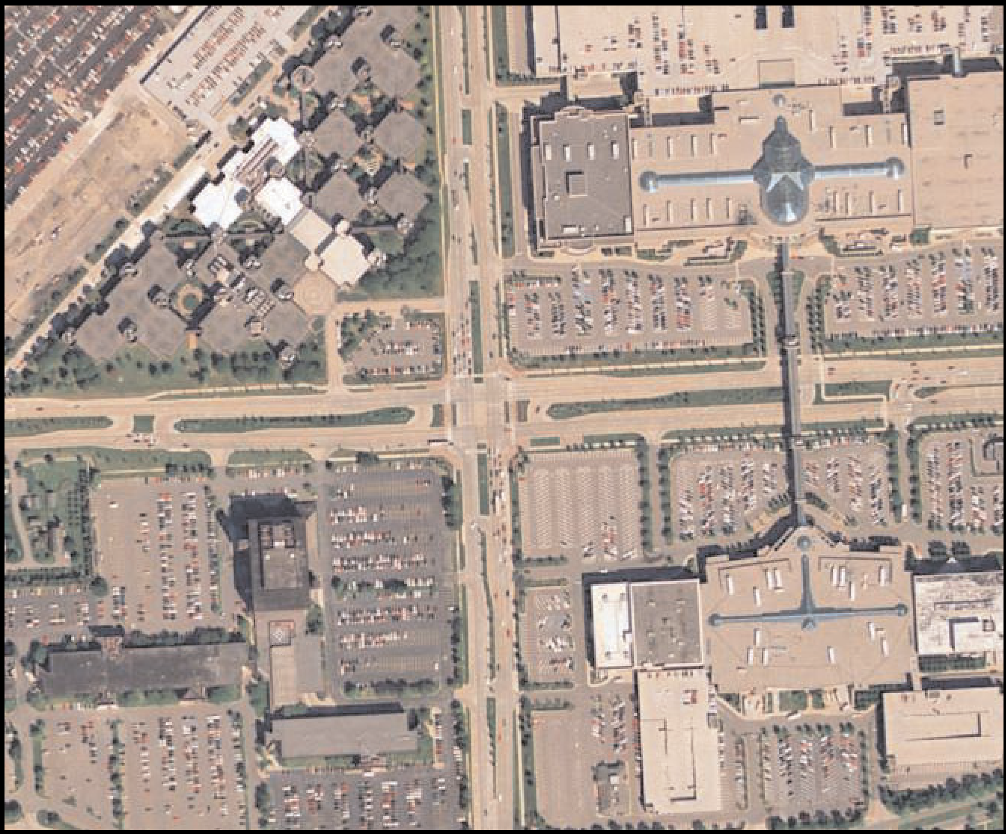
The Median U-Turn design is perhaps the most studied of all the unconventional intersection designs. Several authors have conducted extensive field measurement and traffic simulation modeling research, analyzing the travel efficiency of the Median U-Turn intersection (11,12,13,14). These studies all concur that the Median U-Turn design provides superior travel time and delay measures compared to the conventional intersection design for at least some volume combinations. A recent simulation model study compared Median U-Turn operations to conventional and other unconventional intersection design alternatives. The Median U-Turn typically had the lowest or competitive travel times for all intersection volume combinations studied and always preformed better than the conventional design in overall delay time (15). Another study verified the travel time benefits of the Median U-Turn compared to conventional intersection design and showed that the Median U-Turn operations do not necessarily compromise system travel times during off-peak hours of the day (16).

Over the years, MDOT has performed several “before and after” accident studies on corridors with bi-directional crossovers that were re-constructed as Median U-Turns. Nearly all case studies reported a significant reduction in the number of crashes, particularly right angle crashes (10). Studies conducted by MDOT have also shown that the Median U-Turn design improves traffic flow on average a full level of service grade compared to a comparable intersection with conventional lanes and signal control (see **Exhibit 16**).

PROFILE: MEDIAN U-TURN

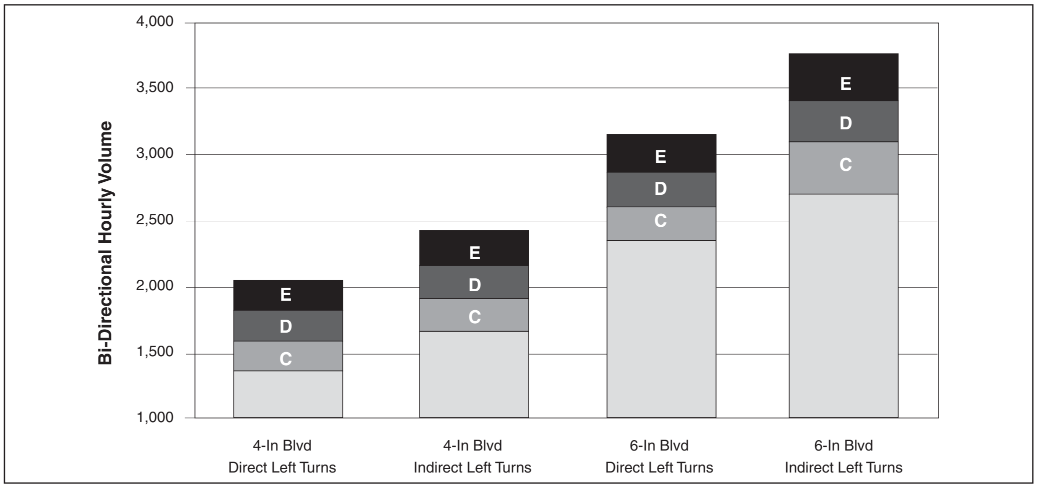
Big Beaver @ Coolidge (Troy, MI)

This Median U-Turn intersection of two eight-lane, divided highways in Troy, Michigan, supports several high-generation land uses in each intersection quadrant, including the world headquarters for the K-mart Corporation (upper left), a combined 1.4-million-square-foot regional shopping mall connected by an overhead walkway (upper and lower right) and a mid-rise office tower (lower left). While this at-grade intersection has congested (but not failing) operations during peak traffic periods, County and State transportation agencies had enough confidence in the intersection capacity of the median U-Turn concept to build and operate this intersection at-grade.



Aerial by AirPhotoUSA, 2003.

Exhibit 16: Divided Highway Level of Service Comparison



Source: Directional Crossovers: Michigan's Preferred Left Turn Strategy, MDOT

Noted advantages of the Median U-Turn design relative to a conventional intersection design include reduced delay for arterial through-traffic; easier through-traffic progression on the arterial; fewer stops for through-traffic; fewer threats to crossing pedestrians; and fewer and more widely spaced conflict points. Disadvantages include greater potential for driver confusion; driver disregard of the left-turn prohibition at the main intersection; increased delay, travel distance and stops for left-turning traffic; and larger median right-of-way requirements.

When to Consider

Studies have shown that the Median U-Turn design provides the greatest travel time savings on arterials that have high through volumes, moderate or low left-turn volumes and any level of cross street volumes. If the left turn volume is proportionately high, the time and distance penalties incurred by vehicles making left turns (as well as increased queuing and spill-back potential) may outweigh through-vehicle timesavings. Additionally, arterials with limited existing or potential right-of-way are not desirable candidates due to the extensive median width requirements for effective Median U-Turn design, with the exception of cases where agencies can build the wide median and crossovers on the cross streets.

3.1.5 Lessons Learned

The Michigan Department of Transportation reports that sections of eight-lane median U-Turn arterials carry volumes in excess of 100,000 vpd with total intersection entry volumes as high as 150,000 vpd. While these locations may experience congestion during peak periods, total system failure is rare (17). Volumes of such magnitude are typically found on freeway or expressway facilities with total control of access and grade-separation; however, the Median U-Turn design can handle these volumes while providing at-grade crossings and indirect access to land parcels along the corridor.

There are no known cases in which a median U-Turn design has been implemented and later removed for safety, capacity or other deficiencies. While new locations have created safety, enforcement and educational issues during the first several months of operation, these issues have in all cases been overcome.

3.2 JUGHANDLE

3.2.1 Evolution of Design

The most prominent user of Jughandle design is the State of New Jersey, followed by a few other northeastern states. The New Jersey Department of Transportation (NJDOT) has used the Jughandle, referred to as “Jersey lefts” in the Garden State, for over 30 years on hundreds of miles of heavy-volume arterials. NJDOT continues to build new Jughandles as a preferred design strategy on high-volume arterials (18). A prominent example of a Jughandle corridor is US 1 from Trenton to New Brunswick, New Jersey. Outside of the northeast, Jughandle intersections can be found in Florida, Hawaii, Missouri and Calgary, Alberta, Canada.

NJDOT’s philosophy for Jughandle design is premised on the fact that land along arterial corridors is expensive. Much of New Jersey’s original roadway system was built in the 1920s and 30s as two-lane concrete roadbeds that needed to be expanded within the right-of-way to multilane facilities in the 40s and 50s. Right-of-way in urbanized areas was limited, particularly at intersections. By designing and implementing Jughandle roadways that allowed no direct left or U-Turns from the arterial, the median could be narrow, and additional ROW purchases along the arterial corridor were avoided. Today, most Jughandle corridors include jersey barrier within the median to control left turns.

3.2.2 Description of Operations

The Jughandle design includes an at-grade ramp from the right side of the roadway at or between intersections by which motorists make indirect left turns, right turns and/or U-Turns. The Jughandle ramps diverge from the right side of the arterial in advance of the intersection, removing turns at the main intersection from active through-lanes. Ramp terminals are typically stop-controlled for left turns and yield-controlled for channelized right turns. The Jughandle movement replaces direct left turn movements at the main cross street intersection, providing greater safety and reduced delay to through-traffic.

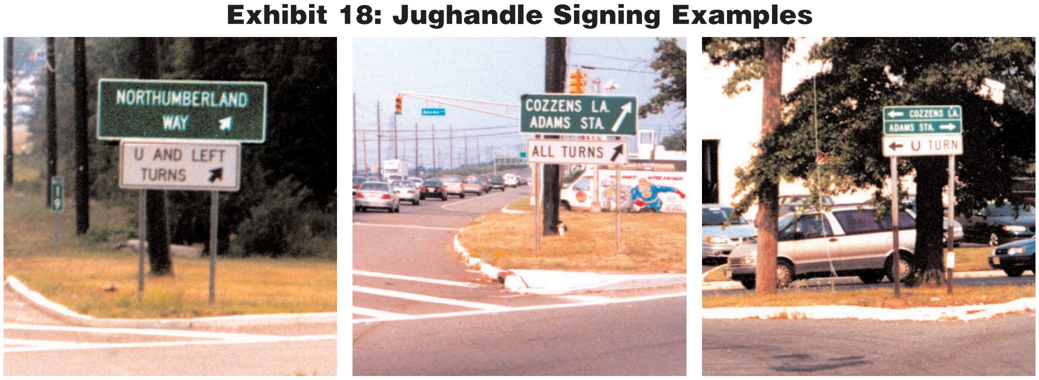
Exhibit 17: Jughandle Intersection

Aerial by AirPhotoUSA, 2003.

In well-designed Jughandles, ramp terminals are several hundred feet from the main intersection to ensure that cross street signal queues do not block the ramp terminal. Since no U-Turns or left turns are allowed directly from the arterial, the median on the arterial may be narrow, often with jersey median barrier and as little as a 2-foot offset separating opposing lanes. Intersections along the arterial often are controlled by two-phase signals; a third phase can be required for left turns from the cross street if the volume is heavy, but the Jughandle design always eliminates the direct left turn movement and signal phase from the arterial.

As Jughandles require all left turn and U-Turn movements from the arterial to be made from the right lane, driver confusion and lane changing may be reduced and travel speeds in the left lanes increased. Jughandles allow drivers in the median lane of the arterial to be virtually free of conflicts (19). Right-of-way requirements along the arterial can be significantly less (10 to 20 feet) compared to a conventional median-divided roadway as the width requirements for median left turn pockets in both directions is eliminated; however, right-of-way requirements at the jughandle intersections can be much greater.

Exhibit 18: Jughandle Signing Examples

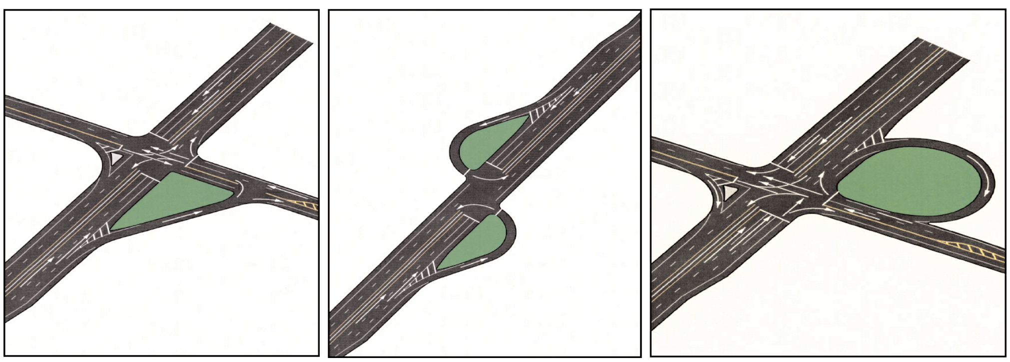


3.2.3 Design and Operational Considerations

There are three basic Jughandle configurations:

- The standard **Type A** Jughandle configuration, typical at four-approach intersections, as described previously.
- Where there are three or less approaches to an intersection, **Type B** Jughandles are typically used. At three-leg intersections, the Type B design uses the right ramps to orient left turns opposite to the "T" intersection leg. The Type B design is also used to permit U-Turns at midpoints along the arterial where there is no cross street movement. In general, Type B Jughandles should be limited to locations where topographic, environmental, or zoning constraints limit future access potential to adjacent land parcels.
- Where left turns from the arterial are moderate to high, with potential to cause storage problems on the cross street or Jughandle ramp, a **Type C** Jughandle is often used. The Type C configuration includes the use of loop ramps located after the cross street intersection. The loop ramp eliminates left turns from the ramp onto the cross street, but can cause conflicts with right turn movements from the cross street onto the arterial where this movement is significant.

Exhibit 19: Jughandle Design Configurations



Type A Type B Type C

Source: New Jersey Department of Transportation, used by permission.

3.2.4 Studies and Research

Several studies comparing the Jughandle operations, travel time and capacities with conventional and unconventional intersection designs showed that the Jughandle was competitive with the conventional design for at least some volume combinations (13,15). Studies have shown that the Jughandle design provides the greatest travel time savings on arterials that have high through movements, moderate or low left turn volumes, and moderate to low cross street volumes. If the left turn or cross street volumes are proportionately high, queues from the cross street may block the ramp terminals and may outweigh any through-vehicle timesavings. The Jughandle is particularly suitable for arterials with limited right-of-way, often requiring less width along the corridor (although more right-of-way at Jughandle intersections) compared to the conventional median-divided highway corridor. The distances between Jughandle intersections should be frequent enough so that cross street intersections are not overloaded.

The advantages of the Jughandle alternative over conventional multiphase signalized intersections include reduced delay for arterial through-traffic; reduced stops for arterial through-traffic; easier progression for arterial through-traffic; narrower right-of-way requirements along the arterial; and reduced and separated conflict points. The disadvantages of the alternative relative to conventional intersections include greater potential for driver confusion; driver disregard for left-turn prohibitions at the main intersection; increased delay for left turns from the arterial, especially if queues of cross street vehicles block the ramp terminal; increased travel distances for left turns from the arterial; increased stops for left turns from the arterial; pedestrians must cross ramps and the main intersection; additional right-of-way requirements at the Jughandle intersections; additional construction and maintenance costs for Jughandle ramps; and lack of access to the arterial for parcels next to ramps.

When to Consider

Designers should consider Jughandles on arterials with high through-volumes, moderate to low left turn volumes and narrow rights-of-way. Suitable corridors also allow generous spacing between major cross street intersections (where Jughandles and/or interchanges would be provided), yet frequent enough minor crossings so that the Jughandle intersections are not overloaded. Corridors with built-out development in most major intersection quadrants are costly for conversion to a Jughandle corridor.

3.2.5 Lessons Learned

The NJDOT Roadway Design Manual recommends acquisition of right-of-way on the interior of Jughandles to promote safe and efficient operations on surrounding access roads. It is also typical practice to restrict on-street parking within the intersection as it can introduce sight distance obstacles and parking vehicle conflicts. The circumscribed area is typically preserved and landscaped by area businesses through the state-sponsored "Adopt-a-Jughandle" program. These areas are also sometimes used for drainage detention.

New Jersey's experience with signal pole placement over the years has led to refined FHWA guidance for placement of signal poles at Jughandle intersections. All new intersections are designed to include signals on mast arms rather than on poles within the center jersey barrier. The mast arm placement removes the pole as a roadside hazard in either the unprotected median case or in the narrow jersey wall design.

Exhibit 20: Jughandle Signal Pole Placement

(a) (b) (c)

Jughandle poles in the median without protection (a) are not recommended; impact attenuators (b) are often used when the pole is within the median wall; FHWA currently recommends (c) pole placement on the outside of the roadway right-of-way.

New Jersey's experience with the Jughandle design has provided some other basic guidelines for design (18):

- Where jersey barrier controls left turn access, speed limits that balance facility efficiency and safety are typically 50 or 55 mph.
- There are only a few examples of Jughandles at isolated locations or without median barrier; these intersections typically experience higher accident rates.
- A minimum 100-foot spacing is desired between the ramp terminal and the intersection to provide at least some room to store vehicles on the cross street waiting at a signal without blocking the ramp access.
- The ability to use shorter signal cycles due to the reduction in signal phases can also reduce the occurrence or frequency of queuing at the cross street intersection.
- On a four-lane arterial, a minimum two-foot offset is desired from the left travel lane to the median barrier; greater separation is desired with a six- or eight-lane arterial.
- Intersection lighting needs vary depending on location, intersection geometrics and traffic volumes. Jughandle intersections without lane channelization seldom include overhead lighting. Studies show that fixed lighting sources tend to reduce accidents at intersections with high concentrations of pedestrians and/or roadside developments.

3.3 SUPERSTREET

3.3.1 Evolution of Design

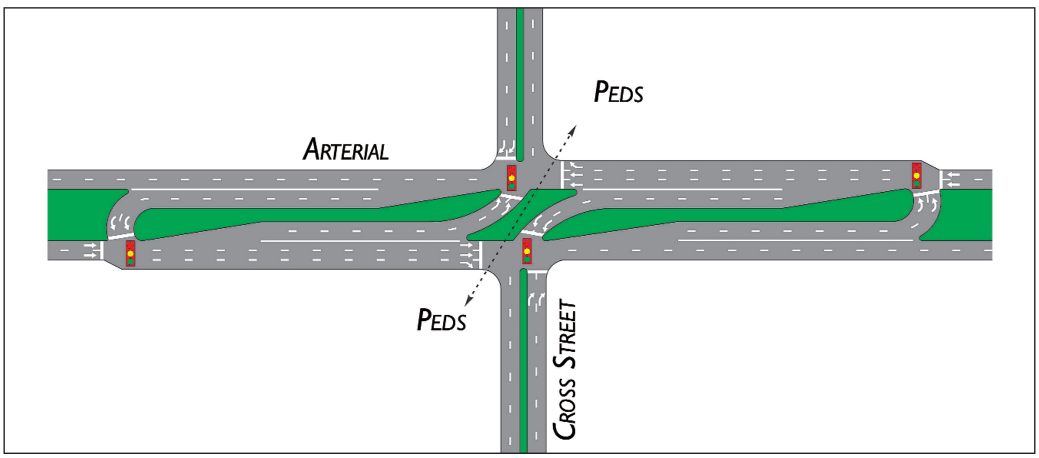
Richard Kramer, a traffic engineer from Huntsville, Alabama, conceived of the Superstreet concept and published a paper on it in 1987. According to the State DOT survey, no state has implemented the full Superstreet alternative, but some agencies have severed cross street through-movements and built directional crossovers on arterials in a piecemeal fashion

(Maryland, Washington State). A single intersection of Superstreet design is currently under construction in Chapel Hill, North Carolina.

3.3.2 Description of Operations

The Superstreet median design is similar to the Median U-Turn concept but features a break in cross street traffic that allows the signals on opposite directions of the arterial to operate independently. The design requires cross street through movements and left turns to and from the arterial to use the directional crossovers. A conventional four-approach intersection becomes two independent three-approach intersections. This independence allows each direction of the arterial to have its own signal-timing pattern, including different cycle lengths if desired, so that engineers can achieve “perfect” progression in both directions at any time with any intersection spacing. As properly timed signals along the Superstreet should not impact the ability to progress through traffic movements, highway agencies may be more liberal in granting signalized access points (within reason), to improve safety for traffic entering the arterial. Pedestrians can make a relatively safe but slow two-stage crossing of the arterial. Many of the other design details of the Superstreet are identical to Median U-Turns.

Exhibit 21: Superstreet Median Design

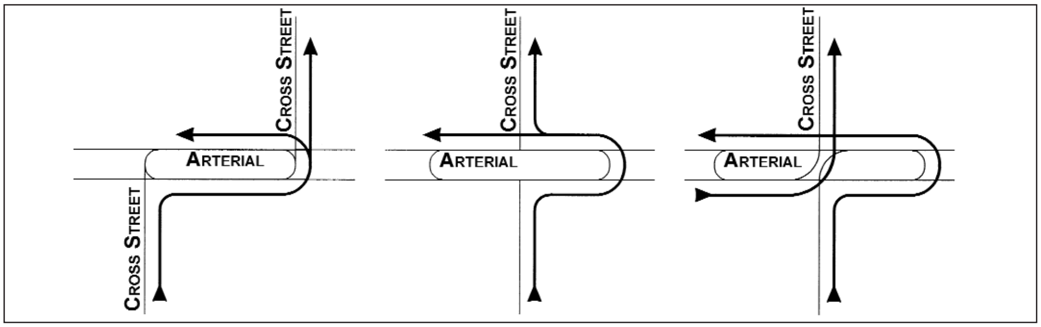


3.3.3 Design and Operational Considerations

Design Variations

There are several methods in which a Superstreet can “break” the cross street movement. As shown in **Exhibit 22**, the cross street can be (a) offset if there is sufficient cross street demand. At intersections with very low or non-existent through-movements, directional crossovers for left turns from the arterial can be removed (b), and left-turning vehicles can make U-Turns at the next available median crossover. The direction of the crossovers can be reversed (c) to allow left turns from the cross street onto the arterial in cases where this movement demand is heaviest; however, these crossovers create a left-merge on the arterial and lengthen the distance to the median crossover.

Exhibit 22: Superstreet Design Variations



(a) (b) (c)

The Left-Over Design Concept

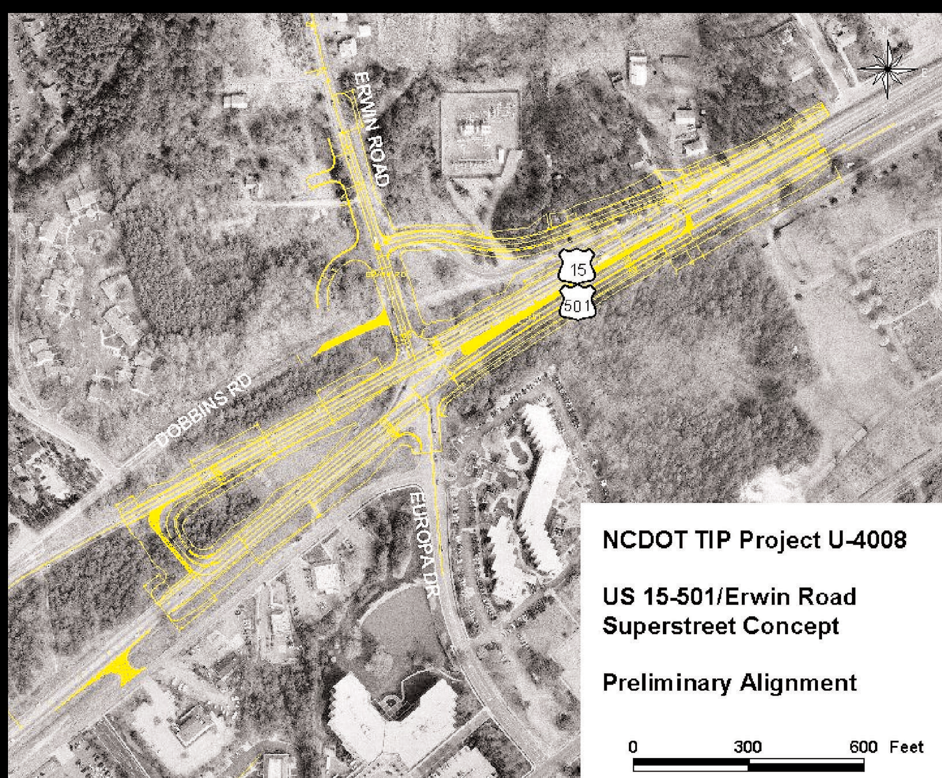
While there are no known Superstreet applications, the principle of the Superstreet design can be found in the common use of the "Left-Over" design. The Left-Over concept eliminates the left turn movement from driveways or cross streets onto an arterial by using a raised median curb. Openings in the median curb allow left turns from the arterial to the cross street or driveway. The left turn movement from a cross street or driveway along the arterial is made by turning right and then making a U-Turn at a downstream crossover, just as in the full Superstreet concept. This movement is typically given lowest priority, typically stop control subject to all other through and turning movements. The concept has typically shown positive effect on safety and operations on the arterial.

The Left-Over design is fairly inexpensive and easy to construct and many applications are placed as part of spot safety improvement programs. The Left-Over design is not practical at major signalized intersections, and in some cases the prevention of mid-block left turns may cause operational problems at adjacent intersections because of increased concentrations of left and U-Turning traffic. The Left-Over channelization can also be built into the initial design of the arterial roadway to locate future access locations. This gives engineers the ability to locate the access points at sufficient distances and where safe horizontal and vertical sight-distance exists. Pre-placement also encourages the development of shared driveway access and land parcel connectivity along the arterial.

PROFILE: SUPERSTREET

US 15-501@ Europa Drive/Erwin Road (Chapel Hill, NC)

On the famed US 15-501 roadway linking North Carolina and Duke Universities, the North Carolina Department of Transportation is constructing a signalized Superstreet design at a single major intersection crossing. The design recommendation was based on traffic capacity considerations and geometric constraints, and the minimization of impacts to land use and traffic ingress/egress as it pertains to pedestrian and bicycle safety on US 15-501. Visual impacts are improved with plantings in the median. The total cost of the intersection improvements was $2.8 million, with $255,000 in right-of-way acquisition. Business owners are wary of the lack of direct access, and the design of signing and pavement markings will be instrumental in helping drivers navigate North Carolina's first Superstreet intersection.



Design Concept courtesy NCDOT and the HNTB Corporation, Raleigh, NC; used by permission.

Exhibit 23: Left-Over Concept

Left-over concept

Example of design pre-placement

3.3.4 Studies and Research

Several studies have examined travel time in a Superstreet arterial corridor compared to conventional and unconventional intersection designs and found improved travel times in some scenarios compared to the conventional design (15,16).

The advantages of the Superstreet over a conventional multiphase signalized intersection include reduced delay for arterial through-traffic and for one pair of left turns (usually left turns from the arterial), reduced stops for arterial through-traffic, “perfect” two-way progression at all times with any signal spacing for arterial through-traffic, fewer threats to crossing pedestrians, and reduced and separated conflict points. Disadvantages of the Superstreet relative to conventional intersections include greater potential for driver and pedestrian confusion, increased delay for cross street through-traffic and for one pair of left turns (usually left turns onto the arterial), increased travel distances for cross street through traffic and for one pair of left turns, increased stops for cross street through-traffic and for one pair of left turns, a slow two-stage crossing of the arterial for pedestrians, and additional right-of-way requirements along the arterial.

When to Consider

Studies have shown that the Superstreet design provides the greatest travel time benefits where high through-volumes on the arterial conflict with moderate to low cross street through-volumes. This will be the case for many suburban arterials where roadside development generates most of the conflicting traffic. The Superstreet should also be given greatest consideration for arterials that have close to 50/50 directional splits for most hours of the day, and uneven cross street spacing that removes any chance of establishing balanced progression in both directions.

The Superstreet is not competitive where the cross street through-movement is heavy enough to require two through-lanes. Arterials with narrow medians and no prospects for obtaining additional right-of-way for widening are also poor candidates for the Superstreet.

3.3.5 Lessons Learned

During the planning process for the Chapel Hill Superstreet design, a series of public meetings was held to consider design alternatives and gather public support for a preferred design concept. Increasing levels of public support were gained for the Superstreet design at each meeting. Concerns raised from the public included driver education regarding a new traffic pattern, clear signage, and provision for truck U-Turn movements.

At the meetings, business owners expressed concerns about access, particularly those that relied on easy access, including a fast-food restaurant on Erwin Road. However most recognized that there would be at least some benefit from increased traffic flow – that the volume of traffic movements (that is, the number of potential customers passing by) on the arterial was as important as ease of access and visibility (20).

3.4 PAIRED INTERSECTIONS

3.4.1 Evolution of Design

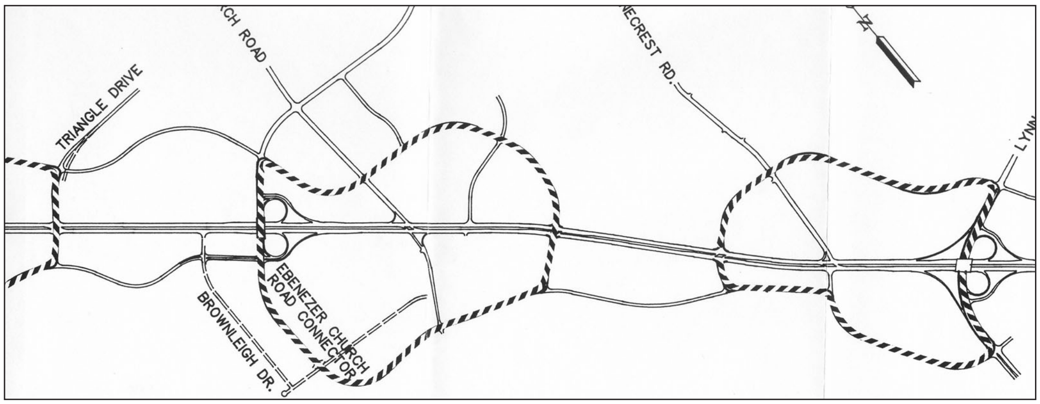
The guiding principles of the paired intersection concept are the separation of left turns and the emphasis of through-vehicle movements. Highway agencies have been prohibiting left turns from or onto arterials for years (particularly in downtown areas), relying on a good parallel street system or frontage roadways to provide circulation. The paired intersection concept allows this to be done in areas without a pre-existing system of parallel streets or frontage roads. Channelizing islands separating right and left turn movements are also commonplace on US roadways, as are this concept's reliance on access management practices, including the use of common access points by multiple parcels.

Edison Johnson, a traffic engineer with the City of Raleigh, North Carolina, conceived of a paired intersection arterial design using directional crossovers in conjunction with parallel collector streets. The concept was born as part of a 1988 study of the US-70 corridor in Raleigh, where conversion to a full-access-control freeway was not politically acceptable (21). The recommended paired intersection design is slowly being phased in by the city as the area develops. Highway agencies in Florida, Virginia and Michigan have applied the paired intersection concept to certain corridors by alternating turning movements, but no agency has applied the paired intersection concept to an entire corridor.

3.4.2 Description of Operations

The paired intersection concept alternates between the use of directional crossovers for left turns from the arterial at one intersection and permissive left turns onto the arterial at the second member of the pair. Left turns are prohibited at cross streets and other access points between the two pairs. Circulation between roadway pairs along the arterial requires two-way collector roads, or "backage" roads, that are set back from the arterial and parallel to it. Backage roads are different from frontage roads, as backage roads are *behind* the development parcels immediately adjacent to the arterial and parking is generally provided from the rear of the parcels. The separation between the arterial and backage road help intersections with the collector to operate more efficiently and avoid the queuing and closely spaced intersections often associated with frontage roads. Backage and collector roads can be designed to a pedestrian scale, with convenient access to parking, on-street parking and/or sidewalks. Local access is provided from these backage roads and therefore the arterial median can be narrow.

Exhibit 24: Paired Intersection Concept



Source: 1992 consultant study, used by permission from the City of Raleigh.

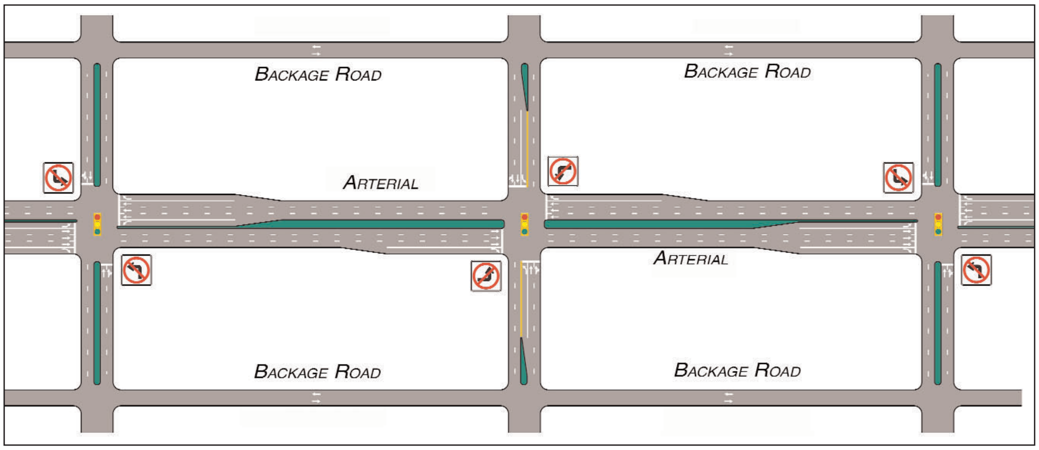
The use of this design can also control spacing of full-service signals to ensure good progression on the arterial (for example, by only allowing these every half-mile). Placement of the backage roads are ideally at least 300 feet from the arterial to avoid spill back and locking left-turns and to provide access to development parcels from the backage road.

The paired intersection design is a holistic plan that first requires key roadway elements to be in place before the full design is implemented. Developments along the arterial can have temporary full access until volumes warrant conversion and/or a backage road system is built out.

3.4.3 Design and Operational Considerations

Safety benefits are expected based on the premise that disaggregating left turns generally improve safety by simplifying conflicts. Benefits to through-traffic can also be expected as the design pushes delays from the arterial to the side street; thus green time can be maximized on the arterial (22).

Exhibit 25: Alternating Arterial Turns



Intersections at cross streets with the parallel collector roads can be stop- or signal-controlled depending on traffic volumes and intersection spacing. If developments fronting the arterial are also provided access from the collector roadways, U-Turn allowances do not have to be provided for in the arterial median and thus the median can be narrow. Similar to the Superstreet design, pedestrians in the paired intersection design can make relatively safe but slow two-stage crossings of the arterial.

3.4.4 Studies and Research

The advantages of the paired intersection design compared to a conventional arterial with multiphase signalized intersections include reduced delay for arterial through-traffic and for some left turns, reduced stops for arterial through-traffic, easier progression for arterial through-traffic, reduced and separated conflict points on the arterial, and optimal two-way progression with the left merge variation. Noted disadvantages compared to the conventional arterial include greater potential for driver and pedestrian confusion, increased delay for cross street through-traffic and for some left-turning traffic, increased stops and travel distances for cross street through- and some left-turning traffic, and slow two-stage pedestrian crossings. There are also additional right-of-way, construction, maintenance and operation costs for the parallel collector roads.

In developing paired intersection corridors, there may be opportunities for partnerships between the highway agency and developers to share the costs of construction or extension of the collector roadways. To implement the paired intersection design in highly developed corridors, a system of parallel streets or backage roads must be present and have the ability to carry additional traffic volumes. In such circumstances, one-way pairs may be a superior alternative.

When to Consider

The paired intersection design is best suited for arterial corridors with high through-traffic volumes and low cross street through volumes. Right-of-way must be available to build and oper ate the parallel collector roads. Additionally, coordination between highway agencies and planning councils is important to ensure that land use controls are in place to plan for access to the collector/backage roads for any future developments.

3.4.5 Lessons Learned

Experiences from the City of Raleigh have shown that the use of a channelizing curb for the left turn in the median is important to prevent side street left-turn violators. Low curb height and/or the lack of overlapping curb edges have caused higher violation rates from aggressive drivers, and some locations had to be modified after installation.

The consultant study of the US 70 corridor is a typical example of strategic corridor growth planning. The US 70 corridor between Raleigh and Durham was fairly undeveloped and the City and State transportation departments did not want the highway to become a strip-mall corridor with many signals and little access control like many other corridors in the area. Average daily traffic projections for the corridor exceeded 80,000 vpd. The plan goal was to protect capacity without having to build a freeway. The study eventually brought the development community to a plan consensus, but it took longer than expected. A planned six-month study took 21 months; however, the additional time was needed to explain the potential benefits of the paired intersection design, and develop partnerships and understanding between the City, State and landowner interests. In the end, the landowners were satisfied with the future commercial viability of the proposed paired-intersection design plan for the corridor.

4.0 ISOLATED AT-GRADE INTERSECTIONS

4.0 ISOLATED AT-GRADE INTERSECTIONS

The at-grade unconventional arterial intersection designs presented in this chapter are best suited for single, isolated intersections where major roadways cross, rather than the system wide design applications presented in the previous chapter. The designs presented in this chapter were developed to manage traffic flow and capacity at singular intersections, with less of a focus on operations along the arterial corridor.

4.1 CONTINUOUS FLOW INTERSECTION

4.1.1 Evolution of Design

The Continuous Flow Intersection (23) design (CFI), also known as the “Displaced Left Turn” and the “Enhanced At-Grade Intersection” (24) is a relatively new design in the US that has generated recent interest from highway agencies in several states, spurred by favorable research on current design operations. The CFI was awarded the AASHTO “Francis B. Francois Award” in 2002 in recognition of its contribution to transportation design innovation.

The first CFI in the US was opened in 1994 at a T-intersection entrance to a research center on the campus of Dowling College on Long Island, New York. A second T-intersection design – the first on a US state highway – opened in 2000 in Maryland. The design is being or has been considered at intersections in California, Arizona, Nevada, Mississippi, and Arkansas, as well as at other Maryland and New York locations. There are at least 15 CFI intersections constructed in Chile, Brazil, Mexico and England (there known as a Displaced *Right* Turn). To date, the CFI has generally been applied to four-leg intersections where there is interest in combining through and left signal phases on the arterial.

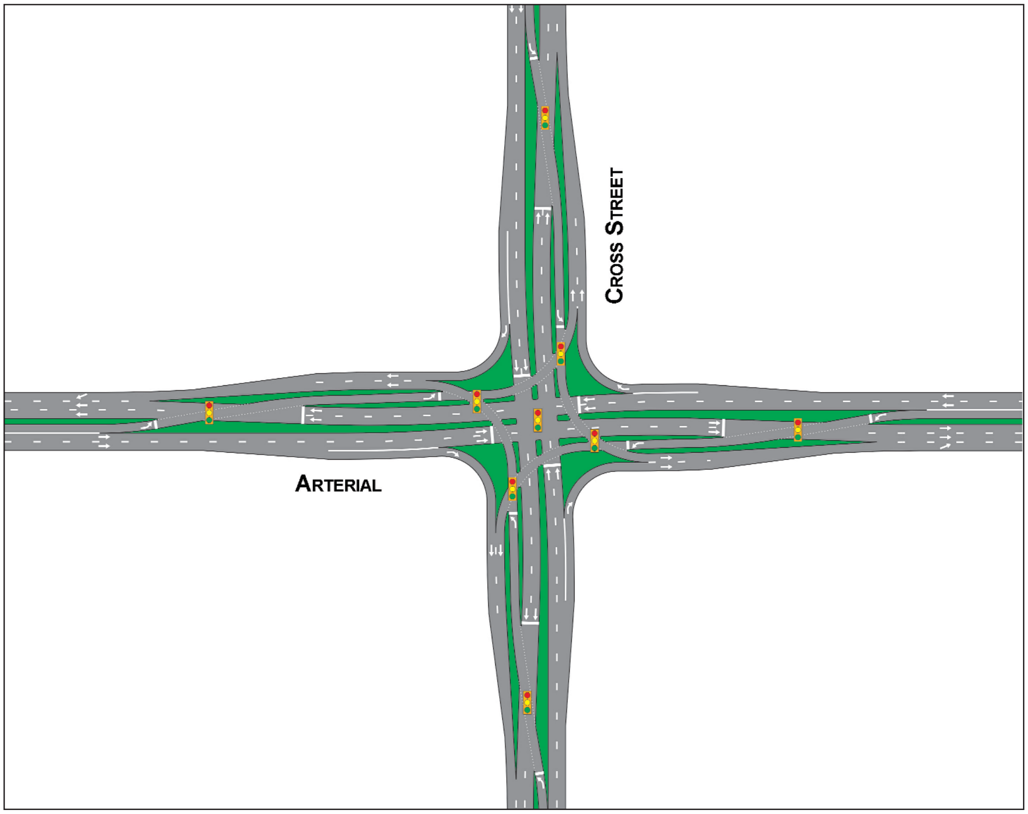
4.1.2 Description of Operations

The term “Continuous Flow” is a bit of a misnomer, as traffic is required to stop at signals at the intersection; however, the CFI design separates left-turn movements from conflicting through-movements, allowing opposing left-turns to be made at the same time as through-movements. Left-turning vehicles begin their turn several hundred feet prior to the main intersection. They are temporarily stored in a bay to the left of the opposing through lanes of travel, and complete the left turn movement under the same signal phase as the through-movement. At the main intersection, previously conflicting through- and left-turn movements can operate simultaneously as protected movements under the same signal phase. The signal cycle is thus reduced to two phases, enabling a reduction in overall cycle lengths and maximizing through-movement green times. The result is a reduction in travel delays and increased capacity at the intersection (25).

4.1.3 Design and Operational Considerations

At high-volume intersections, a signal at the crossover is needed to control left turn movement staging. This signal can be coordinated with the main intersection control so that arterial through-traffic stops no more than once. The CFI design also improves pedestrian efficiency and safety. Pedestrians can cross the intersection in two stages without left or right-turning conflicts. The shorter cycle lengths typical at a CFI intersection also shorten the pedestrian's wait for a walk phase.

Exhibit 26: Continuous Flow Intersection Design



Right turns are removed from conflicts near the intersection with ramps. U-Turns on the arterial are possible at the left-turn crossover if the median is wide enough; however, without U-Turn provisions, the arterial median may be narrow. The left-turn lane crosses the opposing traffic at an intersection approximately 300 feet in advance of the cross street. This distance is a balance between the costs of a longer storage area and the spillback potential from the main intersection.

4.1.4 Studies and Research

Several studies of the CFI designs compared travel times relative to a conventional intersection design and found great timesaving potential, particularly at high volume levels (23,26). A recent FHWA Research and Development study showed the considerable capacity improvement the CFI could have under certain operating conditions compared to the conventional intersection:

Exhibit 27: CFI vs. Conventional Intersections

	Conventional Intersection	CFI
Total Entering Flow (Veh/Hr)	10,000	14,000
Average Intersection Delay (Sec/Veh)	234.2	35.2
Intersection Level of Service	F	C
Average Movement Queue (ft)	594.6	71.1

Source: FHWA Research & Development and Virginia Tech Study Findings. The case study conventional intersection included three through-lanes, dual left-turn lanes and one right-turn lane per approach.

Advantages of the CFI design include fewer and separated movement conflicts, fewer signal phases (reduced to two) at the main intersection, a higher green time percentage for through- and left-turn movements, reduced and separated conflict points, and significantly lower construction costs and shorter construction time compared to an interchange design. Studies have also shown that the CFI can reduce delay for arterial traffic, reduce stops for through arterial traffic, and ease progression for arterial through-traffic.

The disadvantages of this alternative relative to conventional intersections include greater potential for driver and pedestrian confusion, increased stops for left turns from the arterial, restricted U-Turn possibilities, pedestrians must cross ramps and the main intersection (and pedestrians must cross the four-quadrant design in a slow three-stage maneuver), additional right-of-way required for ramps, additional construction, maintenance and operation costs for ramps and extra signals, and lack of access to the arterial for parcels next to ramps. If left turns from the arterial experience more delay than at comparable conventional intersections, the extra delay is likely to be small in magnitude.

When to Consider

Agencies should consider the CFI design where intersecting roadway volumes are high, with significant left-turn demand and low U-Turn demand. There must be available right-of-way at the intersection, and adjacent land parcels must be organized to allow restricted access near the intersection.

4.1.5 Lessons Learned

Several recent planning and design studies completed for state highway agencies have shown the cost savings of the CFI compared to various interchange alternatives. At the MD 210/MD 228 CFI intersection, design, right-of-way and construction costs of a flyover interchange design at that location were estimated at $30 million, while the CFI design was constructed for $5.3 million. The CFI design also minimized environmental and right-of-way impacts and had a much shorter construction duration compared to the flyover, thereby making the intersection available to motorists sooner with fewer construction-related interruptions.

There was initial concern that the CFI design at the MD 210/MD 228 intersection would be confusing to motorists; however, results of a Maryland State Office of Traffic and Safety study for the one-year period after opening of the MD 210/MD 228 application showed no intersec-

PROFILE: CONTINUOUS FLOW INTERSECTION

MD 210 AT MD 228 (PRINCE GEORGES COUNTY, MD)

The MD 228/MD 210 T-intersection opened in September 2000 as the first CFI application on a state highway. The design includes a triple left from MD 210 and a "CFI" movement on the perpendicular T-intersection MD 228 approach. Left turns from MD 228 enter the CFI turn bay while the triple left is red; then both left turn movements can occur simultaneously, reducing the intersection to a two-phase signal. MD 228 left-turn movements enter MD 210 from a left acceleration lane, so southbound MD 210 never has to stop. The CFI was found to be cheaper and less intrusive at this intersection compared to a proposed flyover design. Wetland and forest impacts were reduced by 70% compared to the flyover option. It was for this intersection design that the CFI received the *AASHTO 2002 Francis B. Francois award* for design innovation, as sponsored by the Maryland State Highway Agency. The application is considered successful, as no modifications to signing or marking have been needed.

Aerial by AirPhotoUSA, 2003.

tion accidents had occurred related to the CFI movements (25). Other initial concerns included: driver perception, right-turn traffic safety, proper signage, nighttime headlight confusion (beams facing between lanes), lighting, clearance times, sight distance and landscaping. When considered in the mid-1990s at an Orange County, California intersection, engineers felt that the intersection worked very well in theory but they had reservations about potential driver confusion from forcing motorists to make left turn movements several hundred feet prior to the main intersection (27). Though never implemented, engineers developed a plan of a number of signs and pavement markings to help motorists safely navigate the intersection.

Operational studies at the intersection have found that the CFI has reduced delays and operates at the level of service predicted in pre-design studies. Several field tests on CFI designs with two-lane approaches in Mexico showed approach volume capacities of 3,000 vph, and 600 to 800 vph for left turns. CFI intersections of two six-lane roadways were observed to process peak hour intersection volumes as high as 16,000 vph. Prior to design implementation, several of these intersections had vehicle delays of 7 to 10 cycle lengths (28).

4.2 CONTINUOUS GREEN "T"

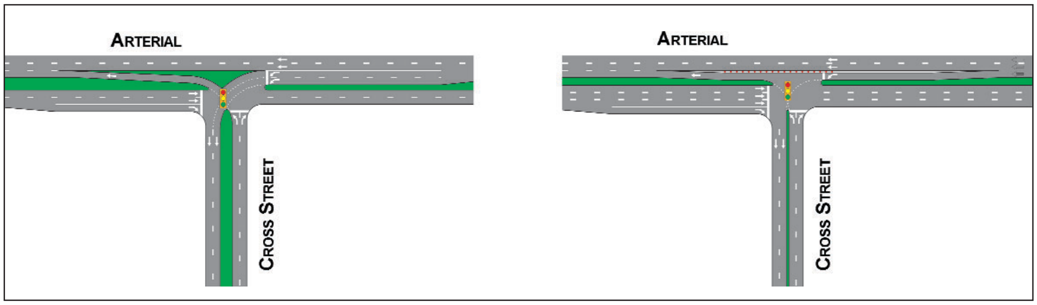
4.2.1 Evolution of Design

While most of the unconventional designs discussed in this monograph can be implemented at intersections with both three- and four-leg approaches, the Continuous Green T-intersection (CGT) design has potential application only at T-intersections. Of the states and other jurisdictions that have constructed CGT-intersections, the state of Florida appears to be the most prominent, with several districts of the Florida Department of Transportation having used the Continuous Green T-intersection (also known as a “Turbo-T” in south Florida) at many intersections for years, with no major apparent problems (29).

4.2.2 Description of Operations

The CGT-intersection is designed so that one direction of the main through-roadway does not have to stop. The design can be enhanced by using free-flow turn and acceleration lanes for right turn movements so that only three approach movements require signal control. There are two basic yet significant design variations on how the CGT-intersection allows one free-flow through-movement:

Exhibit 28: Continuous Green T-Intersection Design



(a) (b)

The two versions of the continuous flow intersection include: (a) merge-control: a free-flow left merge lane onto the arterial and (b) lane-control: an option lane with signal control to eliminate the need for left-turning traffic from the cross street to merge. In both cases, lanes in one direction of flow do not have to stop.

Merge-control Continuous Green T

Signal-controlled Continuous Green T

1. In the first design variation, all through-lanes in the direction on the opposite side of the arterial from the T-approach receive a constant green signal; left turns from the cross street merge onto the arterial from the median using a channelized left-turning movement. Because of the median merge lane, a slightly wider than typical 16-foot median is required on the arterial, at least near the throat of the intersection. The channelizing left-turn island should be positive; some agencies use curbs with pavement markings and reflectors. Due to the operations of the left merge on the arterial, arterials with higher through-volumes will benefit so long as left-turn volumes from the cross street are moderate or low to limit operational breakdowns at the merge point.
2. Under the second design variation, the through lanes in the direction on the opposite side of the arterial from the T-approach are controlled differently. The outside (right-shoulder) lanes receive a steady green signal. The median (inside) lane is separated from the outside lanes by a transitional taper and barrier and subject to signal control (of at least two and probably three phases) that also controls left-turn movements from the T-approach. The channelized separation should extend several hundred feet upstream and downstream from the intersection to minimize hazardous last-minute weaves. The arterial

should have a raised median of some type through the length of the channelized lane to stop vehicles from turning left to or from driveways on the opposite side of the roadway and thereby crossing the through-lane separation. This variation can process higher volumes of left turns onto the arterial, although at the expense of arterial through-traffic capacity and potential driver confusion.

4.2.3 Design and Operational Considerations

Because the CGT-intersection stops only one direction of travel, the intersection can be easily integrated into a progressive traffic control signal system. Arterial progression is more likely to be optimal (in the direction with signal control) when intersection demands for left turns to and from the T-approach are moderate to low.

The CGT-intersection design has applications in both urban and suburban settings, although both the merge- and lane-control design variations are not conducive to pedestrian crossings, as pedestrians would have to cross at least two lanes of moving traffic without the aid of a signal. All of the CGT sites mentioned in the survey responses did not attempt to include provisions for pedestrian crossings.

Right-of-way requirements for both CGT design variations are modest. A wider median is needed on the arterial in the merge-lane design to accommodate the merge and taper.

4.2.4 Studies and Research

Advantages of the CGT-intersection (compared to a conventional multiphase signalized T-intersection design) include significantly reduced delay and fewer stops for arterial through-traffic in at least one direction of travel. Disadvantages of the CGT-intersection include greater potential for driver and pedestrian confusion, lack of a protected (signalized) pedestrian crossing of the arterial, increased merging or weaving maneuvers, and restricted access to parcels adjacent to the arterial through-lanes.

When to Consider

The CGT-intersection has a fairly restricted application niche. Engineers should only consider the CGT at intersections with three approaches, moderate to low left-turn volumes from the cross street, high arterial through-volumes, and where there are few pedestrian crossings and no driveways along the arterial opposite the cross street.

4.2.5 Lessons Learned

Driveways along the continuous green through-lane(s) pose two potential problems. First, through-drivers in the continuous green lanes may not expect to slow for anything in those lanes, even a right-turning vehicle. Second, drivers turning left onto the arterial from the cross street may try to merge into the continuous green through-lane or pass through the lane separation to get to a driveway.

Under the lane-control design, motorists may be confused by the lane signal control and/or may attempt last-minute lane changes to avoid the signal control. The lane separation/channelization should be clearly delineated and identified by proper advance signage. Several studies have shown that at typical intersections on four-lane arterials in Florida, about 77 percent of drivers chose the continuous green lane, while on six-lane arterials about 81 percent of drivers chose one of the two continuous green lanes (29).

Exhibit 29: Stanchion Maintenance Needs at CGT-Intersection

The separation between the signal-controlled lane and the continuous green through-lane(s) can be narrow and should not present a hazardous fixed object; rather most agencies help identify the separation with raised reflectors or rumble strips. The Florida Department of Transportation has found that stanchions can be problematic for maintenance.

Agencies can use more than one continuous green through-lane, but dual left-turn lanes from the cross street require dual signal-controlled through-lanes on the top of the T, and would put great pressure on the remaining continuous green through lane(s).

4.3 MULTI-LANE ROUNDABOUTS

4.3.1 Evolution of Design

The US developed the first rotary traffic circle in 1904 at Columbus Circle in New York City. No right-of-way rules were established, and although an improvement over the previous intersection control, the circle would lock up under heavier volumes and required police control during peak hours. Several initially prominent US traffic circles were either replaced by interchanges or had signals added within the circle, and by the 1950s, Roundabouts had generally fallen out of favor in the US. At about that same time, British traffic engineers began evaluating Roundabout operations and the capacities of larger circles and found that Roundabouts had higher capacities when a "priority-to-the-circle" rule was applied. Roundabouts were then designed with smaller diameters and wider entry points, resulting in 10 to 50 percent increases in capacity.

Roundabouts were "exported" to Australia and France in the 1970s, and several decades of design and operational advancement, as well as user familiarity, have led many European cities to regularly adopt them as a viable alternative to the traditional signal-controlled intersection. France has become a leader in Roundabout implementations with over 15,000 current applications. Other prominent users include Australia, Switzerland, Germany, Spain, Portugal and, more recently, Israel, New Zealand and South Africa. Despite the proliferation of modern Roundabout designs abroad, they have only recently been implemented in the US. The first modern Roundabouts in the US were designed in Summerland (Las Vegas), Nevada in 1992, and others followed in Gainesville, Florida and Avon, Colorado.

Exhibit 30: Modern Multi-lane Roundabout, Kingston, NY

Photo by Howard McCulloch, NYSDOT, used by permission.

Growing interest in the Roundabout design has led to several useful publications on the topic, with perhaps the most inclusive reports being the National Cooperative Highway Research Program's Synthesis of Highway Practice 264 *Modern Roundabout Practice in the United States*, and the Federal Highway Administration publication, *Roundabouts: An Informational Guide*. Other useful US references include the guidelines developed by the Maryland State Highway Agency and the Florida Department of Transportation.

4.3.2 Description of Operations

Roundabouts are often confused with traffic circles from the first half of the 20th century, which are often viewed unfavorably, being cited for congestion, higher accident rates and poor entry conditions. The differences between modern Roundabouts and traffic circles are outlined below:

Traffic Circles	Modern Roundabouts
Circle diameter determined by space available and number of approaches	Roundabout diameter is calculated based on traffic volumes, generally between 75 to 150 feet in diameter
Approaches generally designed to permit a high-speed entry merge into the circle	Approaches are flared and deflected around the central island; movement entry speeds are limited to 10-20 mph by geometry
Large circle diameter allows higher operating speeds (up to 50 mph) that can cause unsafe entering and exiting weaving movements	Entering vehicles must yield to circulating vehicles; smaller diameter provides a low-speed environment (20-25 mph)
Roundabout flows can break down at higher volumes	Queuing on approaches may result at higher volume but central Roundabout movement will not break down

Currently there are multilane Roundabouts in nine states across the US. Prominent multilane examples include the RT 1/ RT 19/Los Coyotes Roundabout in Long Beach, California, which opened in 1993, has an inscribed diameter of 470 feet, and peak hour approach volumes of 4,700 vph. There are eight known multi-lane designs on US roadways that have daily traffic volumes in excess of 20,000 vpd and carry peak hour flows in excess of 2,500 vph. Some multi-lane Roundabouts in England carry more than 6,000 vph (30). Multi-lane Roundabouts can have capacities upward of 40,000 to 50,000 vpd (31).

4.3.3 Design and Operational Considerations

Roundabouts have been successful in Europe for several reasons, including the design's high capacity and fluidity, improved intersection safety, shorter delays and reduced environmental impacts.

Proper signing and marking on the approaches are essential in helping motorists identify and navigate Roundabouts. In US designs, most multi-lane Roundabouts do not use lane markings to identify separate circulatory lanes within the Roundabout. Exceptions include the above Kingston, NY design (Exhibit 30), where central lane striping was included to help manage the higher than normal levels of truck traffic.

Multi-lane Roundabouts have greater circulatory speeds and higher traffic volumes compared to single-lane Roundabouts that can make them less inviting for pedestrian crossings. Vehicle speeds are a primary factor in the comfort and safety of pedestrians and bicyclists. According to the Americans with Disabilities Act (ADA), issues relating to visually impaired pedestrians must be addressed satisfactorily in the Roundabout design process, or the intersection may be excluded from consideration in areas with high pedestrian traffic.

Exhibit 31: Examples of Modern Roundabout Signing

Golden, Colorado Roundabout photo (right) by Bill Baranowski; used by permission.

4.3.4 Studies and Research

Many studies have found that one of the major benefits of Roundabout applications is the improvement in overall safety performance, particularly in reducing the incidence of the severest of intersection crashes, and the number of injuries and fatalities experienced. Crash frequency reductions are most pronounced for vehicles and less pronounced for pedestrians. Reasons for the reduced number and severity of accidents at modern Roundabout applications include:

- 75 percent fewer vehicle conflict points compared to a conventional intersection design
- Physical guidance and separation of the various movements
- Lower and consistent speeds traversing the Roundabout
- Pedestrians cross only one direction of travel at a time

Roundabouts replace the most severe vehicle crossing conflicts with less severe merging conflicts. Multi-lane Roundabouts introduce additional conflicts not present in single-lane Roundabouts, as drivers may use the incorrect lane or make improper turns. A study of three multi-lane Roundabouts that were converted from conventional intersections showed the following reductions in crashes:

Exhibit 32: US Multi-lane Roundabout Conversions Crash Study (3 Sites)

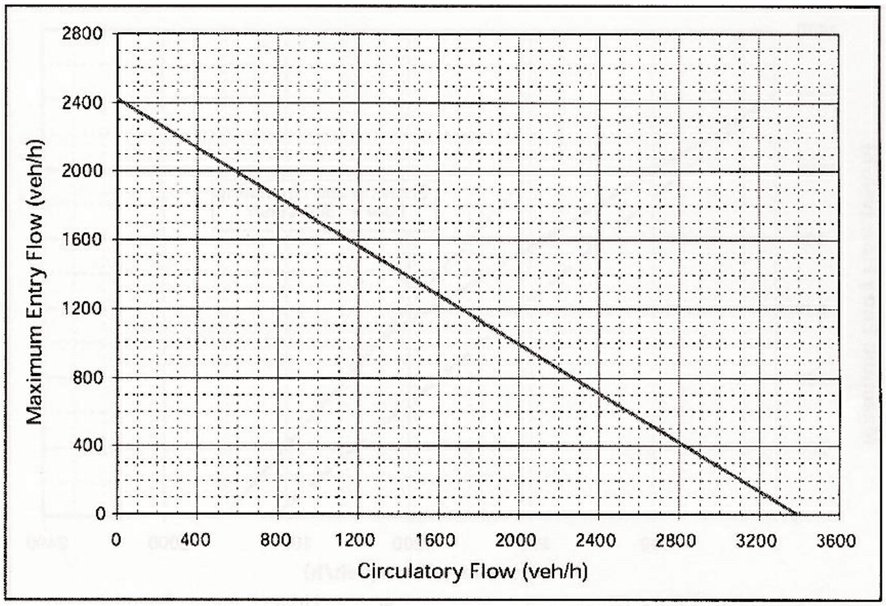
	Accident Rates per 100 million Vehicle Miles Traveled		
	Total Accidents	**Accidents with Injuries and/or Fatalities**	**Accidents with Property Damage Only**
Before Roundabout	21.5	5.8	15.7
After Roundabout	15.3	4.0	11.3
Change	-29%	-31%	-10%

Source: Adapted from FHWA Roundabouts: An Informational Guide.

The study also collected before-and-after crash statistics for 11 Roundabouts in the US, three of which were larger, multi-lane Roundabouts with diameters greater than 120 feet. Total crashes at these 11 intersections were reduced by an average of 37 percent, and injury crashes were reduced by 51 percent.

Another benefit of dual-lane Roundabouts is their higher intersection capacity. **Exhibit 33** shows the approach capacity of a double-lane Roundabout with an inscribed diameter between 130 and 200 feet, based on studies of British Roundabout applications. Modern Roundabouts with larger inscribed diameters can have slightly greater capacities than Roundabouts with smaller diameters. Capacities of individual Roundabout exits have been estimated at 1,400 vph for Roundabouts of this size. Any approach with an anticipated exit volume approaching this capacity should consider a dual-lane exit.

Exhibit 33: Capacity of a Double-Lane Roundabout Approach



Source: Roundabouts: An Informational Guide, Federal Highway Administration.

Roundabouts can produce operational improvements in locations where the space available for queuing is limited. Roads are often widened to create storage for vehicles waiting at red lights, but the reduced delays and continuous flows at Roundabouts may allow the use of fewer lanes near intersections.

Exhibit 34: Non-Circular Modern Roundabout

Roundabout principles can be applied to non-circular shapes; this is particularly useful for intersections with eccentrically arranged approaches.

When to Consider

Appropriate locations for Roundabouts include locations where there is insufficient room for adequate queue storage, such as at interchanges or at entrances to bridges and tunnels. Other potential candidates include intersections with high accident rates, particularly accidents involving cross street through- and/or left-turn movements. Poor candidates include intersections of roads with unequal volumes, which would give a disproportionate advantage to the low-volume approaches.

Exhibit 35: Roundabout Advantages/Disadvantages

Category	Advantages	Disadvantages
Safety	• Reduced number of conflict points compared to signal-controlled intersection. • Lower operational speeds, resulting from intersection geometry, yield fewer and less severe accidents.	• Since Roundabouts are unfamiliar to the average driver in the US, there is likely to be an initial period where accidents increase. • Signalized intersections can preempt control for emergency vehicles.
Capacity	• Traffic yields rather than stops, often resulting in the acceptance of smaller gaps. • For isolated intersections, Roundabouts should have higher capacity per lane than signalized intersections due to the omission of lost time (red and yellow) at signalized intersections.	• When a coordinated signal network can be used, a signalized intersection will increase the overall capacity of the network. • Signals may be preferred at intersections that periodically operate at higher than designed capacities.
Delay	• Overall delay will probably be less than for an equivalent-volume signalized intersection (this does not equate to a higher level of service). • During off-peak, signalized intersections with no retiming produce unnecessary delays to stopped traffic when gaps on the other flow are available.	• Drivers may not like the delays resulting from geometries that force them to divert their cars from straight paths. • When queuing develops, entering drivers tend to force into the circulating streams with shorter gaps; this may increase the delays on other legs, as well as the number of accidents.
Cost	• In general, less right-of-way is required. • Maintenance includes landscaping, illumination, and occasional sign replacement.	• Construction costs may be higher. • In some locations, Roundabouts may require more illumination, thus increasing costs.
Peds and Bicyclists	• A splitter island (see Exhibit 30) provides a refuge for pedestrians that will increase safety. • Low speeds reduce frequency and severity of pedestrian-vehicle accidents.	• Difficult for visually impaired pedestrians. • No stopped phase for pedestrians who want security of a signal. • Longer paths increase travel distances for both pedestrians and bicyclists.

4.3.5 Lessons Learned

Opinion surveys in US cities that have installed Roundabouts have shown 80- to 90-percent approval ratings (32). The same opinion polls taken before construction of a Roundabout design showed much greater uncertainty and a lesser public support of the design, indicating that many of the initial fears regarding Roundabouts are overstated.

In a survey of US departments of transportation, the main reasons highway agencies considered and/or constructed Roundabouts included greater safety, shorter delays, lower costs and improved aesthetics/urban design; once constructed, the greatest benefits realized were shorter delays, increased capacity, improved safety and improved aesthetics. Reasons given for not building Roundabouts included uncertainty that drivers could adjust, and questions about operations and safety (33). Problems encountered at existing Roundabout locations that should be evaluated in new Roundabout design processes have included increased maintenance costs for the central island (additional or difficult snow removal, additional sign costs, and the need to do maintenance at night), lack of signalized pedestrian crossings, larger vehicles running over central islands, and how to locate driveways near Roundabout entrances.

Though a thorough investigation of design and construction costs has not been undertaken, a sampling of dual-lane Roundabouts on state highways has shown a cost range of $350,000 to $500,000 per installation (excluding right-of-way), varying with size, drainage and landscaping costs (34).

4.4 SPLIT INTERSECTION

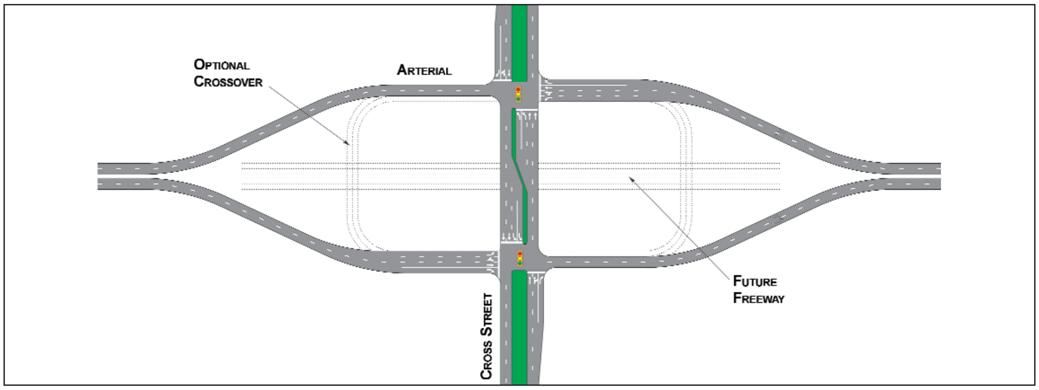
4.4.1 Evolution of Design

The first known application of the Split Intersection concept is in Tel Aviv, Israel, converted from a conventional intersection design in 1975. The design proved to be successful, providing greater intersection capacities than expected, and postponed the construction of a complete grade-separated design at this location (35). Several other Split Intersections have been constructed in Israel and were later converted to diamond at-grade intersections. Other than use as a temporary measure during interchange construction, there is no known application in the US. A recent study in Naples, Florida, identified the split intersection as the best unconventional at-grade design alternative to a controversial $32 million arterial interchange design.

4.4.2 Description of Operations

The Split Intersection separates traffic flow on the main line into offset one-way roadways with two intersections with the cross street, separated by 200 to 300 feet. The concept is similar to a Diamond interchange, yet without having to grade-separate the roadways. The two intersections are controlled by coordinated signals and each intersection is reduced to three signal phases. The separation of roadways and reduced and coordinated signal phasing can provide greater efficiency and higher capacity compared to the conventional intersection design (36). The design can be modified to include indirect left-turn movements using directional U-Turn crossovers, which eliminates the need for storage lanes on the cross street and further reduces the signal phases to two.

Exhibit 36: Split Intersection Design Concept



4.4.3 Design and Operational Considerations

Considerations for a successful Split Intersection design include:

- The distance between intersections must be sufficient to store all left-turning vehicles to avoid potential spillbacks on the cross street and locking through and turning movements.
- It is preferable that the signals at the two intersections be controlled by a single controller to avoid the operational inefficiencies that would occur should the coordination of individual signals' timing fail.
- The Split Intersection requires more right-of-way than most other unconventional intersection designs, and the design's greatest impacts are closest to the intersection, where right-of-way may be more difficult to acquire under a design retrofit scenario.

4.4.4 Studies and Research

Bared and Kaisar (36) and Polus and Cohen (37) have each conducted a series of simulations comparing Split Intersections to conventional designs. Their results show that the Split Intersection has great efficiency potential with delay reductions of 40 and 60 percent under certain high-volume scenarios. Both studies attribute operational timesavings to the reduction in signal phases that yield greater arterial green time and shorter cycle lengths.

While no accident studies are available, there is no reason to assume that the intersections would reduce safety compared to the conventional (grade-separated) Diamond interchange. Further, the separation of conflict points should result in fewer collisions compared to conventional intersections. Left turns from the arterial to the cross street are without opposing movements. Pedestrians have an additional intersection to cross but each intersection crossing is narrower, has fewer opposing vehicle conflicts, and potentially shorter cycle lengths. Noted disadvantages of the Split Intersection design include high initial cost to construct, greater right-of-way needs, confusion for unfamiliar drivers, and the possibility of multiple stops and operational breakdowns if the signals are not properly coordinated.

When to Consider

The Split Intersection is best suited for isolated and congested suburban intersections with mid to high levels of left turn movements. Split Intersections show the greatest benefit at isolated intersections where the total intersection volume is greater than 4,000 vph with mid to high levels of left-turning traffic. The design is most compatible in an arterial system that provides progression and can interconnect with the two Split Intersection signals. The design can be particularly attractive where the creation of a grade-separated Diamond interchange is either planned or under consideration. The design is also possible in an urban setting where parallel streets with adequate available offset can be converted to one-way traffic.

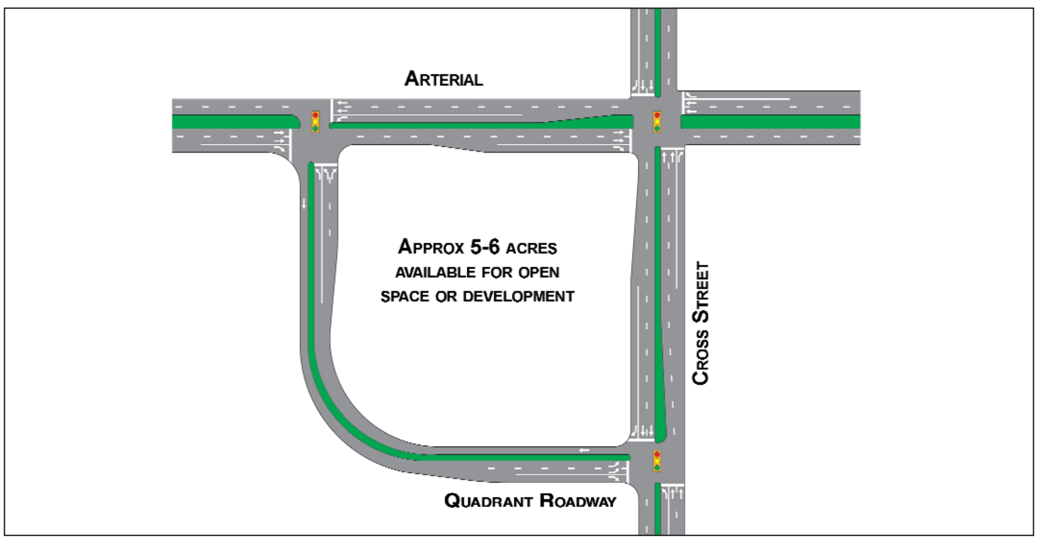
4.5 OTHER UNCONVENTIONAL INTERSECTION DESIGN CONCEPTS

4.5.1 Quadrant Roadway Intersection

The Quadrant Roadway Intersection (QRI) is a relatively new unconventional intersection design concept that was first published in the Institute of Transportation Engineers Journal June 2000 issue (Vol. 70, No. 6). Several inquires have been made about the QRI design (Georgia, Illinois, and Washington State) and other agencies responded having designs similar to the QRI; however, no agency has fully and intentionally implemented the QRI design and operations plan. Some agencies have intersections where a quadrant or similar roadways are used and some turning movements prohibited, but none in conjunction with a signal phase reduction at the main intersection.

The concept for the QRI design is similar to the single-quadrant ramp interchange (described in the AASHTO handbook and in a later section), and the design features are based on concepts from other unconventional designs currently employed throughout the US. The QRI design removes left-turn movements from main arterial/cross street intersections by using an additional roadway (called the quadrant roadway) in one intersection quadrant. Left-turn movements are routed from the arterial and cross streets onto the quadrant roadway to complete the left turn movement at one of the two quadrant roadway T-intersections.

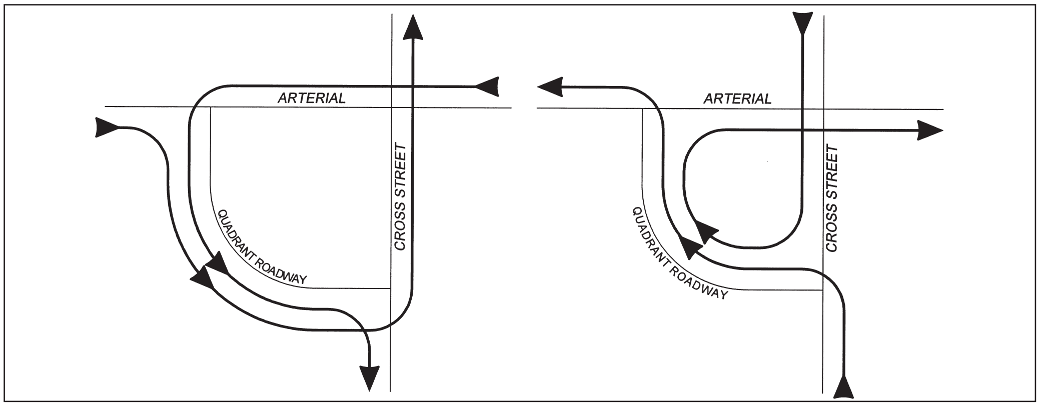
Exhibit 37: Quadrant Roadway Intersection Concept



Note: While the concept illustration shows the quadrant roadway to be in the southwest intersection quadrant, the roadway can be effectively located within any quadrant of the intersection.

Because each directional left-turn movement pattern is different, additional advance signing is needed. This is an added cost consideration but not necessarily a design disadvantage. All left turn movements exist in various designs currently in use in the US, and signing has been designed specifically for unconventional left-turns. Over time, motorists have become familiar with both the geometric design and the advance signing for unconventional left-turn design applications. In addition, design modifications can be made to consider missed left-turn opportunities, such as additional Median U-Turns beyond the main intersection.

Exhibit 38: Quadrant Roadway Intersection Left-Turning Patterns



From Arterial *From Cross Street*

There are several important design and operations considerations needed for successful QRI implementation:

- The spacing of the quadrant roadway intersections from the main intersection is a trade-off between left-turn travel distances versus available storage for the left-turn from the arterial. This dilemma is similar to locating crossover locations in the Median U-Turn design. It is recommended that the quadrant roadway be spaced 500 to 600 feet from the main intersection, similar to AASHTO recommendation for Median U-Turn crossovers (2).
- The area encircled by the quadrant roadway (approximately 5.5 acres assuming 500-foot intersection spacing) can be used to serve a small development within it, or alternatively be left undeveloped to minimize the impact of development traffic at the intersection.
- The QRI design requires that all three signalized intersections be coordinated to serve as one interconnected, fixed-time, intersection-control system. The main intersection operates under a simple, two-phase signal control, while the secondary intersections require three signal phases; however, the offsets to the secondary intersections are programmed to provide perfect progression through the main intersection, thus not impacting arterial through-movements. Therefore, the system operates as if all signals are two-phase.
- A fourth leg must not be developed at either of the quadrant roadway T-intersections to preserve the operations of the coordinated signal system.
- Left turns from driveways between the intersections should be restricted (possibly by raised median sections) to preserve left-turn storage for the main intersection approaches.
- The quadrant roadway should be at least three lanes wide to allow dual left-turn storage at the termini, and to provide a middle-lane refuge for turns to and from driveways along the quadrant roadway.

Studies of the QRI design showed improved intersection stopped delay and travel time, significant reductions in vehicle queuing, and improved total system travel times compared to a conventional arterial intersection design (38,15). As there is no known QRI application built, the operations studies were based solely on computer simulation analysis results with assumed driver behavioral characteristics. Impacts of driver expectation must certainly be considered in any field application.

Noted advantages of the QRI design compared to conventional design include reduced signal phases at the main intersection, the creation of conditions for improved arterial and cross street progression, significant decreases in stop delay and vehicle queuing, fewer and more-separated conflict points, and narrower intersection width requirements. Disadvantages include greater potential for driver confusion and driver disregard of the left-turn prohibition at the main intersection, increased travel distances for left-turning traffic, potential increases in stops and delay for left-turning traffic, and non-conformity of left-turning patterns and advance signing requirements.

The greatest timesavings and operational benefits of the QRI design were observed where arterial through-movements were proportionately high, with moderate or low left-turn volumes and cross street volumes. If the left-turn volume is high, the time and distance penalties incurred by the left turns and the increased spillback potential may outweigh through-vehicle timesavings.

4.5.2 Bowtie

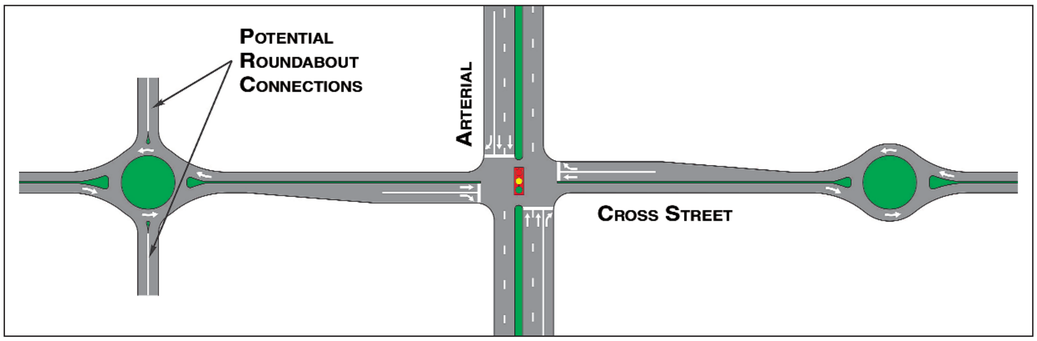
The Bowtie intersection was inspired by the raindrop interchange concept popular in England. The concept is also similar to the Median U-Turn design with directional crossovers on the cross street. Several state agencies are experimenting with roundabouts on cross streets, several that include turning prohibitions, but as of yet no agency has constructed a full Bowtie design. Joseph Hummer, a professor at North Carolina State University in Raleigh, and graduate student Jonathan Boone first conceived of the Bowtie design in a 1992 research report and published a paper in a Transportation Research Record in 1995 detailing the concept and a simulation analysis (11). This and other subsequent studies, including simulation analyses of the Bowtie, have found the design can have modest travel timesavings over conventional intersections for some volume combinations (15).

The Bowtie design was developed to overcome the wider arterial right-of-way requirements of many other unconventional intersection design alternatives. The Bowtie uses roundabouts on the cross street to accommodate left turns, instead of directional crossovers across a wide median. Left turns are prohibited at the main intersection, and the main intersection signal is reduced to a simple two-phase operation. As in most modern roundabout designs, vehicles yield upon entry to the roundabout; however, if the roundabout has only two entrances (as illustrated in **Exhibit 39**), the entry from the main intersection does not have to yield.

As per modern roundabout standards, the Bowtie roundabouts may have diameters between 90 and 300 feet, depending on speed, volume, number of approaches and the design vehicle. The distance from the roundabout to the main intersection may vary from 200 to 600 feet, with trade-offs between spillback potential and travel distance for left-turning vehicles. Because the roundabouts are on the cross street, the arterial may have a narrow median or none at all. Other Bowtie design considerations include:

- The U-Turn movement is difficult, having to travel through both roundabouts and back through the main intersection. Mid-block left turns are therefore recommended along the arterial.
- A T-intersection version of the Bowtie is possible but it would likely be inferior to a three-legged Median U-Turn or Jughandle unless a fourth intersection leg was planned.
- The distances between the roundabouts and downstream signalized intersections should be great enough that potential queuing at the roundabout approaches does not spill back to the signalized intersection.

Exhibit 39: Bowtie Intersection Concept



The advantages of the Bowtie relative to the conventional multiphase signalized intersection include reduced delay for arterial through-traffic, reduced stops for arterial through-traffic, easier progression for arterial through-traffic, fewer threats to crossing pedestrians, and reduced and separated conflict points. The disadvantages of the alternative relative to conventional intersections include greater potential for driver confusion and driver disregard for the left-turn prohibition at the main intersection, increased delay for left-turning traffic and possibly cross street through-traffic, increased travel distances for left-turning traffic, increased stops for left-turning and cross street through-traffic, additional right-of-way needed for the roundabouts, and more circuitous arterial U-Turns.

While no state agency has direct experience with the Bowtie design, survey responses from state agencies that implement modern roundabout designs indicated expectations that the Bowtie roundabouts should see similar accident reductions (particularly of severe accident types) as experienced at constructed modern roundabouts. However, the Bowtie presents additional driver expectation issues beyond the presence of roundabouts because of turn movement prohibitions and route guidance.

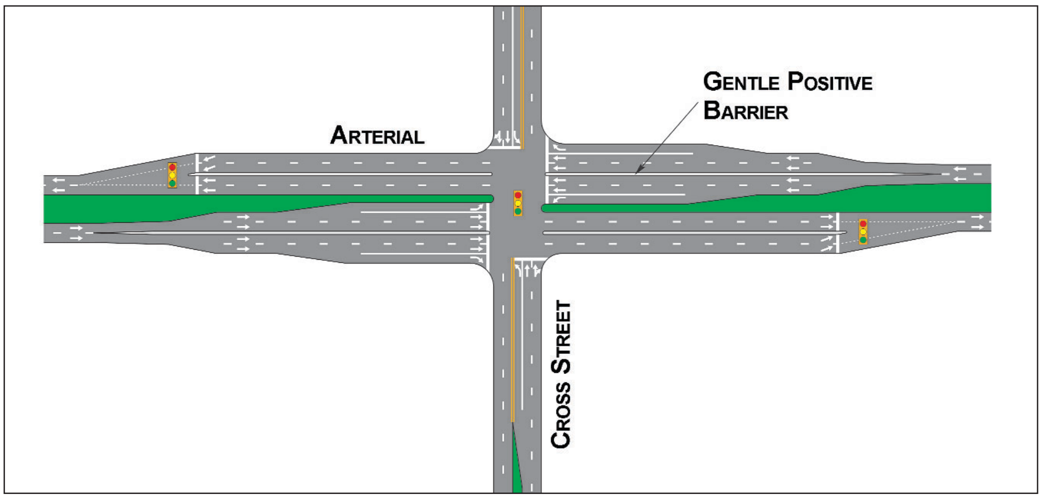
Good candidates for Bowtie designs include arterials with narrow or non-existent medians and/or no prospects for obtaining additional right-of-way for widening. Agencies may consider the Bowtie alternative where generally high arterial through-volumes conflict with moderate to low cross street through and left-turn volumes. If the left-turn volume is proportionately high, the extra left turn travel distance and potential spillback may outweigh the benefits (or timesavings) for arterial through-traffic. If cross street through-traffic is high, delays caused by the roundabout may also counteract benefits/timesavings for arterial through-traffic. Roundabouts are not typically used directly on multilane arterials, so the Bowtie design is not recommended at intersections of two multilane arterials. The design should also not be considered if it is anticipated that the cross street will be expanded to a multi-lane facility.

4.5.3 Double-Wide

Joseph Hummer proposed another new unconventional intersection design in January 2000 called a "Double-Wide" intersection (39). The concept behind the Double-Wide is twofold: the design adds extra lanes near the intersection to move as many vehicles as possible through the intersection along the arterial during the green phase. The design also attempts to fill the gaps between the vehicle platoons created by intersection signals, by controlling merging downstream of the intersection. The design takes maximum advantage of extra lanes near the intersection so that the need for widening the entire arterial can possibly be avoided or postponed.

The Double-Wide intersection separates each direction of an arterial into two separate "barrels" upstream of a signalized intersection. The arterial lanes are split using a transitional taper and barrier (similar to the Continuous Green T-intersection), and an additional through-lane and turning lane is developed on each side of the barrier to "double" the arterial through-movement through the intersection. At some distance downstream of the intersection, a simple two-phase signal (coordinated with the main intersection to provide some progression) is installed to "meter" the two sets of lanes back into the original number of arterial through-lanes, thereby avoiding unsafe merging conditions. The second signal is an important part of the Double-Wide design as it allows the greater number of lanes to be merged without requiring longer taper lanes along the arterial. The placement of this signal should be sufficient to store traffic from a single green through-phase without spillback into the intersection.

Exhibit 40: Double-Wide Intersection Concept



As the design is newly proposed, there are still many possibilities to explore how the intersection is operated. In general, at least some of the through-vehicles should progress through both signals. It is not required that both signals operate at the same cycle length; in fact the second signal may operate best at a half-cycle length. The signals should also be alternated to prevent motorists from trying to anticipate which barrel would receive the green phase at the second signal sooner.

A simulation study showed that the Double-Wide intersection has the potential to significantly increase capacity and reduce delay compared to a conventional intersection at high volume levels (40). The study also compared the Double-Wide to designs that included additional lanes that were dropped at merges downstream of the intersection and found the Double-Wide had higher capacities and competitive or superior travel times at high volume levels. A Double-Wide with a single left-turn and no exclusive right-turn lane was shown to be nearly as efficient as a conventional intersection with dual left and exclusive right lanes under the same volume conditions.

The Double-Wide design is an extension of the “narrow-road-wide-node” concept used in many states in which the arterial adds an additional outside lane beginning approximately 500 feet prior to a major intersection. That lane is typically a shared right-turn and through lane, and serves development parcels prior to and after the intersection. While the additional lane provides some additional capacity as well as a refuge for right-turning vehicles, it does not provide nearly the full lane capacity that the Double-Wide can provide in a much shorter segment of the arterial.

A noted disadvantage of the design is potential motorist confusion that could lead to driver error, including: motorists not expecting the second signal or queue, last-minute weaving maneuvers upstream of the beginning of the barrier, and turning movements onto the arterial encountering an additional obstacle. These disadvantages are similar to those of other unconventional designs in use today, and therefore are not by themselves serious enough to eliminate consideration of the design. Another disadvantage of the design is the restriction of access to adjacent land uses introduced by the barrier for some distance on either side of the intersection. Lastly, the additional width of the extra lanes and barrier will increase the yellow clearance times needed for the cross street movements.

The Double-Wide has the most significant reductions in delays at the highest volume levels (greater than 3,000 vph) on the arterial, and would be best applied on an arterial with moderate to low turn movements, and where the ability exists to restrict driveway access for some distance on either side of the main intersection.

Costs for constructing a Double-Wide design for an intersection in North Carolina were estimated around $2.6 million, including right-of-way costs. This compares very favorably to the $10 to $20 million cost for a typical Diamond and Single-Point Urban Diamond Interchange, respectively (40).

5.0 ARTERIAL GRADE-SEPARATED INTERSECTIONS

5.0 ARTERIAL GRADE-SEPARATED INTERSECTIONS

This section explores unconventional grade-separated intersection designs that may have advantages in urban and suburban arterial contexts. Several of these grade separation design concepts can only be applied to arterial intersections, as they contain no free-flow movements that are typical in traditional freeway-style interchanges.

Increasing traffic volumes on many US arterial and thoroughfare roadways have given engineers cause to consider grade separation of major intersecting roadways to provide sufficient capacity and reduce congestion on roadways otherwise under at-grade signal control. Grade-separated intersections are designed to elevate through-movements on one roadway over the crossing roadway. Ramps are used to handle turning movements, forming secondary, signalized or unsignalized intersections on one or both of the roadways.

There are several justifications for considering grade-separated intersections, including desired intersection capacity, concerns with safety, or favorable grades (41). Although grade separations are not common for arterial streets due to higher construction costs and right-of-way requirements, they may be the only method to provide sufficient capacity at certain high-volume intersection locations. When considering a grade-separated intersection of major (non-freeway) roadways in built-up urban and suburban areas, the engineer is confronted with several design considerations not necessarily present in typical freeway-type interchange designs. Grade-separated intersection designs must be far more sensitive to the land use adjacent to the surrounding roadway network. In built-up areas, there is typically insufficient room for expansive loop ramps. Further, land with frontage at the intersection of two busy thoroughfares can be particularly valuable to retail and commercial uses, because of both the ease of access and the visibility of such parcels. Driveway access to the thoroughfare roadways is therefore of great importance and the structure elevation and subsequent grade and distance to downstream access points should be minimized.

The Diamond interchange **(see Exhibit 41)** is by far the most common grade-separation design in the US because of its simple design. The Diamond interchange works well with low to moderate volumes on the cross street; however, the proximity of the two signals at either ramp termini (typically spaced 250-500 feet apart) can result in inadequate left-turn storage, and make progression on the cross street difficult in both directions. The full Cloverleaf interchange provides direct turning movements without stopping from all approaches but requires substantial right-of-way in all four intersection quadrants (rare in built-up urban and suburban corridors) and can cause congestion within the ramp weaving movements on both the arterial and the cross street. The Partial Cloverleaf (Parclo) interchange has been found to be one of the most efficient interchange designs (42); however, the Parclo interchange can also have high impacts to adjacent properties in at least two intersection quadrants and requires most movements to stop once.

Exhibit 41: Common Conventional (Freeway Style) Interchanges

Diamond Interchange *Cloverleaf Interchange* *Partial Cloverleaf (Parclo) Interchange*

It is possible that some free-flow movements of a conventional freeway-style interchange can overpower the next downstream, signalized intersection on the arterial. If the adjacent arterial signalized network cannot handle the discharge rates from the free-flow interchange movements, the project risks minimal improvements to the arterial at high capital construction costs. In this chapter, many of the unconventional grade separation designs incorporate the use of signals within the interchange to help “meter” traffic releases to downstream intersections. Unconventional grade-separation design elements for arterial streets may also be designed to a lower design speed than for conventional freeway-style interchanges and, therefore, design criteria can be lessened, including tighter loop ramp radii, yield control at ramp accesses, reduced lane widths, shorter weave areas, and use of signalization on the arterial.

5.1 ECHELON INTERCHANGE

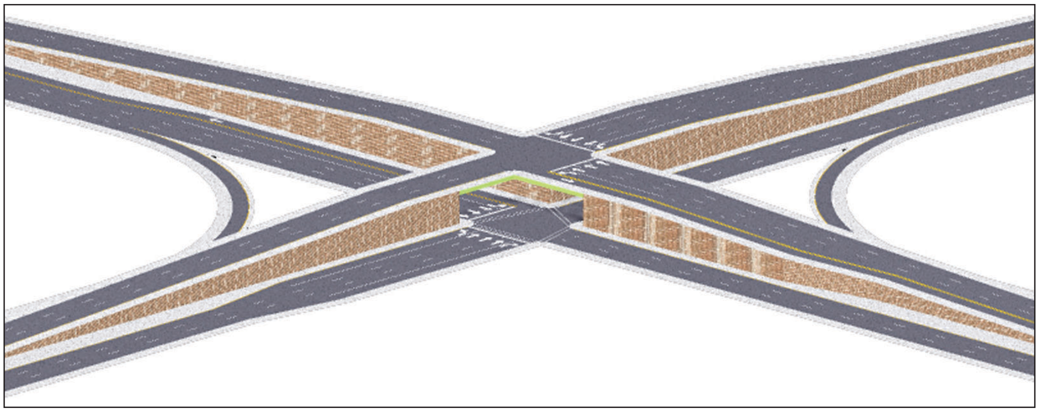
5.1.1 Evolution of Design

The Echelon design was born of necessity for a single intersection improvement project at US 1 and NE 203rd Street in Aventura, Florida. This South Florida design application opened in June 2000, and is currently the only known application in the world. Since its opening, at least one other state (Washington State) has considered the Echelon as a viable design in planning studies. The Echelon Interchange was so named by the late Don Beccasio of the Florida Department of Transportation’s Planning Division, who worked on this initial design application. The design’s feature of one intersection offset and over another reminded him of the US Navy Flight Demonstration Team’s “Echelon” formation, where each plane flies offset and over one another.

5.1.2 Description of Operations

The Echelon interchange has specific application to arterial roadways. The design is unique in that there are no through or turning free-flow movements. Thus this interchange would not be suitable for a freeway facility. The Echelon interchange is a simple concept that uses retaining wall structures to elevate two of the intersection approaches while the other two approaches intersect at-grade. The result is a symmetrical but offset pair of two-phase intersections separated by grade.

Exhibit 42: Echelon Interchange Concept



All intersection approaches essentially become one-way streets and their intersections can be controlled by simple two-phase signals. The signals can operate under different cycle lengths and phase timings. The Echelon design is most appropriate in an urban or suburban arterial roadway network, as the Echelon can "meter" intersecting traffic by controlling all four approaches by signal, yet is rarely itself saturated before its counterpart four-phase signals downstream (43).

5.1.3 Design and Operational Considerations

The Echelon design provides great flexibility for engineers and designers, as any combination of approach lanes and/or ramps can be placed at-grade or elevated, depending on volume forecasts, right-of-way constraints and/or intersection geometric features (such as a rail crossing or intersection skew). The engineer, therefore, can organize adjacent land uses relative to their need for access to the at-grade roadways. Access severances on the arterial and cross street are created on only half of the intersection approaches. The introduction of U-turns on the at-grade roadways can help mitigate the loss of directional access to adjacent land parcels.

Exhibit 43: Sidewalks Through Aventura Echelon Interchange

The design provides logical movements from each approach and requires little advance signing. Motorists experience the same decision processes as at an intersection of two one-way streets. The grade of the approach ramps has significant bearing on the length of the ramps and limitations to adjacent land parcels. It is recommended that the approach grades be on the order of five to six percent to balance the cost and impact of access with the steepness of the approaches and vertical crest sight distances at the elevated intersection. The provision of U-turns on the at-grade intersection will make the bridge span(s) longer.

The Echelon design is fairly pedestrian friendly, as all pedestrian movements can be made directly at the at-grade intersection, which operates under two-phase signal control. Pedestrians are typically not provided for on the structure. Pedestrian movements can be accommodated underneath and through the structure. Direct vehicular at-grade access to adjacent land uses is provided in two of the four quadrants.

5.1.4 Studies and Research

In a study comparing operations of the Echelon versus the Compressed Diamond and single-point urban interchange (SPUI) designs (using Traf-Netsim), the Echelon was able to process the most vehicles and had no failing LOS, while the Compressed Diamond had two failing LOS approaches under the same volume conditions, and the SPUI had three (43). Another study showed the capacity and delays at the Echelon to be competitive with conventional freeway-style interchanges, and found that bottlenecks were not transferred to the downstream intersection in a signalized network. A Florida consulting firm compared costs and operations for several interchange alternatives, illustrating the Echelon operational competitiveness with more traditional interchange designs at a reduced cost:

Exhibit 44: Interchange Cost and Operations Comparative

(US 1 at Port Lucie Boulevard, Port St. Lucie, Florida)

Scenario	Intersection Volume	Delay (avg sec/veh)	LOS	Cost Estimate
No Build	6,516	109.1	F	-
NB Triple Lefts	8,416	54.2	E	$700K
SPUI	8,756	17.0	C	$11.1 M
NB Left Flyover	8,902	19.4	C	$5.6 M
CG-T Interchange	8,707	22.5	C	$4.7 M
Echelon	8,617	8.6	B	$8.4 M

Source: Miller Consulting, Inc., 2001.

While there is only one case to study over a short time period, some assumptions on safety aspects of the design can be made. The presence of fixed roadside objects and left merges onto the arterial are of some concern, but the simplification of motorist decision points will most likely provide a good overall safety record at this type of interchange.

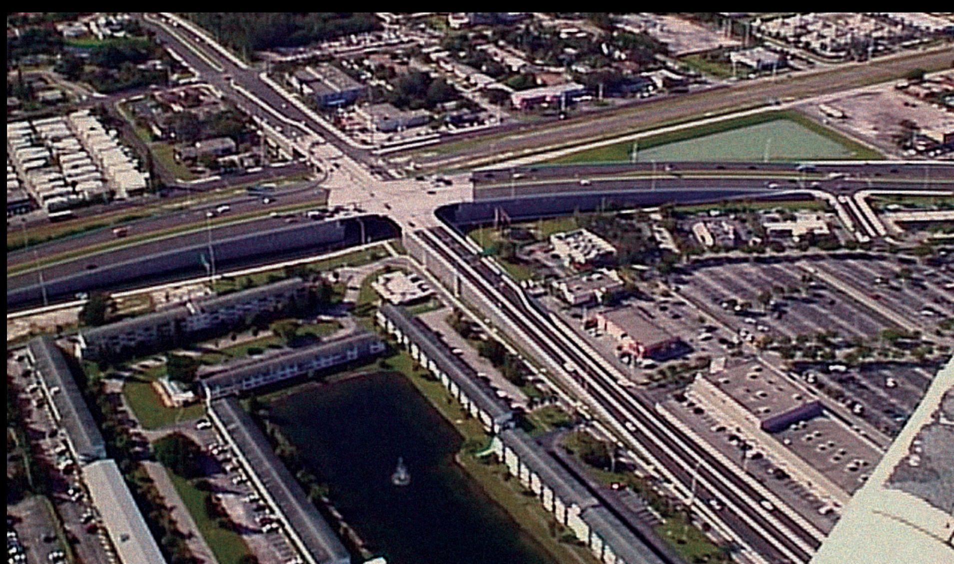
When to Consider

The Echelon design is most appropriate at high-volume intersections located within a signalized network. It is also worth considering where an interchange is desired in an urban or suburban location where right-of-way is limited and/or expansive loop roadways are impractical. The Echelon interchange has the greatest overall operations benefits where the arterial and cross street volumes are similar. At locations where the cross street volumes are low to moderate, a design that does not require the arterial to stop may provide superior operations.

PROFILE: ECHELON INTERCHANGE

US 1 at NE 203rd Street (Aventura, FL)

This "Modified" Echelon Interchange, as seen from an aerial view (top), was constructed at the intersection of US 1 and NE 203rd Street in Aventura, FL. This interchange elevates three of the four approaches, modified from the concept of elevating alternating (two) approaches. The raised eastbound approach ramp, which crosses over an active rail line, is pictured from both the lower terminus (bottom left) and from atop the structure (bottom right). The design is a first of its kind in the US and opened to traffic in June 2000. The design was developed after ten years of failed interchange planning studies, and received the support of the local community. This interchange design won a "Grand Award" from the Florida Institute of Consulting Engineers (FICE) for engineering excellence.



5.1.5 Lessons Learned

Prior to the opening of the Echelon Interchange, the intersection of US 1 and NE 203rd Street regularly experienced 1- to 2-mile peak period back-ups. To complicate the design selection process, designers had to consider impacts of a school in one intersection quadrant, and a major freight railroad crossing the western leg of the intersection. Over a 10-year period, over 35 different designs were proposed to alleviate congestion at this intersection – all of which were rejected by City council and community groups (most being freeway-style interchange designs). The Northeast Transportation Corridor Team, charged with oversight of this intersection improvement project, called for a design solution that would provide, at a minimum, LOS E conditions, including the impacts of two trains crossing per hour. Several of the earlier interchange design proposals achieved LOS E without considering the rail crossing impacts, but failed miserably when the crossings were taken into account. The presence of the railroad also forced any structure design to have a greater clearance height (21 feet, nearly 5 feet higher than a standard highway clearance) and the vertical curve had to crest west of the intersection to clear the railroad. These factors combined to make this particular application both larger and more expensive than a typical Echelon design application.

Three major community forces (including a condominium complex, the school site, and a shopping center) initially opposed plans for a conventional freeway-style interchange design. All but the shopping center owner were convinced the Echelon design would work and lent their support accordingly. After much debate, the politicians voted in the majority for the design. The community felt the Echelon was the best alternative to facing 2-mile backups. After construction, the impacts to the shopping center were less than feared: a subsequent independent market research study showed that the shopping center's market area had nearly doubled because the center could be reached with less delay on the roadway system.

The only post-construction safety concern that needed to be addressed was the southbound US 1 approach's permissive left turn on a crest curve. While sight distance was adequate, several collisions prompted a signal change to allow only protected lefts, and the problem has since disappeared (44).

5.2 CENTER TURN OVERPASS

5.2.1 Evolution of Design

The principal feature of the Center Turn Overpass (CTO) design is the grade separation of all left-turn movements from the intersection to maximize left-turn capacity. The design also attempts to minimize construction costs and direct impacts to adjacent properties by building ramps within the intersecting roadway medians. Unlike freeway-style flyover designs, the CTO ramps fit vertically within a wide center median, replacing dual left-turn bay slots with two-lane roadways on structure.

Bob Clayton of Clearwater, Florida, conceived of the CTO, and currently holds US Patent No. 5921701 on this design. The CTO design concept is relatively new and is continuing to be refined. Though several highway agencies have considered the design (Maryland, Nevada, North Carolina), there is currently no design application of its kind in the US.

5.2.2 Description of Operations

The CTO grade separates turning traffic from through and right-turning traffic by placing the left-turn volumes on a separate, independently timed level. Both the ground and upper level intersections are governed by two-phase signals, a departure from multi-phase signals at conventional intersections. As left-turning traffic is grade-separated from through-traffic, heavy turn volumes are less likely to choke the intersection compared to a conventional intersection design (45).

Descending from the raised left-turn intersection, traffic accelerates downhill and merges left into the through-traffic flow. Ideally, the CTO would have a dedicated passing/turning lane to receive the cars coming off the ramps. If this is not possible, and the merge is difficult, the upper-level lights can be synchronized with the lower-level lights so the merge occurs when through traffic is stopped. U-turns on the major and minor roadways can be supported on the ground level by a dedicated U-turn under the structure (shown in **Exhibit 45**).

Exhibit 45: Center Turn Overpass Conceptual Design

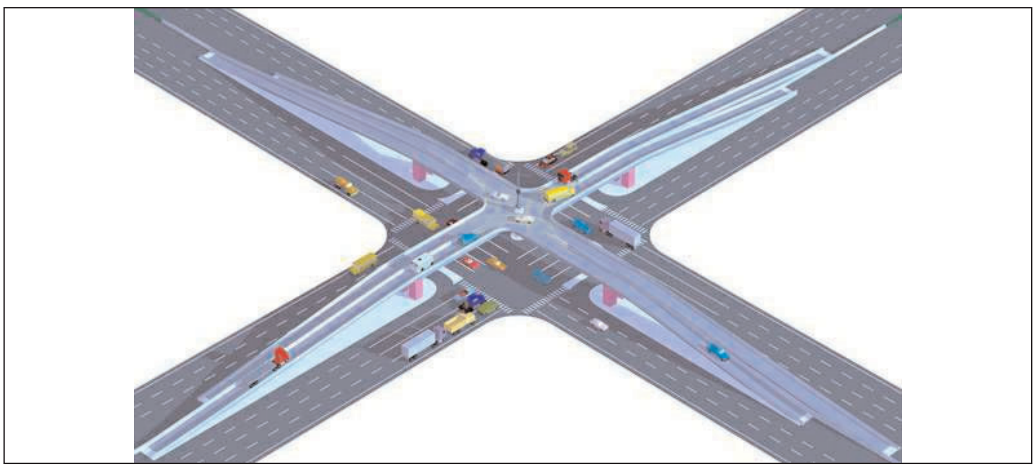


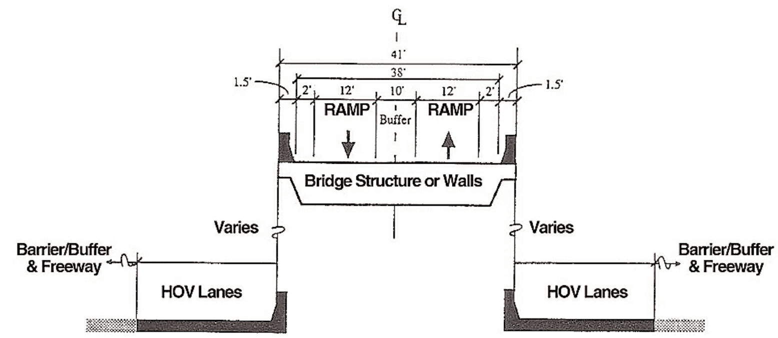
Illustration from CTO Website (www.centerturnoverpass.com); used by permission.

5.2.3 Design and Operational Considerations

The CTO raises all left-turning traffic approaches on retaining wall or steel girder structure to a level above the through and right-turn movement approaches. Turning traffic moving up the ramp is decelerating (with the aid of gravity) to stop or slow turning conditions at the top of the ramp; therefore, ramp speeds are slower (compared to high-speed flyovers) and can be designed steeper and up to 65 percent shorter than conventional ramps.

The CTO can be simpler to construct than a traditional fly-over overpass. Column and retaining wall supports are confined to the center median, minimizing their impact on the outside right-of-way and adjacent properties. A minimal CTO approach roadway can be built within a 32-foot median, assuming two 12-foot approach and departure lanes and 2-foot offsets to the outside 2-foot concrete barriers; however, a wider ramp roadway section may be desired to pass stalled vehicles and provide lateral clearance to arterial lanes similar to T-Ramp designs on HOV facilities (see **Exhibit 46**).

Exhibit 46: Recommended Two-Way Reduced Standard HOV Drop Ramp Layout



Source: HOV Design Guide Manual

The CTO can be built for as little as one-fifth the cost of a conventional fly-over interchange with frontage roads. The North Carolina Department of Transportation included the CTO in a planning study for an intersection in Wilmington, North Carolina, and estimated costs to be $8 million for a retrofit design at an existing high-volume intersection. Cost savings can result from the design's reduced right-of-way requirements (the CTO ramps can fit within a wide highway median), and the use of pre-fabricated box-channel girders to construct the ramp structures (often standard designs for all four approaches). The center column support can be constructed by using low-maintenance concrete designs, or, at slightly greater cost but greater design flexibility, by using steel structure, including box-channel girders (120-foot sections).

5.2.4 Studies and Research

In a study comparing operations of the CTO to several other arterial interchange designs, the CTO design was found to have considerably greater capacity compared to the traditional Diamond interchange, and had the greatest operational benefits on a six-lane or wider arterial with moderate to high left-turn volumes (46). Capacity studies have shown that the CTO can have up to 75 percent more green time allotted for left turns compared to dual left-turn lanes at a conventional intersection, and ground level through-volumes can receive up to 40 percent more green time (45). Pedestrians are accommodated on the ground level and can make one or two-stage crossings. Pedestrian phases are at greater frequency due to shorter cycle lengths, and pedestrian crossing with left-turning vehicles are eliminated by grade separation.

When to Consider

The CTO design is most appropriate at high-volume intersections located within a signalized network. The CTO's greatest operational benefits compared to a conventional intersection design occur where the arterial and cross street volumes are similar, and left-turn volumes are moderate to high. The slender design of the CTO makes it a good fit in an urban or suburban location where right-of-way is limited. Also, because the CTO is specially designed to preserve access to adjacent properties, the most likely location for a successful design application would be along a commercial arterial corridor.

5.2.5 Lessons Learned

In locations with greater concerns about property access, the CTO design could be modified to permit ground-level left turns for direct access to corner parcels. These modifications would also support access by emergency and over-sized vehicles. These turns would not have protected phases, thus negating some of the benefits of the two-phase intersections. Also, there are additional safety and routing impacts to consider, including the ability to "see through" the structure to make unprotected left turns safely and creation of adequate storage lanes without requiring additional intersection width and/or locking left turns.

Several issues remain as potential obstacles to the first design application. In northern climates, snow and ice removal may be problematic, as the slender ramp approaches leave little room for snow on the shoulders, and ice may be a concern on shorter, steeper grades. Accident response and clearance could also be an issue on the ramp approaches. Sight distance issues for both the elevated and at-grade roadways can be overcome with a wider, more open structure design made possible using steel construction. Provision for U-turns on either level would require a greater structure length and/or width, thus increasing costs.

To date, several states have expressed interest in the CTO design for its ability to handle large turning-traffic volumes and minimize impacts to adjacent properties and right-of-way, but so far all have selected to implement a more conventional design or no immediate improvement at all.

5.3 SINGLE POINT URBAN INTERCHANGE

5.3.1 Evolution of Design

The Single Point Urban Interchange (SPUI) design, also known as an "Urban Interchange," was first proposed in the US at two different sites in the 1970s. Today, there are over 300 SPUIs in the US and others can be found in Australia, Canada, Greece and Germany; however, most of the existing designs are along interstate or other freeway-type facilities. There are several applications on non-freeway facilities (albeit limited access facilities) on Maryland and Washington State Highway systems.

5.3.2 Description of Operations

The SPUI design allows free-flow operations on the priority roadway by creating a separate, signalized intersection of major and minor roadway left turns and minor roadway through-movements at a signalized intersection separated by grade. Right turns are made at unsignalized ramps separated from the main intersection. The creation of a single, signalized intersection on the cross street improves the ability to progress traffic compared to a conventional Diamond interchange (with closely spaced signals at both ramp terminals).

The SPUI intersection without frontage roads is typically controlled by a three-phase signal. Concerns about frontage roadway impacts are not relevant to arterial roadway applications, as the arterial(s) provide development access along the corridor. Two of the signal phases are dedicated to opposing left-turn movements (each allowing simultaneous opposing left turn movements) with the third phase allowing through-movements on the cross street. The priority roadway is separated by grade and does not have to stop.

Exhibit 47: Arterial Single Point Urban Interchange (Overpass)

Aerial by AirPhotoUSA, 2003.

5.3.3 Design and Operational Considerations

While the SPUI design right-of-way requirements are similar to a typical Diamond interchange, the pavement area and the footprint of the structure at the intersection is considerably wider. The larger intersection width can require greater structure length and depth, which increases costs for bridge construction, retaining walls and earthwork. Also, the stopbars at the signals are set much further back to allow clearance for crossing movements to traverse a much wider intersection, which yields longer clearance (amber plus all red) times between signal phases. In a study comparing operations of an SPUI with the Compressed Diamond interchange (discussed in Section 5.4), the SPUI was found to provide greater capacity for most traffic volume scenarios (47).

Design Variations

There are two basic variations of the SPUI design: the “overpass” and “underpass” designs where the road travels “over” or “under” the cross street. The overpass SPUI, as illustrated at the Maryland MD 100/MD 170 intersection in **Exhibit 47**, elevates the freeway (or arterial) over the cross street using a simple but long span bridge structure, with the SPUI signalized intersection below at grade. The underpass SPUI (see **Exhibit 48**) raises the arterial ramps to a single, elevated intersection with the cross street. There are significant operational differences between the overpass and underpass SPUI designs (48):

Exhibit 48: SPUI “Underpass” Design Variation

Both the overpass and underpass SPUI designs can be designed into a smaller footprint compared to a conventional Diamond interchange. The SPUI overpass can have a simpler structural design compared to the underpass design. There may also be a trade-off between bridge length and horizontal sight distance for left turn lanes. The overpass SPUI has more difficult lane path guidance and opposing traffic movements are more difficult to see underneath the (dark) structure.

The underpass SPUI design uses highly visible signal heads mounted on a single mast arm spanning the entire elevated intersection, providing greater movement visibility. In this configuration, ramp acceleration and deceleration works with gravity, reducing stopping distance and acceleration lane length requirements. The underpass SPUI has the advantage of reduced noise impacts and has potentially fewer sight distance conflicts compared to the overpass SPUI design. Design disadvantages may include the need for excavation, drainage and utility relocation in a depressed design.

Another variation of the SPUI, shown in **Exhibit 49**, was found at the intersection of two arterial roadways in Greensboro, North Carolina. This “inverted” SPUI design separates the directional free-flow arterial lanes and brings the ramps to an intersection with the cross street in between the arterial roadways. The design includes left exits and merges onto the arterial from the central at-grade intersection. Because of the separation of the arterial lanes, the overpass bridges can be simple structures of considerably shorter length.

5.3.4 Studies and Research

The SPUI design is an increasingly popular form of urban interchange. There has been considerable research published over the past ten years on the design, but most of the stud-

Exhibit 49: Inverted SPUI Interchange Design, Greensboro, NC

Aerial by AirPhotoUSA, 2003.

ies and completed designs have been in the context of freeway interchanges rather than grade-separated intersections of arterial streets.

AASHTO (2) notes the advantages of the SPUI as follows:

- Beneficial in urban areas because it can be constructed in limited rights-of-way.
- Reduces signal phases from four to three.
- Turning paths are flatter and can be made at higher speeds, thus increasing saturation flow rates and intersection capacity.

Noted SPUI disadvantages include:

- Higher bridge costs – either longer spans (overpass) or butterfly shape (underpass).
- Need for positive marking guidance (including lane markings projecting the turning path through the intersection that in some cases is illuminated) and additional signage.
- Pedestrian crossings can be more difficult, particularly where there are free-flow movements. Adding separate pedestrian phases decreases intersection efficiency and capacity for vehicular movements.
- If frontage roads are a required part of the design, operations efficiency is significantly decreased.

When to Consider

The SPUI design is attractive where higher interchange capacities are sought, and where costs are not the primary design selection issue. The SPUI is particularly efficient compared to other interchanges where left–turn movements are heavy and/or where there are other signalized intersections nearby. The SPUI can be a poor choice where frontage roads are present.

5.3.5 Lessons Learned

The design and construction costs for a larger SPUI bridge structure – including either long bridge spans in the “underpass” design or the wider, more complicated butterfly shape design in the ”overpass” design – has been a hindrance to more widespread use. However, recent improvements in construction techniques have begun to reduce the cost gap between SPUI and conventional bridge structures. The use of post-tension concrete box design has made fabricating the unusual bridge form less expensive, and the use of finite element analysis can verify structure strength and reduce costs of previously over-designed structural elements.

Cost of steel has also produced a regional SPUI design materials consideration: more steel structures are seen on the eastern US coast (closer to where the steel is produced) and more concrete structures are being designed and built in the western US. As design and construction costs improve with more structures built, the SPUI will likely become even more attractive for arterial roadway application.

5.4 ROUNDABOUT INTERCHANGES

5.4.1 Description of Operations

There are two different types of grade-separated Roundabout interchanges: 1) the Double Roundabout interchange, which is basically a variation of the traditional Diamond interchange, and 2) the Single Roundabout interchange, which grade-separates one major through movement below a roundabout or traffic circle that handles all other cross street and turning movements.

The Diamond interchange is by far the most common freeway or arterial interchange design, providing sufficient capacity in low to medium traffic volume scenarios. As traffic volumes rise, Diamond interchanges can experience delay and queuing on ramps and on the bridge structure. Narrow bridges must often be widened to accommodate single or dual left-turn bays on the cross street. The Double Roundabout interchange uses Roundabouts instead of signal- or stop-control at Diamond interchange ramp terminals. Intended benefits include reduced delay for ramp traffic, a narrower bridge width, and the elimination of signal coordination and progression issues between the two ramp terminals. Studies of Double Roundabout operations show queuing is typically not present on the bridge between the Roundabouts because the movements entering either Roundabout from the bridge are virtually unopposed (only yielding to U-turns).

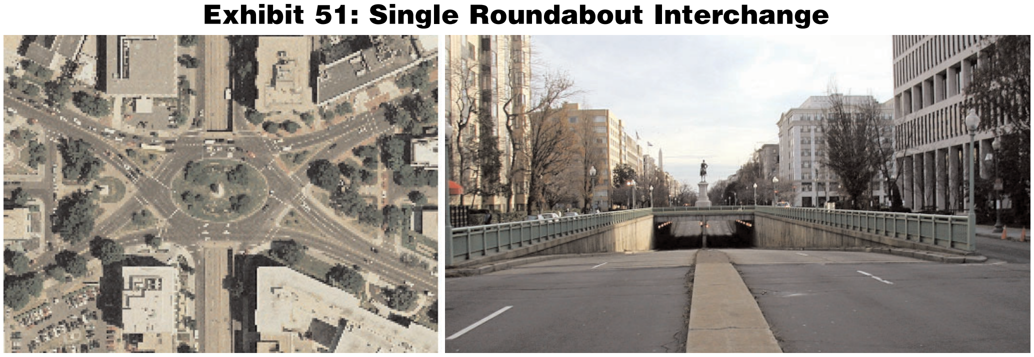
The Roundabouts in the Double Roundabout design can have two different shapes, either circular or “raindrop.” The use of true circular islands is desirable when U-turns or access to other approach legs are to be permitted. Raindrop-shaped central islands eliminate direct U-turn movements (U-turns can be made by circulating around both Roundabouts), but reduce yielding conflicts for vehicles entering the Roundabout from the ramps, thus improving the capacity of the Roundabouts and reducing ramp delays and queuing. The first modern Double Roundabout interchanges in the US were built in Colorado and Maryland in the mid-1990s.

Exhibit 50: Double Roundabout Interchange, Maryland

Aerial by AirPhotoUSA, 2003.

A second form of Roundabout interchange is the Single Roundabout interchange, which uses a larger Roundabout centered over the through-roadway. Turning traffic from the free-flow roadway is combined within the Roundabout with cross street through and turning movements, as well as any frontage traffic accessing the parcels at the interchange. The central Roundabout uses multiple entry points that can be either merge- or yield-controlled depending on volumes, number of lanes and/or central roadway radius. Several examples of the Single Roundabout interchange can be found in the nation’s capital.

Exhibit 51: Single Roundabout Interchange



Aerial and ground view of Thomas Circle, Washington, DC.

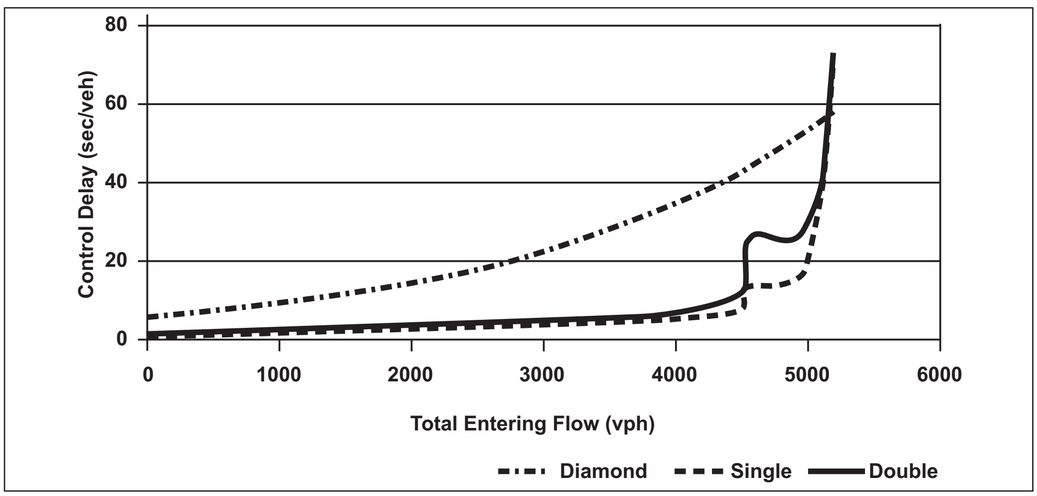
5.4.2 Design and Operational Considerations

The Single Roundabout interchange requires curved bridge structures as part of the circulatory roadway, which can add to the project expense. The grade on the free-flow street must be short and steep in an urbanized grid setting (such as the DC examples) to descend underneath the Roundabout and ascend before the next signalized intersection. Trucks may be restricted from using the below-grade roadway to minimize the bridge height requirements and thus soften the gradient. In addition to reducing intersection delay and queuing, the Single Roundabout interchange can handle more than four intersecting roadways and serve as a frontage road for adjacent interchange parcels.

5.4.3 Studies and Research

Studies have shown the capacity of the Single Roundabout to be greater than the capacity of the Double Roundabout design because it has a larger inscribed diameter. However, the Double Roundabout interchange in some instances may be able to handle more vehicles because some traffic movements enter only one circle. Capacities have been estimated to be between 4,000 and 4,300 vph for Double Roundabout interchanges and 4,500 to 4,700 vph for Single Roundabout interchanges.

Exhibit 52: Roundabout Interchange Delay and Capacity



Source: Public Roads, November/December 2002.

When to Consider

A Double Roundabout interchange may be appropriate where there is a high proportion of left turns to and/or from the ramps of a Diamond interchange during peak periods and/or where there is limited queue storage space on the bridge. The Double Roundabout design has also been used in other countries as a temporary measure to postpone the need to widen the bridge structure of a standard Diamond interchange, for example, where operations at a Diamond interchange are failing due to lack of storage room on the bridge, but the bridge is still structurally adequate.

The Single Roundabout design is particularly suitable in built-up urban areas with moderate capacity requirements. Single Roundabout interchanges should receive strongest consideration where there is an intersection of five or more roadways and/or where right-of-way is very restricted.

5.4.4 Lessons Learned

The first Double Roundabout interchanges experienced notable successes in improving traffic operations and safety. The Vail, Colorado, interchange replaced a conventional Diamond interchange that had to be controlled by police officers during peak ski season, with a Double Roundabout interchange that can handle peak operational periods (49).

5.5 MICHIGAN URBAN DIAMOND INTERCHANGE

5.5.1 Evolution of Design

The Michigan Department of Transportation (MDOT) developed the aptly named Michigan Urban Diamond Interchange (MUDI) as an extension of the Median U-Turn indirect left turn strategy applied to many of its arterial corridors (see Section 3.1). MDOT has applied the MUDI design at several freeway interchanges where right-of-way was limited and where a parallel one-way frontage road existed. There is no known application of a MUDI at the intersection of two arterial roadways.

5.5.2 Description of Operations

The MUDI uses directional crossovers beyond the main intersection to handle all left-turn movements. The arterial turn movements are diverted onto separate frontage roads on either side of the grade-separated through-lanes. Off ramps are directed onto these one-way frontage roads (ramp movements are typically given priority over through-movements on the frontage road) approximately 500 to 600 feet prior to the main intersection. At the main intersection, right turns can be made and left turns proceed to the directional crossover beyond the main intersection and make a U-turn and then a right turn onto the cross street. Left turns from the cross street are made by turning right at the main intersection, and using the same directional crossovers. Entry ramps onto the priority roadway are provided just beyond the crossovers. Both of the main intersection signals are two-phase, and the crossover signals (if needed) can be progressed perfectly with the main intersection signals.

A properly designed signalization strategy (considering offsets and cycle lengths favorable to the distance between the main intersection and the crossovers) will allow left turns from the arterial to receive a green indication at both the main intersection and the second crossover. Thus these vehicles will not have to stop as frequently, and left turn travel time and delay is further reduced.

Exhibit 53: Michigan Urban Diamond Interchange

Aerial by AirPhotoUSA, 2003.

5.5.3 Design and Operational Considerations

The MUDI is fairly pedestrian friendly, as pedestrians crossing the arterial have a two-stage crossing of two one-way streets under signal control. The two-phase signal provides for greater pedestrian "walk" times. Pedestrians along the arterial cross only the main intersection. The MUDI also provides for positive access management and access to adjacent business development along the parallel one-way frontage roads. The right-of-way needed at the intersection is narrower than that needed for the traditional Diamond interchange, and businesses can have access along the frontage roads with direct right-in right-out access and left-turn access using the directional crossovers.

A variation on the MUDI design allows direct left turns from the arterial at the main intersection to reduce the travel distance and time for arterial lefts. This strategy requires consideration of the storage capacity on the bridges to ensure that the intersection does not lock up under higher turning volumes. Additional storage capacity on the main intersection bridge may require a wider structure and incur additional costs.

A criticism of the MUDI design is that left-turning vehicles are penalized with additional travel time and distance compared to the more conventional interchange forms. Also, the MUDI requires two additional structures for the crossovers compared to the traditional Diamond interchange, which increases design costs. However, the crossover structures eliminate the need for turn lanes on the main structure, and the area of bridge decking may be comparable, thus partially offsetting these costs.

5.5.4 Studies and Research

A simulation model analysis comparing MUDI operations to a conventional Diamond interchange showed that the MUDI design outperformed the Diamond interchange at all turning movement volume scenarios (12). At lower intersection saturation levels the capacity and operations benefits were small but, as volumes increased, the benefits became significantly greater, up to a 60 percent reduction in delay and travel time compared to the conventional Diamond interchange. The study also noted that the MUDI design does not necessarily "dump" traffic at downstream nodes causing additional delays.

When to Consider

The MUDI can be a good strategy where frontage roads are present on the arterial. The MUDI has the greatest timesaving benefits on arterials that have high through-movements and moderate or low volumes of left-turns and cross street movements.

5.6 OTHER ARTERIAL INTERCHANGE DESIGNS

There are several interchanges of more common or conventional design that are applied to arterial intersections, where one or more variations may be more appropriate at non-freeway applications and/or may fit into an urban or suburban context more appropriately. Drivers on arterials are more aware of the surrounding environment and hazards than drivers on freeways, and are typically traveling in an environment with lower design and operating speeds. Therefore, it is unnecessary to provide freeway-like interchange movements designed for higher speeds and conditions. Motorist expectations on surface street systems include proper signing and marking guidance to safely navigate an intersection or interchange.

Exhibit 54: Integrated Arterial Interchange

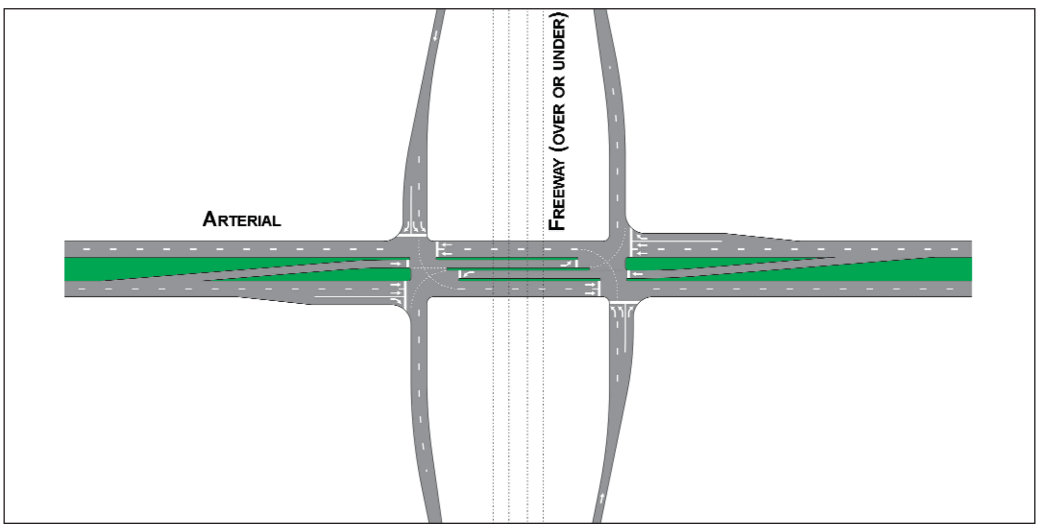
This interchange of two arterials incorporates several design forms, including a Partial Cloverleaf (western legs) and Single Loops (eastern legs). The eastern ramps include development access inside the interchange. The northeast loop shares access with roadways within shopping center.

5.6.1 Contraflow Left Interchange

The Contraflow Left (CFL) interchange concept was first implemented in the 1960s at the intersection of RT 7 with US 441 in Sunrise, Florida. The design replaced a Tight Diamond interchange that was failing due to the number of signal phases. A narrow overpass and business development tight to the arterial right-of-way prohibited the possibility of adding adequate opposing left-turn bays at the interchange approaches. Therefore the contraflow lanes, which are built within the intersection, were introduced. Originally the design was to be an interim solution until funds were made available to reconstruct the interchange. However, the design worked well for nearly 20 years until the bridge was rebuilt in the 1980s. Today, there are at least two other known CFL interchanges still in operation in Florida, one of which was originally constructed as a CFL.

The CFL design is a variation on the Diamond interchange, and is best used as an alternative to a Tight Diamond interchange (see Section 5.6.3). All movements in a CFL interchange are the same as those of a typical Diamond interchange configuration except for left turns from the cross street. Cross street left turns move over into left turn storage lanes (separated from the cross street through lanes by raised median) approximately 300 feet prior to the first ramp intersection. The Florida Department of Transportation recommends that the contraflow lane extend at least 300 feet prior to the first ramp intersection, but actual design should consider expected queue lengths. From this left-turn storage lane, vehicles move past the first signal and into contraflow lanes within the interchange, before making the turn onto the ramp. These special lanes run in the opposite direction from the adjacent through-lanes, and overlap within the interchange.

Exhibit 55: Contraflow Left Interchange Concept



The CFL design reduces the number of signal phases compared to a Tight Diamond interchange from four to three by allowing the two opposing left-turn movements to be made during the same signal phase. The same requirements for additional intersection clearance time exist in the CFL design as with both SPUI and Tight Diamond interchange designs. The greatest design benefit of the CFL is the reduction in the need for left-turn storage, as most left turns do not have to be stored in the area between the two interchange signals.

Exhibit 56: Contraflow Left Interchange in Coconut Creek, Florida

Photos: (left) Interchange at State Toll Route 869 and Lyons Road in Coconut Creek, FL.; Courtesy of Craig Miller, used by permission. Aerial by AirPhotoUSA, 2003.

To date, all known Contraflow Left Interchanges are designed where the arterial or freeway crosses over the cross street, but similar reductions to the bridge width can be expected if the cross street is the elevated roadway.

There are no known studies comparing the operations of the CFL to Diamond or other interchanges. However, studies of the existing in-field examples provide some guidance to operational expectations and design criteria. In the development of the RT 7 interchange design, there were concerns that drivers might be confused by design geometrics and enter the wrong way into the contraflow lanes. Special attention was paid to signing and marking for the project. In 20 years of operations, there was never an accident caused by a motorist entering the wrong way into the contraflow lanes. Accident rates were reduced compared to the Tight Diamond conditions by reducing stop-and-go traffic on the cross street and reducing ramp queues.

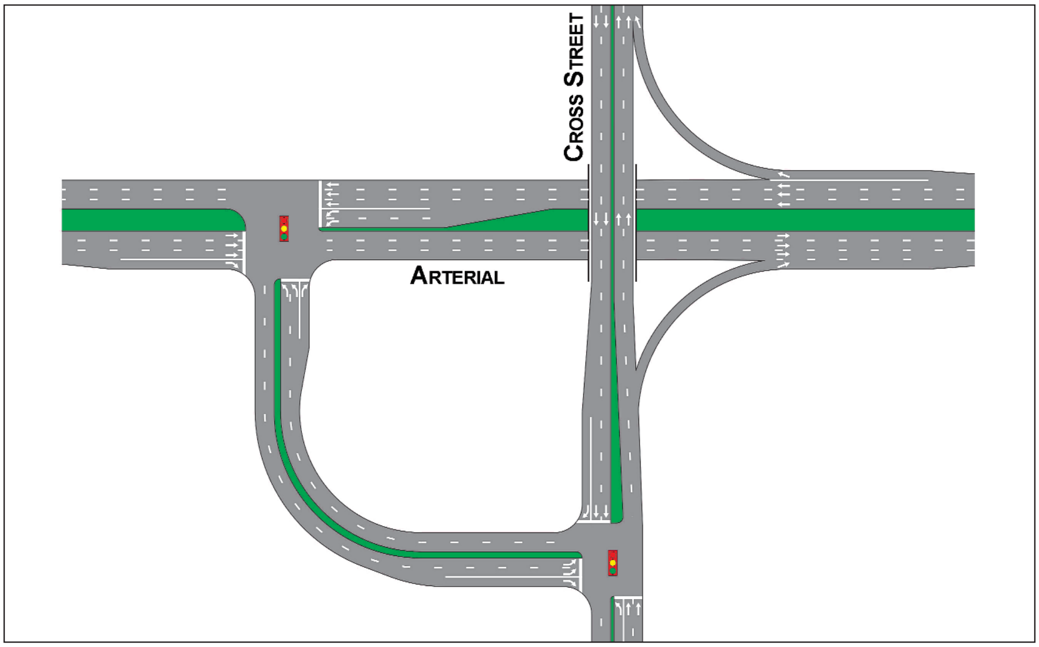
The CFL interchange has the greatest potential for application as a replacement of or alternative to a Diamond interchange, particularly where there is tight ramp spacing and/or where left-turn demand exceeds storage capacity between the ramps. The design may also be attractive where right-of-way is limited along the cross street and additional left-turn storage is desired. The CFL interchange design may not be as operationally effective where the left-turn volumes are significantly imbalanced.

5.6.2 Single Loop Interchange

The Single Loop interchange (also called a "Cutoff" interchange) uses a roadway in a single intersection quadrant to handle most interactions between the arterial and the cross street.

While typically used in rural locations, the single loop design can be enhanced with multiple turning lanes and coordinated signal phasing to operate well in more urbanized locations. The design also includes ramps for right turns in two other intersection quadrants, increasing the right-of-way and property impacts of the design, as well as introducing merge lanes on the cross street and arterial that may cause conflicts with upstream driveways.

Exhibit 57: Single Loop Interchange



The single loop roadway intersections with the arterial and cross street roadway are controlled by a three-phase signal. The loop roadway can be placed in any intersection quadrant, and thus is flexible with respect to land availability. The roadway may also provide access to the interior of the quadrant. The arterial can cross either over or under the cross street, and the bridge is typically narrow, as turning lanes on the bridge are not required. Signing is an important design consideration, as each directional turning movement pattern is different. The single loop interchange is generally not as costly as a Diamond form of interchange and is more easily coordinated with other signals on the arterial (41).

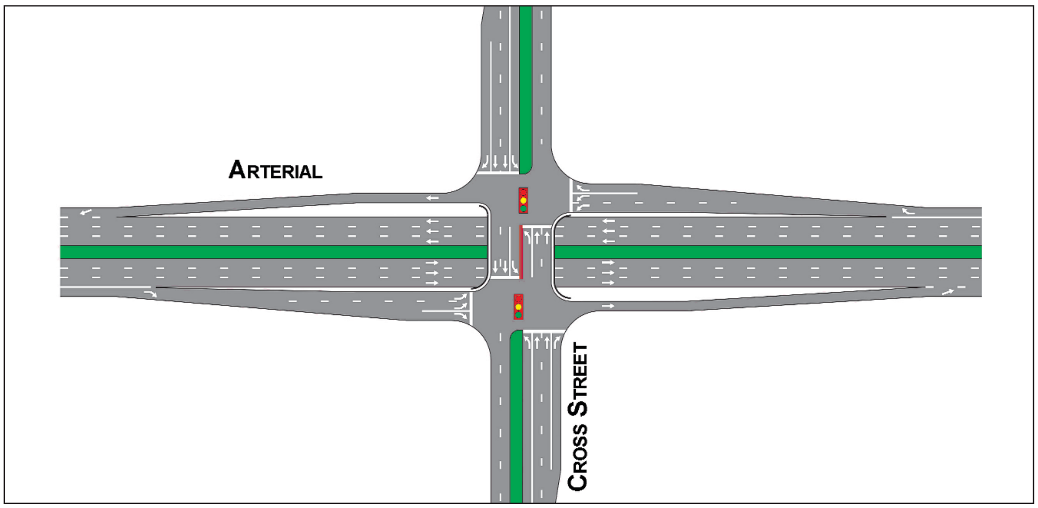
In a recent simulation study of several grade-separated intersections, the Single Loop was found to have competitive operations with Diamond and Parclo interchanges at low- to medium left turn volumes (46).

Advantages of the Single Loop include minimized right-of-way requirements compared to the Parclo interchange (requiring significant right-of-way in only one intersection quadrant), adaptability to future arterial or cross street widening, and simpler pedestrian crossings. Disadvantages include greater left turn storage requirements, difficulty in providing access to parcels within the loop roadway and greater potential for motorist confusion.

5.6.3 Compressed Diamond Interchange

The Compressed Diamond (also called a Tight Diamond) is a common interchange design in heavily developed urban areas because of its minimal right-of-way requirements. In the Compressed Diamond design, the cross street crosses over the priority roadway with ramps tight to the roadway edge, often including retaining walls in narrow rights-of-way. Assuming the use of retaining walls to pull the ramp terminal intersections as close as possible (to represent best-case traffic operations) over a six-lane barrier-separated priority roadway the distance between signals may be as tight as 100 to 130 feet. The ramp termini on the cross street are signal-controlled. Due to the close intersection spacing, there is a lack of left-turn storage space between the signals and it is difficult to progress traffic through both signals on the cross street; therefore, the Compressed Diamond uses a four-phase overlap signal that coordinates both intersections as one control.

Exhibit 58: Compressed Diamond Interchange



In a study comparing the Compressed Diamond with SPUI and conventional Diamond interchanges, the Compressed Diamond performed better where turning volumes were greatly imbalanced, or where they were much heavier than through-traffic volumes, and also where arterial frontage roads were involved (42). A second study used Transyt 7F to evaluate operations efficiencies compared to a SPUI. The study found that the signals within the Compressed Diamond were often optimized at a shorter cycle length, which can lead to decreased delays and shorter queues (50). Advantages of the Compressed Diamond include minimal right-of-way requirements, adaptability to frontage road connections and future widening, and normal driver expectations. Disadvantages include reduced queue storage space, signal phasing inefficiencies, and difficulty in progressing through traffic on the arterial.

6.0 UNCONVENTIONAL DESIGN IMPLEMENTATION

6.0 UNCONVENTIONAL DESIGN IMPLEMENTATION

"Everyone is a bit afraid of trying something new." – Herman Kimmel, president of a Newport Beach transportation engineering firm, on cities' responses to implementing the CFI design.

If unconventional designs can substantially reduce intersection and arterial delay and congestion, and potentially save or postpone expensive interchange construction, then why are they not more commonplace on the US highway system? Why are many of the designs limited to regional use only? Why do engineers, politicians and the driving public need to be encouraged to study their benefits?

This chapter explores the many answers to these questions, including regional traditions, misperception of costs and benefits, and lack of awareness. The chapter continues by discussing specific benefits and impacts, describing analysis tools for demonstrating traffic impacts, and concludes with a discussion of implementation issues, including signage, markings, and public information campaigns.

6.1 BEYOND REGIONAL USE

6.1.1 Niche Markets

Many of the unconventional intersection designs have their own niche markets that make consideration a greater possibility at the planning level. Much of this is due to time-honored traditions of construction that prefer the known to the new, and respect driver familiarity with past practices. Also, because there are so many forms of unconventional design, it may simply be the case that certain designs will only be found in regional or isolated locations, and therefore will always appear unconventional to the visiting driver population. Further, there are some arterial intersections where no unconventional alternative will work and, of course, there are numerous intersections where conditions are such that unconventional designs are not warranted.

Nearly every study comparing the operational efficiency of unconventional intersection design operations to either conventional or other unconventional intersection designs has concluded that, while the studied unconventional design may compare favorably in travel efficiency, delay and/or safety under certain volume or geometry scenarios, there is no single unconventional design that is superior in all circumstances.

6.1.2 Project Beneficiaries

Perhaps another reason that unconventional intersection designs are not more prevalent is the lack of understanding of intended benefits. While motorists are quick to recognize turning restrictions, circuitous routing, and any perceived loss of direct access, benefits in travel time, vehicular safety, construction impacts and pedestrian safety may go unnoticed. For unconventional designs and principles to effectively be introduced to highway agencies and the traveling public, it is important to communicate an understanding of the range and depth of benefits that unconventional intersections can achieve. Unconventional intersection designs applied to arterial transportation systems have shown the following benefits to specific transportation user groups:

- *Motorists*: reduced traffic accidents, travel delays, and recurring congestion.
- *Land Owners*: increased economic potential for development of land along an efficient transportation corridor; increased market area that can be reached efficiently.
- *Developers and Highway Agency Staff*: ability to establish access design criteria and predetermine access locations, thus reducing the high cost of impact assessment and redesign for new access points.
- *Taxpayers and Elected Officials*: prolonged functional life of existing roads at acceptable congestion levels; capital investments focused on operations, not expensive widenings.
- *Pedestrians and Bicyclists*: improved intersection safety and longer/more frequent crossing times.

A clearer understanding of the benefits of many of the unconventional designs presented should lead to more widespread and accepted use.

6.1.3 Building Sustainable Highways

A further factor that should encourage the use of unconventional designs in the coming decades is the growing recognition of the importance of sustainability. As states are focusing more and more on maintaining existing facilities versus building new lanes and corridors, roadway designs are under increasing scrutiny for their ability to manage and sustain traffic over the long term. In addition, communities are beginning to recognize the significance and value of preserving investment by maintaining a roadway's particular function. Many unconventional designs, particularly those that help manage the arterial corridor, promote operations and management consistent with arterial roadway function.

When a commercial arterial corridor combines high traffic volumes with inefficient intersection control and too-frequent conflict points, the roadway quality declines, as does the adequacy of service to abutting properties. On the other hand, widening an overburdened commercial arterial, or upgrading it to a freeway, while undoubtedly increasing vehicular throughput, may do so at potentially high costs to surrounding businesses, residential areas, the environment and local circulation, not to mention highway agencies' budgets. Design, operation and management consistent with roadway function (arterial, collector, local street, etc.) protect investments in existing roads, as well as investments in surrounding land uses. Protecting the roadway capacity of existing facilities can also reduce the need for additional new highway corridors or bypass facilities that can have substantial economic, social and other environmental impacts (51).

Since the enhancement program was incorporated into the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1992, the practice of improving communities and the environment as part of highway projects has become mainstream. AASHTO's description of environmental stewardship encourages design criteria geared to serving traffic needs for 20 to 25 years in the future – thinking in terms of decades rather than years, ensuring that transportation projects benefit a community's future generations. Projects should be planned, designed, operated and maintained so that there is an overall net positive benefit to the environment and community. In particular, highway projects should be designed to support existing land use policies as well as policies that control the access and management of traffic flows (52).

6.2 AWARENESS AND ACCEPTANCE

Major changes to existing transportation facilities are often controversial, and proposing unconventional designs can draw additional objections from business owners and the motorist public, as well as create added anxiety on the part of often cautious agency officials. This section explores the attitudes of highway agencies, the driving public and landowners regarding implementation of unconventional intersection design and arterial access management. Often initial fears are unwarranted by eventual outcomes, as is shown in a number of studies discussed below.

6.2.1 Highway Agencies

When surveyed on how state highway agencies typically react to unconventional design or design innovation, responses from officials were all over the spectrum including comments such as:[1]

- Management is looking for proactive ideas where possible for all future projects.
- We investigate them (unconventional or innovative design concepts) as they come along.
- Generally like to stick to conventional, proven concepts, as design innovation involves certain risks.

The survey also asked highway agencies for reasons they would or would not consider unconventional at-grade and grade-separated designs: A complete summary of survey responses and ranking of alternatives is included in the Appendix.

Exhibit 59: Reasons Agencies May Consider Unconventional Designs

(Total Score is cumulative of survey ratings of 1 to 5, with a number 1 response receiving 5 points, number 2, four points and so forth)

A. Reasons to consider unconventional at-grade intersection design

Issue	Rated #1 Concern	Total Score
Safety	18	96
Congestion/capacity	7	83
Left-turn volumes	1	44
Progression	0	43
Pedestrians	0	39
Other	1	5

B. Reasons to consider unconventional grade-separated intersection design

Issue	Rated #1 Reason	Total Score
Congestion/capacity	13	93
Safety	9	85
Alignment	3	52
Route priority	0	50
Never consider	2	10

[1] Note that these comments were obtained from individual agency staff and do not necessarily reflect the policies and practice of the entire agency.

6.2.2 Public Acceptance

For unconventional intersection designs to be seriously considered for implementation, highway agencies must first be convinced that highway users will understand and accept the idea that limiting direct access at their trip termini will result in reduced travel time and improved safety for their trip overall. Agencies must also be convinced that driver error or disregard will not be a serious problem. Unconventional arterial intersection designs by definition re-route certain turning movements and have the potential to cause more driver confusion than conventional intersection designs with direct access. Several of the older unconventional intersection designs have shown that agencies can effectively mitigate confusion inherent in restricting direct access. Highway agencies have throughout the years developed logical and understandable signing and marking to guide drivers through unconventional configurations, even in communities with large amounts of tourist traffic.

One of the issues designers cite most often as a reason for not using unconventional design concepts is the concern that motorists will not know how to properly or safely navigate the unique designs, particularly when they are new (53). In the survey of state highway agencies conducted for this research, driver expectation was rated as the highest factor in rejecting unconventional design.

Exhibit 60: Reasons Agencies May Reject Unconventional Designs

(Total Score is cumulative of survey ratings of 1 to 5, with a number 1 response receiving 5 points, number 2, four points and so forth)

Issue	Rated #1 Concern	Total Score
Driver expectation/safety	16	84
Cost	8	70
ROW requirements	1	65
Access impacts	0	48
Driver disregard	1	36

6.2.3 Developers and Land Owners

Because unconventional intersection designs typically re-route or restrict driveway access along an arterial or near intersections, adjacent business owners, who in part rely on direct access to attract customers, are often very concerned about the implementation of these designs. Several journaled studies have examined the impact of indirect access to driveways and adjacent roadside parcels. Studies in Kansas, Texas, Florida and Iowa provide strong anecdotal evidence that changes in access or traffic operations, except under extreme cases of circuitous operations, did not negatively impact the highest and best uses adjacent to the altered roadway. A 1999 study of the economic impacts of left-turn restrictions in Texas (54) included the following findings:

- Over 90 percent of business owners reported that regular customers were as likely or more likely to continue their patronage after the installation of median control that caused at least some restriction on or elimination of direct access.

- Specialty retail and fast-food restaurant types of businesses were much more likely to show an increase in customers after a highway improvement project that included median control, while gasoline and auto-service stations were likely to show a decrease in customers and sales.
- Negative perception of the business owners prior to loss of some direct access movements (due to the installation of a median) was far more pessimistic than the final project outcomes.

A 1997 statewide study of access-managed corridors in Iowa reported that (55):

- Over 90 percent of business patrons surveyed had favorable opinions of roadway improvements that involved restriction in access, citing safer and more efficient operations, and improved travel to retail and business establishments.
- Average failure rates of businesses along access-managed corridors were below the Iowa statewide average.
- 80 percent of business owners along access-managed corridors reported sales at or above the levels prior to the roadway improvement projects.

The most extensive research into impacts of median and access management along arterial corridors is collected in National Cooperative Highway Research Publication 420. The report concluded the following regarding economic impacts to businesses located along arterials:

- Where direct left turns are prohibited, some motorists will change their driving or shopping patterns to continue patronizing specific establishments.
- Some repetitive pass-by traffic will use well-designed or conveniently located U-turn facilities.
- Impacts will also be reduced at locations where direct left-turn access is available.
- In some cases, retail sales may increase as overall mobility improves (56).
- The likelihood of left turns decreases as the opposing volumes increase, and therefore the introduction of medians will have relatively no impact during peak periods (51).

Market area analyses have demonstrated that overly congested arterials can reduce business market areas and reduce the economic viability of the corridor (57). Research to date has not identified the long-term economic benefits to unconventional design management, but there are many anecdotal examples of economically thriving corridors with unconventional arterial intersection designs, including US 1 between Trenton and New Brunswick, New Jersey (Jughandles), and US 24 in southeastern Michigan (Median U-Turns).

Unconventional intersection design can also bring significant political and institutional issues to the surface. For example, many in the business sector believe that anything less than direct access will hurt their business. Some users question the logic of forcing a more circuitous entry to or exit from land uses with restricted access. Considerable political pressure is often exerted to reduce the amount of access control because of fears that developers might be “turned off” and decide to build elsewhere, or that voters will object to perceived inconvenience and risk. To gain further acceptance, developers, business owners, and the public in general must see access management as an ally rather than as a threat.

6.3 BENEFITS AND IMPACTS

Traffic volumes, development access, safety concerns, pedestrian/bicycle crossings and right-of-way considerations will all guide decisions on whether an unconventional intersection design should be implemented. Some of these issues are localized, but others are common to all locations and are discussed in this section, including safety, capacity, pedestrian movements, air quality, economic and community impacts, and project costs.

6.3.1 Intersection Safety

While much of the safety information available on unconventional intersection designs is positive, there are still gaps in the data.

The older Median U-Turn, Jughandle and Roundabout designs have longer track records that typically show fewer collisions than comparable conventional arterials, but no explicit controlled safety experiments have been performed to validate these trends. Without controlled experiments, it is particularly difficult to separate the effects of the smaller number of conflict points from the effects of better access control, which is not exclusive to the unconventional alternative.

For unconventional intersection designs where sufficient accident study data isn't available (for new designs, for example), a reduction in accident rates can be reasonably expected based on a design's reduction in conflict points. Unconventional intersection designs where the number of unprotected conflicting movements has been reduced are theoretically safer than conventional designs but, in many cases, convincing collision data do not exist. Validated accident rate factors or accident models should be developed to help agencies study a greater variety of unconventional designs.

6.3.2 Intersection Capacity

Many of the unconventional designs presented have been shown through field data and/or traffic simulation modeling to be superior in both capacity and efficiency at major intersections. In a study of seven at-grade unconventional solutions, in each volume scenario, at least one (and in many cases several) unconventional designs had significantly better intersection operations compared to the conventional intersection design (15).

While a number of local factors including right-of-way considerations are always involved in selecting an interchange design, unconventional designs can provide superior operations in most cases.

6.3.3 Pedestrian Impacts

Pedestrian safety is an important design criterion for the engineer to consider. The simplified signal operations of most unconventional designs benefit the safety of pedestrian crossings by decreasing wait times, thereby reducing the likelihood of pedestrians crossing against their signal. However, many designs force pedestrians to make two-stage crossings or to cross free-flow movements. One study attempted to rank the relative safety of pedestrian crossings for four conventional and six unconventional designs (58). As shown in **Exhibit 61**, the Median U-Turn and Bowtie designs have the potential to make pedestrian crossings easier than many conventional designs, while other unconventional designs have the potential to make pedestrian travel more difficult.

Exhibit 61: Pedestrian Crossing Efficiency

	Pedestrian Movements													
	Number of Roadways Crossed				Number of Free-Flow Crossings				Right Movement, Free-Flowing (1), Controlled (0)					
Design	Major (1)	Minor (1)	Major (2)	Minor (2)	Major (1)	Minor (1)	Major (2)	Minor (2)	Major (1)	Minor (1)	Major (2)	Minor (2)	Total	Rank
Conventional (c)	1	1	1	1	0	0	0	0	0	0	0	0	4	1
Bowtie	1	1	1	1	0	0	0	0	0	0	0	0	4	1
Median U-Turn*	2	1	2	1	0	0	0	0	0	0	0	0	6	3
Conventional (b)	2	1	2	1	0	0	0	0	0	0	0	0	6	3
Conventional (a)	1	1	1	1	0	0	0	0	1	1	1	1	8	5
Conventional (d)	2	1	2	1	0	0	0	0	1	1	1	1	10	6
Superstreet*	2	1	2	1	2	0	2	0	1	0	1	0	12	7
Jughandle*	3	2	3	2	1	1	1	1	1	0	1	0	16	8
Roundabout*	2	2	2	2	2	2	2	2	1	1	1	1	20	9
Continuous Flow*	3	2	3	2	2	2	2	2	1	1	1	1	22	10

Source: Guidance on the Safe Implementation of Unconventional Arterial Designs, NCSU, Raleigh, NC

*Notes: * = assuming medians; Study examined the path of pedestrians crossing both the arterial and the cross street at an intersection; (1) and (2) refer to the first and second stages of crossing an individual roadway approach. The study examined four variations of the conventional intersection design: (a) no median & free right turn, (b) median and no free right-turn, (c) no median & no free right turn, (d) median and free right-turn. An extra point was added to the total for any free-flowing right-turn movements.*

6.3.4 Air Quality

While significant reductions have been made in motor vehicle emissions since the Clean Air Act of 1970, there remains a strong relationship between traffic congestion and air quality in urban areas. Vehicles moving smoothly down the highway burn fuel more efficiently and thus generate less air pollution per mile traveled. Idling vehicles and stop-and-go traffic conditions greatly increase fuel consumption and therefore emissions of most types of vehicular pollutants.

Efficient travel on arterials can have air quality benefits, as both maximum fuel efficiency and minimum carbon monoxide and volatile organic compound emissions occur between 35 and 50 miles per hour. Efficient and progressive travel reduces the continual vehicle acceleration and deceleration involved in stop-and-go traffic, where fuel efficiency and pollutant emissions rates are generally at their worst.

6.3.5 Economic and Community Impacts

Most (not all) unconventional designs require greater right-of-way width along the arterial or at least at the intersection compared to conventional intersection or interchange designs. Notable exceptions include the Bowtie and Tight Diamond interchanges. However, many of the designs can have much more appealing aesthetics in the median rather than left-turn lane pavement. Additionally, where unconventional designs eliminate the need for grade-separation, economic and community impacts can be reduced.

The grade separation that accompanies conversion of arterials to freeways has several drawbacks that can be especially problematic in developed urban and suburban corridors. Right-of-way and construction costs associated with the structure are significantly higher, and many communities oppose the physical separation and unappealing aesthetics associated with interchange design. Additionally, grade separation along commercial corridors can alter the visibility of signs and buildings, reducing the ability of some businesses to attract customers.

6.3.6 Cost Impacts

Aside from right-of-way costs, which vary by location, perhaps the greatest distinguishing cost factor among unconventional designs is the use of overhead signs. While no known unconventional design explicitly requires overhead signs, several designs may benefit greatly by their use, particularly ones in which movements are contrary to the logical movements at a conventional intersection design, or where movements must be made in advance of the intersection.

Nearly all of the at-grade unconventional intersection designs require additional signal heads and/or additional pole placements, which can also raise the costs of the designs. Additional pavement markings are needed for most of the unconventional designs as well, but at costs insignificant relative to overall construction costs.

6.4 ANALYSIS TOOLS

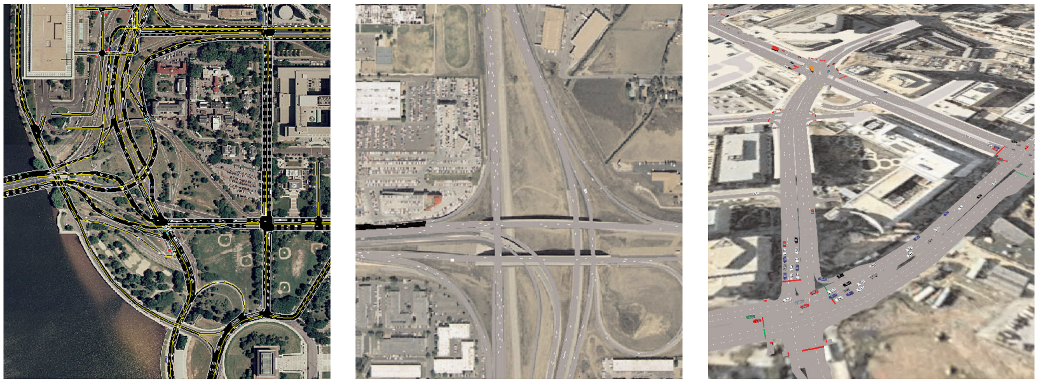
The use of traffic analysis and simulation tools has been extremely important and effective in showing the operational benefits of many of the unconventional intersection designs. It is standard practice today to use microsimulation to evaluate design alternatives in project planning. The benefits of the widely used simulation models are twofold: 1) they can provide very detailed traffic operational results within a network, where previous generations of static models could not, and 2) they provide visual animation of the traffic network results, providing credibility in the operational results to both technical and general audiences. Existing field conditions can be calibrated within most models, and potential solutions can be quickly tested and advanced or eliminated without wasting time or money on design and/or field experimentation. **Exhibit 62** provides a brief description of some of the most popular analysis tools used by state and local highway agencies for analysis of arterials.

Exhibit 62: Traffic Analysis Software Description

Traffic Model	Model Description
CORSIM (simulation)	One of the most widely used traffic microsimulation models and best utilized in the analysis of complex intersection or arterial operations. CORSIM provides realistic car-following and lane-changing desires, the ability to model complex signal systems, animation displays for validation and presentation, and a number of vehicle and system performance measures of effectiveness.
Synchro (urban street analysis & signal optimization)	Widely used signal-timing software that can model two-way stop, all-way stop, and roundabout intersections using HCM 2000 methods. Output measures of effectiveness include vehicle delay and level of service queue length, stops and fuel usage. Synchro can optimize splits, cycle lengths, phase orders and offsets and can export into easy to use text files for sharing data, including SimTraffic, the simulation animation model developed for Synchro networks.
Transyt 7F (signal optimization)	A traffic signal timing optimization software package for traffic networks, arterials or single intersections of simple or complex conditions. It has broad capabilities including: phase length optimization, phasing splits and offsets sequencing, traffic-actuated control, simulation of platoon dispersion, queue spillback and spillover, and flexibility in modeling unusual lane configurations and timing plans.
SIDRA (intersection and network analysis)	SIDRA is an Australian software package based on gap acceptance algorithms that can effectively model most intersection geometries. SIDRA is particularly known for its ability to analyze roundabout operations, having been shown to accurately predict delays and capacity for Australian and US roundabout designs.
HCM Software (intersection & network analysis)	HCS 2000 software is based on procedures defined in the 2000 Highway Capacity Manual (HCM) and is widely used for operational, design and planning analysis. It is considered as the standard traffic analysis tool for many public agencies as it is based on the accepted practices of the HCM. Modules include: basic freeway sections, weaving areas, ramps and ramp junctions, urban arterial streets, multi-lane highways, signal and unsignalized intersections and transit. It provides a user-friendly graphic entry option for lane configuration and volume data and generates interactive, formatted reports that produce forms like the HCM2000 worksheets.
VISSIM (urban streets, transit networks)	A stochastic microscopic simulation model, capable of simulating traffic operations in urban areas with special emphasis on public transportation and/or multimodal transportation. The car following logic of VISSIM is based on a psycho-physical driver behavior model, capable of simulating up to ten times per second. VISSIM is also capable of modeling in 3D animation, allowing the user to customize individual vehicle types with a 3D graphic generator.

The use of traffic simulations played a major role in the Maryland State Highway's acceptance of the first Continuous Flow Intersection design. Analyses using NETSIM and Synchro concurred that the design would provide travel timesavings, and a 3-D model of the intersection helped illustrate the design concept. In Michigan, the CORSIM model proved invaluable in an analysis comparing a Median U-Turn design to a conventional intersection design, as operational results included an accurate representation of left-turn movement and total network delays for comparison. Despite the additional left-turn path, the model identified improved signal operations and a net travel time benefit compared to the conventional design for most volume scenarios.

Exhibit 63: CORSIM, Synchro and VISSIM Simulation Graphics



Examples of Synchro/Sim-Traffic (left), CORSIM (center), and VISSIM (right) simulation graphic capabilities

The survey of state highway agencies conducted as part of this research effort included questions on which software analysis tools were being used by the highway agencies in evaluating arterial intersections or networks. The agencies were asked to rank several software packages on how often they are used, from 1 being the most commonly used to 5 being the least frequently used (or not at all). **Exhibit 64** summarizes survey results.

Exhibit 64: Traffic Software Tools Used for Arterials Analysis

Software	Agencies Rated #1 Used	Never Used	Total Score*
HCS	13	1	91
Synchro	12	0	82
CORSIM	0	3	42
Transyt 7F	1	3	36
Passer (II or III)	1	3	33
SIDRA	0	7	16
VISSIM	0	11	3
Other	0	-	2

** Total Score is cumulative of survey ratings of 1 to 5, with a number 1 response receiving 5 points, number 2, four points and so forth.*

A similar survey of randomly selected members of the Institute of Transportation Engineers was conducted in 2000 to determine the most prevalent traffic engineering software being used. Respondents to this survey averaged nearly 15 years of experience and included employees of local government (29 percent), private engineering companies (60 percent) and state departments of transportation (11 percent). **Exhibit 65** summarizes the survey results:

Exhibit 65: Traffic Software Packages Used By Traffic Engineers (1995-2000)

Package	% Used	Applications
HCS	93	Capacity Analysis
Synchro	54	Capacity Analysis; Signal Timing Optimization
SimTraffic	35	Simulation
Transyt 7F	25	Signal Timing Optimization
CORSIM	22	Simulation
Passer-2	23	Signal Timing Optimization
TEAPAC	19	Capacity Analysis
Passer-3	9	Signal Timing Optimization
TRAFFIX	9	Capacity Analysis
HCS Cinema	6	Capacity Analysis, Simulation
SOAP	4	Signal Timing Optimization
Passer-4	4	Signal Timing Optimization
CORFLO	3	Simulation
Integration	3	Simulation
PARAMICS	2	Simulation
TSSP Draft	2	Signal Timing Optimization
VISSIM	0.2	Simulation

Source: Institute of Transportation Engineers. User Survey, 2001.

6.5 IMPLEMENTATION ISSUES

Once an unconventional design has made it beyond the planning and testing stages, there are additional special considerations during the design and operations phases.

6.5.1 Designing for Drivers

Visualizing Operations and Impacts

A new intersection design or operations plan may not be difficult to understand looking at it on the drawing table as a plan view, but the real test to understanding is from a driver's perspective at the ground level. Engineers should take all necessary steps in visualizing the driver's path through the intersection, including reaction to signal and sign placements and other periphery vision encroachments. Today's technology can make this easier with 3-D simulation tools available to view the intersection operations. Similar technologies can also be used to show the visual impacts to right-of-way and adjacent properties. These tools and efforts can be expensive but more than make up their cost in explaining the visual impacts to motorists and property owners along the corridor.

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Driver Expectation

Driver expectations are often cited as reasons to reject unconventional design. To gain a better understanding of motorist behavior related to design geometrics, driver expectancy issues can be divided into two categories:

- Ad hoc experiences are short term based on site-specific encounters while driving. Ad hoc experiences can be improved by marketing the design before it opens but, more importantly, with attention to design details including signing, marking and design elements that bear a close resemblance to conventional design and practice. This may include a consistent signal control use and placement along the arterial, removal of any non-essential sign "clutter" near the intersection, and a consistency in pavement edge through the intersection (removal of subtle lane shifts or reverse curves in the design).
- Prior expectancies are long term based on experience and learned action. Drivers can more safely navigate intersections that they know or that have become standard through consistent design criteria. Unconventional designs should strive toward consistency in design as they are further propagated, to move more drivers' experiences from ad hoc to prior.

Agencies also have found that driver expectancy is best met if unconventional alternatives are used at several nearby locations or on a whole section of the arterial.

6.5.2 Signing and Marking

It is not necessary to re-invent signage plans for each new location, although each state or local jurisdiction may have differing advance signing requirements. Many of the unconventional designs that have been in place and/or utilized for a number of years by a particular agency already have consistent or institutional signing plans available (some states have signing and marking roadway design standards or supplements to the Federal Highway Administration's Manual of Uniform Traffic Control Devices) that appear to be effective, which can serve at least as a starting point, if not an end point, in preparing signing and marking plans.

6.5.3 Enforcement

Unconventional designs do not require any formal enforcement once the design is in place. Most of the designs are self-enforcing; that is, it is the drivers' own sense of self-preservation and his or her desire to avoid the wrath of other drivers (honking of horns) that serves as the deterrent to performing illegal, unsafe, or inefficient movements. However, stationed enforcement can be an aide and deterrent during the initial few weeks after a design goes into operation to assist in discouraging illegal intersection movements. The level of enforcement effort can be based on the number of "illogical" movements that the unconventional design requires (some designs have none), and can be gradually reduced as drivers get used to new turning patterns.

6.5.4 Public Information Campaigns

In addition to being essential in the planning stages, informing the public is also an important aspect of implementing unconventional designs. Many of the unconventional designs presented in this monograph have been introduced safely and effectively through pro-active education campaigns and by using effective signing and marking designs. However, a costly marketing campaign may not always be necessary, depending on the segment of the public to be reached. An extensive and/or costly campaign may not be effective in an area with a large out-of-state tourist population. Also, extensive marketing may not be necessary for a design where most motorists could navigate it given proper signing and marking.

Methods of educating the public on new designs include informational packets and brochures, press releases and driver educational programs. Public information brochures can be distributed to motorists through driver education teachers, student councils, safety program participants, highway department public information officers, traveler centers, driver license renewal stations, trucking associations and civic groups. State highway press releases very often lead to newspaper stories. Newspapers and other media outlets will typically run columns or articles about new traffic patterns, designs or pattern updates, often based on their perceived importance to the driving public.

Summary

For unconventional intersection designs to effectively be introduced to highway agencies and the traveling public, it is important to communicate the range and depth of benefits that unconventional intersections can achieve for motorists, pedestrians, land owners, developers, highway agencies, taxpayers and elected officials. Planning and operations studies should consider project impacts to safety, capacity, pedestrian movements, air quality, the community and environmental and project costs. The use of traffic simulation tools has been extremely effective in analyzing and illustrating operational benefits of unconventional intersection designs and providing result credibility to both technical and general audiences.

Highway agencies and property owners must be convinced that highway users will understand and accept changes to intersection navigation and access without compromise of safety and economic development interests. Established unconventional intersection designs have shown that agencies can effectively mitigate confusion seemingly inherent in navigating unconventional intersections with proper intersection geometric signing and marking design, and public awareness campaigns. Marketing studies and surveys often show that initial fears are unwarranted by eventual outcomes.

APPENDICES

GLOSSARY OF TERMS

Access Management - The systematic control of the location, spacing, design and operations of driveways, median openings, street connections and interchanges along a roadway corridor, with the aim of improving vehicular flow and reducing and separating conflict points.

Actuated Signals - Traffic signals that use detectors embedded in the pavement or mounted on overhead poles that detect vehicles and/or queue lengths and make adjustments to the order and/or duration of movements permitted.

Arterial - A major roadway intended to serve primarily through traffic, generally of regional importance and intended to serve moderate to high volumes of traffic traveling longer distances at higher speeds. Arterials generally allow at least some direct access at major cross street intersections.

Bi-Directional Crossovers - Provisions within a wide median that permit left and/or U-turns from the divided roadway and cross street in both directions, thus introducing the potential for turning movement conflicts.

Channelization - The separation or regulation of conflicting traffic movements into defined paths of travel by traffic islands or pavement markings with the aim of facilitating safe and orderly traffic movements for both vehicles and pedestrians.

Clearance Phase - An allotment of time within a traffic signal cycle where all movements show either a yellow or red signal as the priority movements are transitioned from one approach (or tuning movement) to a conflicting approach.

Conflict Point - A location within an intersection or along a roadway where vehicle movement paths conflict with other opposing vehicle or pedestrian movement paths, creating the potential for crashes.

Conventional Intersection - Intersection of two roadways that provides direct turning movement in all directions for all approaches under signal control.

Cycle Length - The amount of time (usually measured in seconds) it takes to go through all phases of a traffic signal and return to the beginning phase. Typical cycle lengths vary from 60 seconds (short and simple phases) to 180 seconds and greater (long and multiple phases).

Directional (Left Turn) Crossovers - Exclusive, one-way lane designed into a wide roadway median for left and U-turns. The one-way movement eliminates conflicts with opposing left and U-turning vehicles present with bi-directional median openings.

Driver Expectation - Design geometrics, signals or signage that are anticipated by the average driver under normal circumstances. Deviation from typical movement paths through an intersection may give rise to driver confusion and/or error, particularly if the geometry is unique and/or signage and pavement marking is unclear.

Free Flow - An unopposed movement that can be made freely, typically referring to a right turn lane that does not have to stop at the intersection.

Freeway - A major roadway, such as an interstate, intended to serve long-distance through-traffic at high speeds. Freeways are distinguished from other road types by their free-flow movements and limited access. Freeways do not allow driveway access or stop- or signal-controlled access from cross-streets. All access is from ramps at grade-separated intersections.

Inscribed Diameter - For a roundabout, the greatest distance across the interior (usually raised) area around which traffic circulates. Inscribed diameter is measured from the inner (left) edge of roadway pavement.

Jersey Barrier - Interlocking concrete barriers that are often used to form a wall restricting access across a median. It is used extensively in the Jughandle design popular in New Jersey, thus coined "jersey" barrier.

Level of Service - A measure of driver expectation, comfort, and average delays experienced at signalized and unsignalized intersections. This measurement of service is associated with a letter-grade scale of A to F, with A representing virtually no intersection delay and F representing severe congestion (with long queues and stop-and-go conditions). Level of service can also be used to define service levels along roadways.

Locking Left Turns - Locking left turns occur at median locations or on two-way left-turn lanes where left-turn movements from opposing directions share the same pavement space and cause conflict in movement hierarchy and/or queuing on the arterial or cross street.

Mobility - The ability to move within a roadway network. Roadways with excessive congestion and few alternative routes and/or no transit alternatives are said to have poor transportation mobility, and a roadway with higher speed limits and limited congestion is said to have good vehicular mobility.

Multi-phase Signal - A traffic signal controlling a single intersection that has more than the minimum two phases, typically including left-turn movements under a separate movement phase.

Oversaturated - Conditions at intersections where the vehicle arrival demand is greater than the ability of the intersection to process arriving vehicles, resulting in queues approaching the intersection that grow until demand is reduced.

Permissive Left Turns - At an intersection, left-turn movements that are not protected by an exclusive green-arrow signal phase, requiring motorists to wait for an adequate gap in opposing traffic to complete a left-turn movement.

Progression - The movement of traffic along a roadway in platoons regulated by traffic signals. Signal systems that are timed to allow platoons of traffic to pass through several intersections without stopping can be said to provide "good progression."

Spillback - Vehicle queues that extend beyond the length of an intersection approach turning bay or queues that extend back from one intersection through the previous intersection, often causing operational problems at the intersection.

Start Up Lost Time - A measure of intersection inefficiency, the time from the start of a green phase to when optimal travel speed through the intersection is achieved, typically after the first four to five vehicles that require start-up reaction and larger acceleration headway times.

Sustainable Highways - Roadways that have been planned and designed to promote the protection and enhancement of environmental and community needs to ensure that transportation projects benefit communities in the near-term as well as for generations to come.

Two-Phase Signals - The simplest form of traffic signal control that alternates right-of-way between two intersecting roadways, with no additional signal phases protecting turning traffic.

Unconventional Intersection - A departure from a "conventional" intersection that allows direct turning movements in all directions. Unconventional intersection designs have one or more left-turn movements that are made indirectly, involving a longer or more circuitous turning path.

Warrants - A set of criteria by which adequate grounds are given to recommend safety or geometric improvements to roadways or signals, typically based on pre-set standards or formulas.

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Abbreviations

AASHTO - American Association of State Highway and Transportation Officials
ADT - Average Daily Traffic
BRT - Bus Rapid Transit
CFI - Continuous Flow Intersection
CFL - Contraflow Left Interchange
CTO - Center Turn Overpass
EPA - Environmental Protection Agency
FHWA - Federal Highway Administration
HCM - Highway Capacity Manual
HOV - High Occupancy Vehicle
ITE - Institute of Transportation Engineers
ITS - Intelligent Transportation Systems
LOS - Level of Service
MDOT - Michigan Department of Transportation
MUDI - Michigan Urban Diamond Interchange
NCDOT - North Carolina Department of Transportation
NJDOT - New Jersey Department of Transportation
Parclo - Partial Cloverleaf
SPUI - Single Point Urban Interchange
TTI - Texas Transportation Institute
VMT - Vehicle Miles Traveled
vpd - vehicles per day
vph - vehicles per hour
vphpl - vehicles per hour per lane

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Survey and Results

INNOVATIVE INTERSECTION AND GRADE-SEPARATION DESIGNS

Please include your agency's experience with the following intersection and interchange designs, and include information on any other innovative intersection design that your agency has experience with. Keep in mind that interchange designs must be applicable to surface roadway applications and not freeway-type facilities.

AT GRADE INTERSECTION DESIGNS

1. Median U-Turn: Removes all left-turn movements at the main intersection using one-way crossovers in the median. Left turning vehicles pass through the intersection twice, once as a through movement, and once as a right turn.

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
☐	☐	☐	☐	☐

Example in-field intersection:

______________________ *(Streets)*

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Comments on use, acceptance, effectiveness, safety, operational issues, etc:

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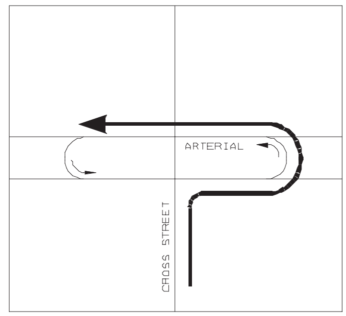

2. Superstreet: Similar to the median u-turn, but features a break in cross street traffic that allows independent signals on the arterial. Signals in both directions on the arterial can be progressed perfectly, at differing cycle lengths and collector spacing.

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
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Example in-field intersection:

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Comments on use, acceptance, effectiveness, safety, operational issues, etc:

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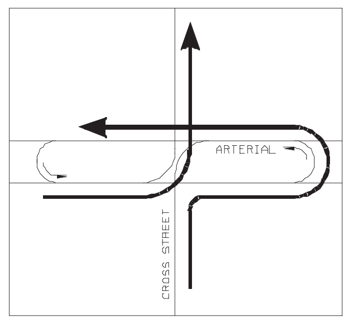

3. Split Intersection: Separates the collector into one-way pairs, with signals at both intersections with the arterial. Signals have three phases that operate similar to a diamond interchange ramp intersection.

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
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Example in-field intersection:

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Comments on use, acceptance, effectiveness, safety, operational issues, etc:

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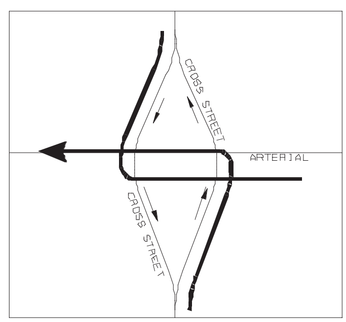

4. Jughandle: Uses right-diverging ramps to accommodate all turns from the arterial. Arterial lefts turn onto the cross street at the ramp termini that can be stop or yield controlled. Design may include loops to remove left turns from collector to arterial.

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
☐	☐	☐	☐	☐

Example in-field intersection:

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Comments on use, acceptance, effectiveness, safety, operational issues, etc:

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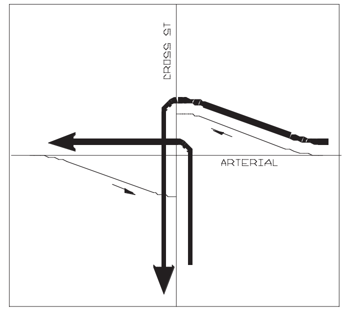

5. Two-Lane Roundabouts/Traffic Circles: Use large circular roadway (a least 2 lanes) to handle all through and turning movements. Can be both yield controlled (roundabout) or free-flow merge control (traffic circles with larger diameter).

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
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Example in-field intersection:

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Comments on use, acceptance, effectiveness, safety, operational issues, etc:

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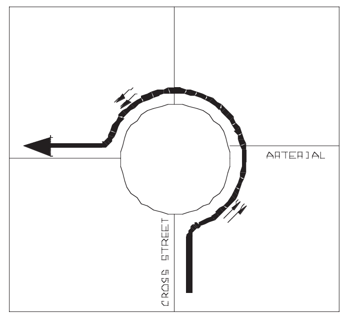

6. Quadrant Roadway: Removes left-turn movements from the main intersection using an additional roadway in one intersection quadrant with T-intersections at both ends. Each directional left-turn pattern is different.

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
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Example in-field intersection:

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Comments on use, acceptance, effectiveness, safety, operational issues, etc:

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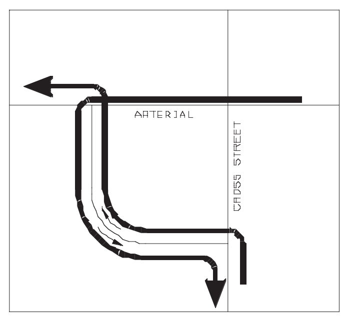

7. Continuous Flow Intersection: Features a short roadway segment to the left and upstream of the main intersection to handle left turning traffic, resulting in a two-phase signal with simultaneous through and protected left turns at the main intersection.

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
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Example in-field intersection:

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Comments on use, acceptance, effectiveness, safety, operational issues, etc:

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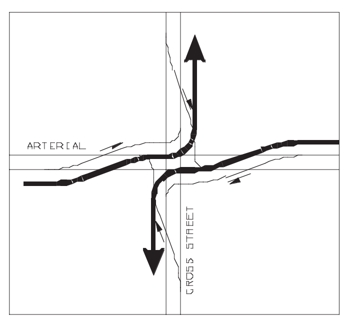

8. Offset T-Intersections: Splits cross street movements using arterial roadway. Through traffic jogs onto arterial for short distance, and each cross street intersection operates as a three-phase signal.

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
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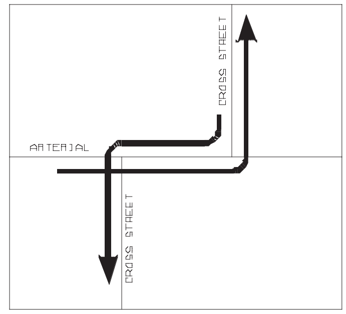
Example in-field intersection:

(Streets)

(City)

Comments on use, acceptance, effectiveness, safety, operational issues, etc:



9. Continuous Green T: Used only at T-intersections, one direction of arterial travel does not have to stop at the cross street. Left turns from the cross street onto the arterial merges from the left onto the free-flowing arterial lanes.

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
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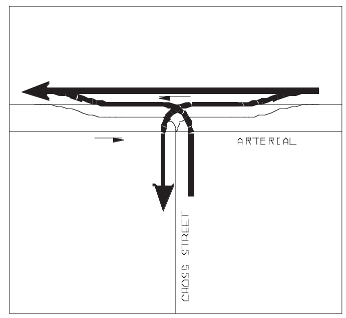
Example in-field intersection:

(Streets)

(City)

Comments on use, acceptance, effectiveness, safety, operational issues, etc:



10. Bowtie: Uses roundabouts on the collector to accommodate left turns, negating the need for a wide median on the arterial. Left turns are prohibited at the main intersection resulting in a simple two-phase signal.

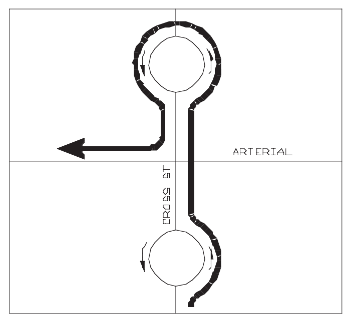
Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
☐	☐	☐	☐	☐

Example in-field intersection:

(Streets)

(City)

Comments on use, acceptance, effectiveness, safety, operational issues, etc:



11. Paired Intersections: Prohibits left-turns from the arterial to the cross street then from the cross street to the arterial at alternating intersections, resulting in three-phase signals at all intersections. Intersections are linked with frontage roads (collectors) to serve all movements.

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
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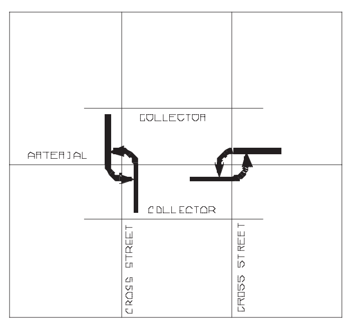
Example in-field intersection:

(Streets)

(City)

Comments on use, acceptance, effectiveness, safety, operational issues, etc:



GRADE-SEPARATED INTERSECTION DESIGNS

12. Partial Cloverleaf: Includes two loop ramps to accommodate left-turn movements from the arterial. Loops can be in different quadrants, which effects bridge width and/or turn bay requirements on cross street.

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
☐	☐	☐	☐	☐

Example in-field intersection:

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(Streets)

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Comments on use, acceptance, effectiveness, safety, operational issues, etc:

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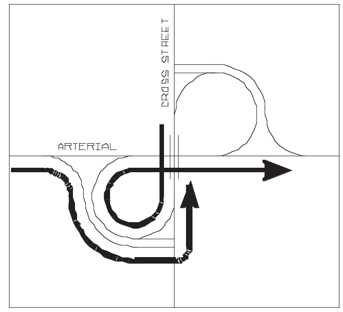

13. Compressed Diamond: Ramps to cross street above are tight to the arterial, often requiring retaining walls. The ramp intersections at the cross street are closely spaced often including four coordinated progressive phases.

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
☐	☐	☐	☐	☐

Example in-field intersection:

____
(Streets)

____
(City)

Comments on use, acceptance, effectiveness, safety, operational issues, etc:

____

____

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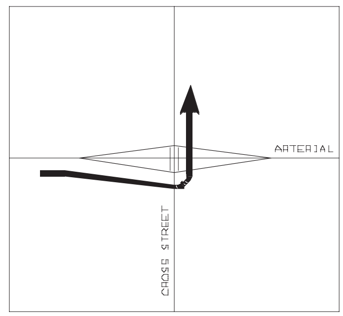

14. Single Loop Interchange: Uses a roadway in a single intersection quadrant to handle turns between arterial and cross street. More typical in rural locations, the single loop design can be enhanced with multiple turning lanes & coordinated signals.

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
☐	☐	☐	☐	☐

Example in-field intersection:

____
(Streets)

____
(City)

Comments on use, acceptance, effectiveness, safety, operational issues, etc:

____

____

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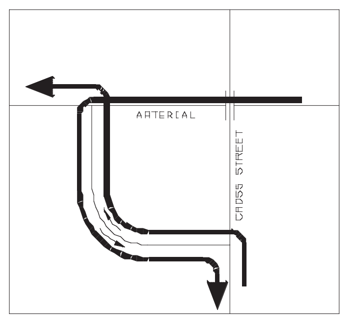


15. Rotary Interchange: Arterial is grade-separated under the cross street, built as a large roundabout. Ramp and cross street intersections can be signal or yield controlled, depending on the circle diameter and cross street traffic volumes.

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
☐	☐	☐	☐	☐

Example in-field intersection:

____
(Streets)

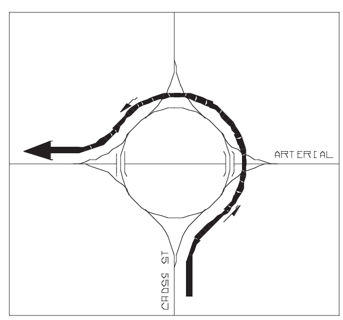
____
(City)

Comments on use, acceptance, effectiveness, safety, operational issues, etc:

____

____

____



16. Raindrop Interchange: Cross street grade-separated over arterial uses roundabouts at each ramp intersection to handle all left-turn movements to/from ramps to the arterial.

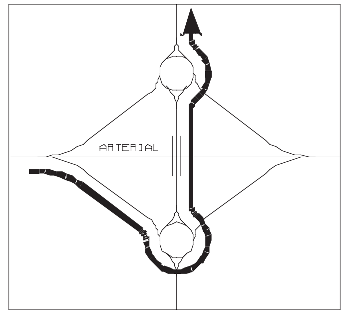
Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
☐	☐	☐	☐	☐

Example in-field intersection:

(Streets)

(City)

Comments on use, acceptance, effectiveness, safety, operational issues, etc:



17. Echelon Interchange: Elevates one-half of each intersection approach to elevate on structure while the other halves intersect at-grade. All intersection approaches become one-way streets and can be controlled by 2-phase signals.

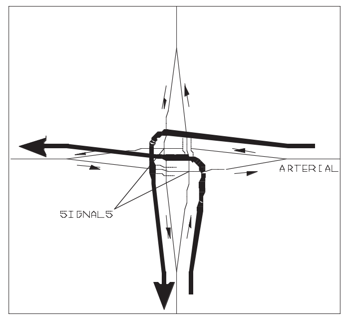
Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
☐	☐	☐	☐	☐

Example in-field intersection:

(Streets)

(City)

Comments on use, acceptance, effectiveness, safety, operational issues, etc:



18. Center Turn Overpass: Raises all left-turning traffic approaches in the median on structures to a level grade-separated from the intersection of through and right-turn movements. Each level is governed by two-phase signals.

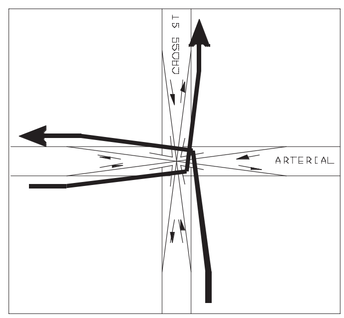
Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
☐	☐	☐	☐	☐

Example in-field intersection:

(Streets)

(City)

Comments on use, acceptance, effectiveness, safety, operational issues, etc:



19. Single Point Urban Diamond: Creates a single intersection of arterial left turns and cross-street through and left turns over (or under) the free-flowing arterial. The signal is typically 3-phase, with left-turn movements turning inside each other.

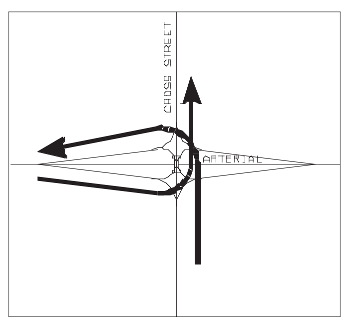
Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction	Considered in planning study but rejected	No design or planning application to date
☐	☐	☐	☐	☐

Example in-field intersection:

(Streets)

(City)

Comments on use, acceptance, effectiveness, safety, operational issues, etc:



OTHER ARTERIAL INTERSECTION DESIGNS

Please indicate other innovative intersection designs not listed in the previous section that your agency uses at high-volume arterial intersections. An **at-grade** intersection design considered innovative removes at least one left-turn phase by diverting left turning vehicles in some fashion. A **grade-separated** intersection design considered innovative includes any interchange design (excepting the standard diamond interchange) that can be applied to arterial (non-freeway) roadways.

Name & Description:

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction
☐	☐	☐

Example intersection:

Streets:

City:

Comments on use, acceptance, effectiveness, safety, operational issues, etc:

Sketch of Intersection

Name & Description:

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction
☐	☐	☐

Example intersection:

Streets:

City:

Comments on use, acceptance, effectiveness, safety, operational issues, etc:

Sketch of Intersection

Name & Description:

Widely used on principal arterial system	Used at few isolated intersection locations	First use currently in design or construction
☐	☐	☐

Example intersection:

Streets:

City:

Comments on use, acceptance, effectiveness, safety, operational issues, etc:

Sketch of Intersection

Traffic Operations, Policy and Funding:

Please answer these questions to the best of your ability or leave blank if unclear. The name and position of the respondent will remain confidential, but all responses given may be included in written material including comparison to other agencies' responses.

---

1. Does your agency permit **left turns on red** onto a one-way cross street?

Yes, unless prohibited by sign	Only if signed	Never
☐	☐	☐

2. Does your agency permit U-turns at signalized intersections along divided median roadways?

Yes, unless prohibited by sign	Only if signed	Never
☐	☐	☐

3. Does your agency have an established maximum cycle length for principal arterials? Is there preferred common cycle length? Does your agency have a minimum green split (percent of total cycle) requirement for regional arterials (if no for any response, write "none")?

Maximum cycle length	Preferred common cycle	Minimum green split
______sec	______sec	______sec

4. Does your agency have an established policy for selecting right-of-way widths for arterial corridors at the planning level?

Yes, minimum width	Common width	No, varies depending on corridor
____________ ft	____________ft	☐

5. In **your opinion**, is your agency **proactive** towards design innovation? List reasons why or why not.

____

____

Yes	No	Sometimes
☐	☐	☐

6. Rank in order (#1 being most important) the reasons why your agency **would consider** an innovative intersection design solution.

Would never consider	Reduce left turn impacts	Reduce congestion	Improve safety	Improve pedestrian crossings	Improve arterial progression	Other ________
☐	( )	( )	( )	( )	( )	( )

7. Rank in order (#1 being most important) the reasons why your agency **might recommend against** innovative intersection design.

Driver expectation (safety)	Additional ROW requirement	Increased cost	Negative Impact to access	Driver disregard	Other _________
( )	( )	( )	( )	( )	( )

8. Rank in order (#1 being most important) the reasons why your agency **would consider** grade separation of two surface (non-freeway) roadways, if at all.

Would never consider	Volumes / capacity	Improve safety	Route importance	Terrain/ alignment	Other _________
☐	( )	( )	( )	( )	( )

9. Rank in order (#1 being most often) the traffic analysis tools your agency uses to evaluate intersections and arterials (place an "N" beneath the tools never used).

CORSIM	Synchro / SimTraffic	VISIM	Transyt 7F	Sidra	HCS	Passer (II or III)	Other ________
( )	( )	( )	( )	( )	( )	( )	( )

10. Does your agency have a set methodology to determine when left-turn phasing is warranted? If so, please briefly describe methodology and/or attach standards.

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11. What are your agency's primary & secondary sources of capital project and/or spot intersection improvement funding (e.g., TIP, general fund, CMAQ, sales tax, etc.)?

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Optional: Please provide a short list of reference materials, design standards, reports, articles or websites that your agency has found useful in designing high-volume intersections. In the included return envelope, please include any agency reports, studies, plans and/or aerial photos pertaining to innovative intersection designs.

____

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____

____

Agency Contacts:

As noted in the cover letter, I intend to follow-up by phone contact and possible field visit with those agencies that have extensive experience with specific or unique innovative intersection designs. Please provide this survey's respondent name and title, the most appropriate person for a phone interview about specific innovative designs, and a field engineer who may be willing to meet in the field to conduct an on-site survey.

Survey respondent agency: ____________________________

Survey respondent name: ______________________________

Survey respondent title: ________________________________

Telephone interview contact
(if different from respondent): ____________________________

Contact telephone number: ______________________________

Field engineer contact: ________________________________

Contact telephone number: ______________________________

Survey Results Summary

State	Designs Used	In Design / Construction	Considered & Rejected	LTOR	U-Turn	Cycle	ROW	Innovative Policy	LT Phasing Standards	Funding	Resources
AK	Parclo, SPUI	Roundabout Interchange		Yes	Yes	None	varies		None	FHWA	
AR	Parclo, Compressed Diamond			No	Yes	None	No		Guidelines from *Traffic Control Handbook*	STP funds	NCHRP Synthesis 225
CA	Multi-Lane Roundabout; Paired Intersection			No	Yes	120 max; 100 sec pref	120' common	No - old city, ROW difficult	Priority lost in California Traffic Manual left turn signal warrants.	Measure M, gas tax, TEA-21, OTS, TSI area fund	
CT	Jughandle, Roundabout, Offset-T, Single Loop				Yes	None	No		None	1) STPA; 2) State Bonds	
FL	Median-U Turn; Split Intersection; Jughandle; Quadrant Roadway; Paired Intersection; Continuous Green-T; Parclo; Compressed Diamond; Single Loop; SPUI			Yes	Yes	120 pref	80' min	No - low acceptance for change	*Traffic Control Handbook* (section 4C-1); Volume Warrant - left turn x opposing thrust > 100,000; Sight distance met; Crash - > 4 left turn crashed within 1 yr.	Primary - Gen Transp Fund (gas tax, user fees), FHWA State Funds; Spot - District safety/operation funds, CMAQ, Local agency funds	
HI	Jughandle; Roundabout			Yes	Yes	None	Varies	Generally like to stick to conventional, proven concepts. Innovative ones involve certain risks.	Peak left turning vols > 300 vph	State Highway Funds; Federal Aid Finds (STIP)	
IA				Yes	Yes	120 max		Slow to try innovative designs; more comfort with standard design.	None	TIP, Transportation Safety Improvement Program, Urban State Transportation Engineering Program	
IL	Quadrant Roadway; Parclo; Compressed Diamond; Single Loop; SPUI		Median U-Turn; Multi-Lane Roundabout; Continuous Green-T; Roundabout Interchange	Yes	Yes	None	Varies	Moderate, if not proven nationally difficult.	None	Federal (STP, IM, NHS, HES); State Funds	
KA	Continuous Green T; Compressed Diamond; SPUI	Multi-Lane Roundabout		Yes	Yes	None	Varies		Crashes, Volumes, lefts	Federal and State Safety Funds	
ME	Split Intersection; Jughandle; Multi-Lane Roundabout; Single Loop	Multi-Lane Roundabout	Continuous Green-T; SPUI	No	No	120 max	200' new; 66-100' existing		No, consider volumes & crashes	1) BTIP; 2) Federal CMAQ	
NE	Jughandle			Yes	No	None	No	No - lack of law enforcement, few high-volume locations, confuses elderly population.		Gas tax only	HCM
NH	Parclo, Compressed Diamond; Rotary, SPUI	Multi-Lane Roundabout, Bowtie, Roundabout Interchange		No	Yes	120 pref	Varies	No - Department will use only proven design techniques.	AASHTO procedure	Primary - Federal Highway Aid, State Turnpike Revenue; Secondary - State Gas Tax revenue	FHWA: *Roundabouts: An Informational Guide*; NCHRP reports; TRB reports

Reasons to Consider Unconventional Intersection						Reasons to Recommend Against Unconventional Design					Reasons to Consider Arterial Grade Separation					Traffic Analysis Software Used to Evaluate Intersection Operations						
Left turns	Congestion	Safety	Pedestrians	Progression	Other	Expectation	ROW reqd	Cost	Access	Disregard	Never Con	Capacity	Safety	Route	Alignment	CORSIM	Synchro	VISSIM	Transyt 7F	Sidra	HCS	Passer III
	2	1				1	2	4		3		1	2	3	4		1				2	
4	2	1	3	5		1	4	5	2	3		3	1	4	2		2		4	5	1	3
5	3	1	4	2		4	2	1	3	5		3	2	4	1	6	1	5	3		4	2
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3	4	1	2	5		3	1	4	2	5		1	2	3	4	4	1	N	2	5	6	3
5	2	1	4	3		1	3	4	5	2		1	2	3	4				2		1	
	2	3	1	4		1	4	3	2	5		1	2	3	4	3	2	N	5	N	1	4
4	2	1	5	3		3	2	1	5	4		2	3	4	1			N		N		
4	2	1	5	3		1	4	3	5	2		2	1	3	4	2	3	N	6	4	1	5
4	2	1	3	5		3	2	1	4	5		2	3	4	1	3	1			4	2	
1	4	2	5	3		1	4	2	5	3		3	2	1	4	2	1				3	
2	3	1	5	4		1	2	4	3	5		2	1	4	3	3	2	N	N	N	1	N

Survey Results Summary (cont.)

State	Designs Used	In Design / Construction	Considered & Rejected	LTOR	U-Turn	Cycle	ROW	Innovative Policy	LT Phasing Standards	Funding	Resources
NJ	Jughandle; Multi-Lane Roundabout; Offset-T; Continuous Green T; Bowtie (partial); Parclo	SPUI		No	Yes	Pref 120	std 15' median	Community relations program involves stockholders in planning and design. Some innovative concepts have emerged for consideration.	Delay study	FHWA; State transportation trust fund	
NM	Median U-Turn; Jughandle; Paired Intersection; Continuous Green T; SPUI				Yes	120 pref	Varies	Yes	R/W, LOS & mainline progression considered	1) Safety; 2) TIP	
NV	Multi-Lane Roundabout; CTG		Bowtie; CTO	No	Yes	140-160 max; 90-120 pref	Varies	Investigate ideas as they come along.	Dual turn pockets for protected phasing; number of lanes thru traffic must cross; opposing volumes; safety.		
NY	Jughandle; Multi-Lane Roundabout; CFI; Offset-T; Parclo; Compressed Diamond; Rotary; SPUI; Trumpet; Elevated Circle; Scissor		Roundabout Interchange	Yes	Yes	None		Developing a number of multilane roundabouts and are open to new ideas to solve transportation problems.	NYSDOT HDM chapter 11, page 139	TIP	NYSDOT HDM chapters 5 & 11 available at: www.dot.state.ny.us/cmb/consult/hdmfiles/hdm.html
PA	Jughandle	Multi-Lane Roundabout; SPUI		No	No	None	No		None	TI, CMAQ	
RI					Yes			No	None	TIP, Federal Funds	
TX	Multi-Lane Roundabout; Continuous Green T			Yes	Yes	None	Varies	From a structural standpoint, our agency is innovative. For high-volume interchanges, we use the standard cross interchange w/signals.	None; each intersection looked at independently considering number of lanes, speed, ADT, left turns, geometry.	CMAQ; STP Metro Mobility; STP Urban Mobility	TxDOT Roadway Design Manual, TMUCD, AASHTO
WA	Multi-Lane Roundabout; Offset-T; Continuous Green T; SPUI; Parclo, Compressed Diamond	Roundabout Interchange; "False Roundabout"		Yes	Yes	None	No - see std.	Always willing to think "outside the box."	Attached sec 850.06	Gas tax, motor vehicle and license fees	www.wsdot.wa.gov
WY	Compressed Diamond	Roundabout Interchange						Sometimes	1. Cross product of lefts x opposing thrust < 100,000; 2. Left turn delay exceeds 20 to 30 seconds.	Gas tax; general fund; mineral severance	

Reasons to Consider Unconventional Intersection						Reasons to Recommend Against Unconventional Design					Reasons to Consider Arterial Grade Separation					Traffic Analysis Software Used to Evaluate Intersection Operations						
Left turns	Congestion	Safety	Pedestrians	Progression	Other	Expectation	ROW reqd	Cost	Access	Disregard	Never Con	Capacity	Safety	Route	Alignment	CORSIM	Synchro	VISSIM	Transyt 7F	Sidra	HCS	Passer III
5	2	1	3	4		1	4	3	5	2		1	2	4	3	4	2	N	5	6	1	3
2	1	3		4		4	3	1	2	5		1	4	2	3	5	4		2		1	3
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4	1	2	5	3		3	2	1	4	5	1					4	2	5		3	1	
	1	2										1	2				2			3	1	

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