Research Article

TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Transportation Research Record
1–12

DOI: 10.1177/03611981211004978
journals.sagepub.com/home/trr
SAGE

Designing Crossing Islands for Speed Control and Intersection Safety on Two-Lane Collectors and Arterials

Peter G. Furth[1], Milad Tahmasebi[1], Sepehr (Steve) Shekari[2], Jay Jackson[3], Zhao (Howie) Sha[4], and Yousef Alsharif[1]

Abstract
Crossing islands at unsignalized intersections, in addition to their pedestrian crossing safety benefits, can also serve as speed control chicanes by forcing vehicles to make a reverse curve. A method is developed for determining the chicane length (and thus, parking setback) needed for a two-lane road for a given lane width, island width, and target speed, based on models of the relationship between road geometry vehicle path radius, and speed. New data on the speed–radius relationship is presented. The concept of "informal flare" is also introduced; it is a common approach geometry that allows a left-turning vehicle to wait for a gap in opposing traffic without blocking through traffic behind it. Using informal flares can make it possible to prevent left-turn blockage without sacrificing a crossing island for a left-turn lane. Curb continuation lines at median openings are presented as a means to enhance informal flare function. Original data are presented relating informal flare function (the tendency of through vehicles to bypass a waiting left-turner) to a road's half-width. Geometric analysis shows that intersections with crossing islands can fit on roads with right of way as narrow as 60 ft, and with curb-to-curb width as narrow as 40 ft, while still accommodating turning school buses and bike facilities and preventing left-turn blockage. Various performance measures are used to evaluate intersection geometry, including measures related to through vehicle speed, turning vehicles, and pedestrians. With crossing islands, pedestrian safety with respect to left-turning vehicles is substantially improved as the turning path becomes square to the crosswalks, making the vehicle path more predictable and reducing vehicle speed, conflict area size, and pedestrian exposure distance.

On arterial and collector roads, speed control is widely recognized as vital for safety and livability. However, it remains a persistent challenge because such roads are not amenable to speed humps and similar traffic calming devices because of their function as through roads, emergency response routes, and (often) transit routes.

On roads with one through lane per direction, installing median islands that force traffic to swerve to the outside and then back again to the inside can be a way to control speed. Treatments that create this kind of horizontal deflection are called chicanes, a term borrowed from racing. While speed control islands can be installed anywhere along a road, there is a strong safety advantage to locating them at intersections, where they can also function as crossing islands, also called pedestrian refuge islands. This study is limited to roads with one through lane per direction because on multilane roads, any horizontal deflection strong enough to limit speed would create a high sideswipe risk.

Limiting speed is critical not only for lowering crash risk and severity, but also for engendering yielding compliance at crosswalks. Bertulis and Dulaski (*1*) found that on streets whose 85th percentile speed was in the range 20–23 mph, the yielding compliance rate for staged crossings was 70%, versus only 41% on streets whose 85th percentile speed was 29 or 30 mph.

Apart from speed control, crossing islands are also a powerful tool for making crossings safer by making them shorter, simpler, and more conspicuous. One crosses a single direction at a time, and, on a road with one lane per direction, only one lane at a time. This makes crossings more accessible to children and to slower pedestrians. Their conspicuity promotes motorist yielding.

[1]Department of Civil and Environmental Engineering, Northeastern University, Boston, MA
[2]Environmental Partners, Quincy, MA
[3]Massachusetts Bay Transportation Authority, Boston, MA
[4]HDR, Inc., Dallas, TX

Corresponding Author:
Peter G. Furth, p.furth@northeastern.edu

Crossing islands also prevent cars from making wide, sweeping left turns, a danger that has been highlighted in a recent New York City safety study that prompted a strategy of “hardening the centerline” (*2*). A review of several before-after studies has assigned crossing islands a crash modification factor of 0.68, meaning that they are expected to reduce the number of crashes by 32% (*3*).

In European countries, including Germany and the Netherlands, crossing islands are extensively used on two-lane arterial and collector roads at unsignalized intersections. American guidance has promoted their use at roundabouts and on multilane roads, but has been oddly silent as to whether they might be of benefit on two-lane roads (*4*).

Several reasons can be suggested for the relative paucity of crossing islands on two-lane roads in the U.S.A. compared with Europe. One is that the U.S.A. has historically had weaker standards of pedestrian crossing safety. In both Germany and the Netherlands, an unsignalized crossing may not span more than two through lanes. (In effect, that caps road width in built-up areas to four lanes, with a median island, unless the road has traffic signals at every crossing.) In the U.S.A., there is no such limit; unsignalized crosswalks that span four lanes and more are common. Some European cities, including Delft, go still further, making it a policy that no unsignalized crosswalk may span more than one marked lane—a policy that effectively mandates crossing islands at all unsignalized intersections except those between local streets, which typically have no marked lanes. A second reason is that it is often hard to find the space to widen a road at an intersection. In the U.S.A., unlike in Europe, it is not common to have extra right of way (ROW) at intersections. Another practical obstacle is that installing crossing islands can involve losing parking spaces. This may be a reason they are less popular as an intersection safety treatment than corner bulbouts, which make crossings shorter, but have nowhere near the same safety impact as crossing islands.

A final practical barrier to implementing crossing islands is the need for a left-turn lane or its functional equivalent, so that a car waiting to turn left will not block through traffic. This functionality is especially important in road diet projects, which restrict traffic that formerly used two lanes per direction to a single lane per direction. Because of this need, the standard form of a road diet has a pair of through lanes plus a center turning lane which becomes a left-turn lane at intersections—consuming space that might otherwise have been used for a crossing island.

Three main sections follow, corresponding to this paper’s three objectives. The first develops a method for designing crossing island chicanes for speed control based on the geometry and physics of reverse curves. It includes an account of an experiment measuring vehicle speed versus vehicle path radius at a crossing island chicane. The second section introduces the concept of *informal flare*, meaning providing left-turn lane functionality without marking an auxiliary lane. It also describes *curb continuation lines* at median breaks as a treatment for increasing the effectiveness of informal flares. The third section aims to test the feasibility of fitting crossing island chicanes into the limited ROW of an intersection between a narrow collector road and a local street while still accommodating large turning vehicles, left turns (without blocking through traffic), and bicycles.

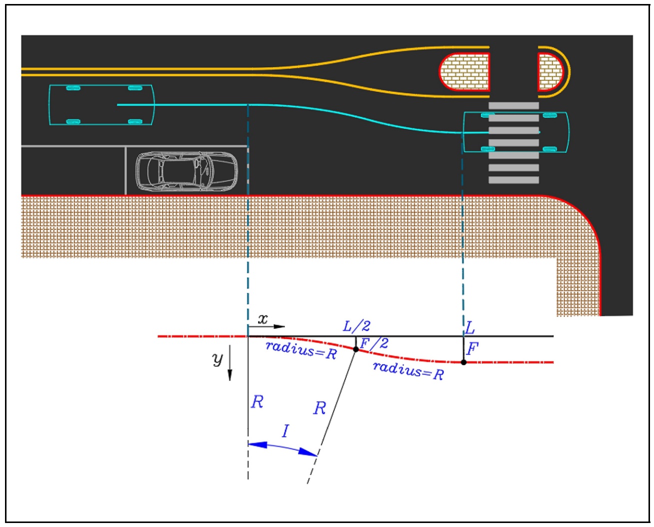

Figure 1. Geometry of a crossing island chicane.

Crossing Island Chicane Geometry and Speed Control

As shown in Figure 1, the path of a vehicle that shifts its lateral position when negotiating a crossing island can be modeled as a pair of equal radius, opposite direction curves with combined lateral offset F and combined length (measured along the road’s axis) L. It is reasonable to assume equal radii because the lateral force felt by the driver is inversely proportional to the radius, and for a given L and F, a driver minimizes the maximum force felt by equalizing the radii of the two curves. If the internal angle for each curve is I, the coordinates of the curve reversal point can be expressed as

$$x = R\sin(I) = \frac{L}{2}$$

$$y = R[1 - \cos(I)] = \frac{F}{2}$$

Then using the trigonometric identity $sin^2\ I\ +\ cos^2\ I\ =\ 1$, radius of curvature R can be inferred as a function of F and L:

$$R = \frac{F^2 + L^2}{4F} \tag{1}$$

Radius of curvature is important because the lateral acceleration of the car, from basic physics, is

$$a = \frac{v^2}{R}$$

where

v = car speed

a = lateral acceleration.

The lateral force needed to keep the car on track, transmitted from the road surface via the tires, is this acceleration multiplied by the car's mass, and is generally expressed as the product mfg, where

m = mass of the car

g = acceleration from gravity = 32.2 ft/s^2

f = side friction factor

Therefore, speed and side friction are related by the equation

$$f = \frac{v^2}{Rg} \tag{2}$$

A road's cross-slope or superelevation, an important factor in highway curve design, is ignored in this analysis because cross-slope will be favorable for half of the S-curve and unfavorable for the other half, canceling its effect.

Drivers experience the same lateral forces as their car. Lateral forces to keep them from sliding across their seat are transmitted via the seat as well as by holding the steering wheel—however, the latter is tricky because drivers are also using the steering wheel to control the car. Driver comfort—including feeling that one still has control of the car—is what limits the side friction drivers are willing to experience. It is well known that the limiting side friction factor varies with speed (*5*); at lower speeds, drivers are willing to experience greater lateral forces.

The offset of the vehicle path depends partly on the chicane geometry, but also partly on driver choices as to initial and final lateral position. Minimizing lateral forces, which is the same as finding the fastest path, means minimizing F by beginning close to the parking lane and ending close to the island, as in fastest path analysis done for roundabouts (*6*, *7*). Of course, drivers also have competing concerns about hitting a parked car and hitting the island. Initial and final lateral position can be expressed as offsets from the center of the vehicle to the centerline and to the edge of the island:

F_o = initial vehicle offset from the centerline

F_{isl} = vehicle offset from center of vehicle to the edge of the island

W_{isl} = island width

$IslEnc$ = distance that the crossing island encroaches into the approach lane; for a symmetric road, $IslEnc = W_{isl}/2$

The vehicle path offset is then given by

$$F = IslEnc + F_{isl} - F_o \tag{3}$$

In the field test described below, it was observed that drivers approaching next to a parking lane center their vehicles roughly between the centerline and a line 9 ft from the curb, and that at the crossing island, drivers position the edge of their car about 3 ft from the edge of the island. This latter finding differs from the standard assumption in roundabout fastest path analysis that the center of a vehicle can come within 5 ft of a curb, meaning, for a car 6 ft wide, a 2 ft offset from the edge of the island; part of the reason for the difference is that the present analysis models average vehicle speed at a chicane, not the theoretically fastest vehicle. Assuming a car width of 6 ft, then,

$$F_o = \frac{H - 9}{2} \tag{4}$$

$$F_{isl} = 6 \tag{5}$$

where H = road half-width (curb to centerline). For a symmetric layout with parking on the approach roadway, F can be restated with regard to direct road geometry:

$$F = 10.5 - \frac{H - W_{isl}}{2} \tag{6}$$

In Equation 6, it should be noted that $H - W_{isl}$ is the road's *half*-width minus the island's *full* width, and therefore does not correspond to any directly observable width.

Field Test of Speed Versus Chicane Geometry

A field test was conducted on March 17, 2017, at a mid-block crossing island at 2730 Washington Street in Boston's Roxbury neighborhood, on the northbound side of the road (see Figure 2). The test was conducted in the early afternoon under clear weather and with dry pavement. The road width is 40 ft and the island width is 9.2 ft. From snowplowing operations in a past storm, there was an icy snowbank along the curb extending about 1.5 ft into the road, effectively reducing the road half-width.

The parking lane along the entire block was empty except for cars parked by the experimenters, one upstream of the island and one downstream, at the limit of the No Parking zone, resulting in L = 63.5 ft on both sides of the island. The speed of passing cars was measured as they passed the island using a radar gun operated from the downstream parked car.

Three different chicane geometries were tested by adjusting the lateral position of the parked cars. In the "no chicane" case, the parked cars were removed, allowing cars to pass with virtually no lateral shift. In the "mild chicane" case, the cars were parked immediately at the curb (which required shoveling into the snowbank), reaching 5.5 from the curb. In the "severe chicane" case, the cars were parked about 1 ft from the snowbank, reaching 8 ft from the curb.

Speeds were measured for 51–72 cars per scenario. Only cars with no vehicle less than 5 s ahead of them were measured. Results, summarized in Table 1, indicate that compared with the no chicane case, mean speed and 85th percentile speed both declined 2 mph with the mild chicane and another 2 mph with the severe chicane. Radius of curvature was calculated from the road geometry and previously stated assumptions about vehicle position. Side friction factor, calculated using Equation 2, was found to be greater in the scenario with lower speeds, consistent with other studies of side friction.

Figure 2. Experiment site.

Table 1. Speed versus Chicane Geometry Test Results

	No chicane	Light chicane	Severe chicane
F_o (ft)	na	6.5	5.25
F (ft)	na	4.1	5.35
R (ft)	na	247	190
Mean speed (mph)	29.2	27.3	25.2
85th percentile speed (mph)	33	31	29
Sample size	51	61	72
Calculated f	na	0.202	0.223

Note: na = not applicable.

Relationship of Speed to Side Friction Factor and Vehicle Path Radius. Observations of speed and inferred side friction factor from this study as well as several past studies are shown in Figure 3, which is reproduced from the AASHTO Green Book (*3*) with the two data points used in this test added. One can see that this data is consistent with that of other studies. A simplified, linear relationship between speed and side friction factor was estimated from the two data points; one can see that it closely matches the fitted curve in the Green Book for speeds in the range of 15–30 mph, speeds one would expect for crossing island chicanes. This relationship is

$$f = 0.475 - 0.01 * Speed\ for\ Speed < 30\ MPH \qquad (7)$$

with speed in units of mph.

Chicane Design to Achieve a Target Speed

Combining Equations 2 and 7, one can determine the vehicle path radius R needed to achieve a target speed at a chicane. That relationship is plotted in Figure 4, with curves for the same relationship found in the NCHRP roundabout design guide shown for comparison (*6*). The curves from the roundabout design guide use the speed–friction factor relationship given in the AASHTO Green Book (*5*) rather than the linear simplification used for the present curve; they also assume a contribution to lateral force from superelevation, e, at values of $\pm 2\%$. Overall, there is little difference between the curves.

This curvature–speed relationship, together with accounting for drivers' fastest path tendencies, forms the basis for designing a crossing island chicane: choose a target speed, determine the vehicle path radius R needed, and then tailor the parameters of the chicane—the width of crossing island, which will determine F, and the parking setback, which will determine L—to achieve that value of R, using Equations 1 and 6 (or, for more general assumptions on driving initial and final positioning, substitute Equation 3 for 6).

For the assumptions embodied in Equation 6, the design process can be further simplified using Figure 5, which shows the relationship between target speed, chicane length, and the quantity $(H - W_{isl})$. Usually H is known, and there are usually only a few practical choices for W_{isl}; a designer can then use Figure 5 to read the chicane length needed for a selected target mean speed. For example, suppose approach half-width is 20 ft and one is considering an island 6 ft wide. Then, to achieve a target mean speed at the island of 22.5 ft/s, the needed length of the chicane—that is, the distance from where the parking lane ends to the island—should be 43 ft.

Comparison with Other Methods of Chicane Design. These results can be compared with existing guidance for chicane design. Guidance developed in Denmark in the late 1980s was based on a laboratory test in which a chicane's

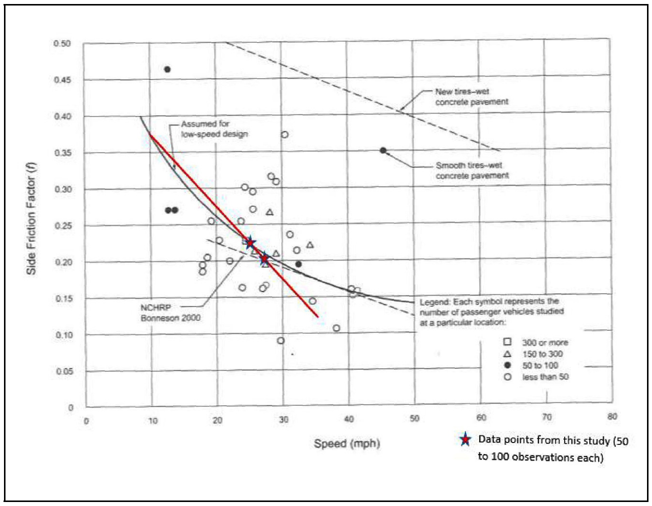

Figure 3. Side friction factor versus speed.
Source: Reproduced from Zegeer et al. (*3*) with data points and trend line from this study added.

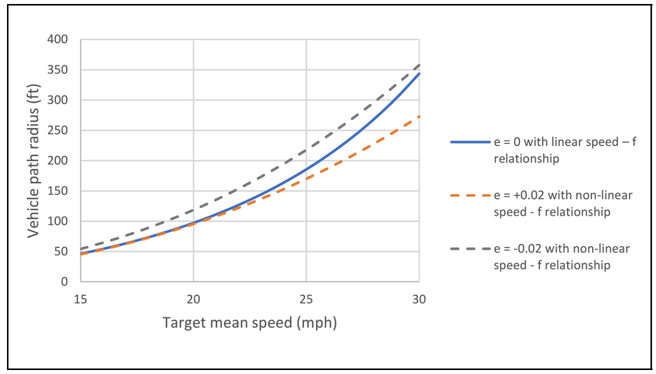

Figure 4. Vehicle path radius needed to achieve a target speed at a chicane.
Source for the two curves with dashed lines: NCHRP Report 672 (*6*).

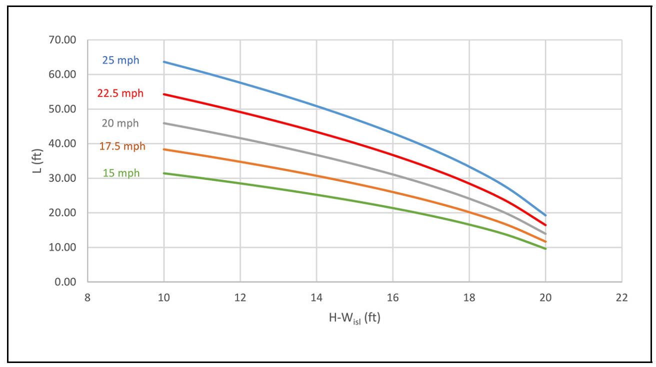

Figure 5. Chicane length needed to achieve a target speed for a given approach half-width H and island width W_{isl}.

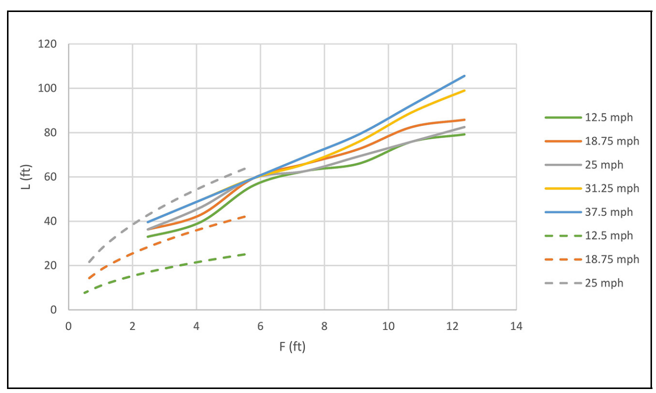

Figure 6. Chicane length (L) versus path offset (F) for different target speeds: Danish method from Kjemptrup, K. (*7*) (solid lines) and proposed method (dashed lines).

dimensions were adjusted until a driver could just get through at a specified speed (*8*). To restate those specifications for chicane length and offset, in this study, it was assumed that a car 5 ft wide (typical for European cars of that era) enters the chicane 2 ft from right lane edge and departs 2 ft from the left lane edge, with the 2-ft offset assumed because the experiment used a single driver instructed to drive though as fast as practical. The Danish guidance is plotted in Figure 6 with corresponding curves based on the theory presented in this paper shown for comparison. One can see that the proposed method shows a considerably greater sensitivity of speed to chicane length, and that, compared to the Danish method, it calls for longer chicanes for a 25 mph (40 km/h) target speed and shorter chicanes for target speeds of 18.75 mph (20 km/h) and lower.

The MUTCD specifies the minimum length over which a lateral shift of a lane takes place, also called a taper, in construction zones. For speeds up to 40 mph, it is given by

$$L = \frac{FS^2}{120} \text{ for } S < 40 \text{ mph} \tag{8}$$

where L = taper length (ft), F = offset (ft), and S = speed (mph). If used for chicane design, this formula calls for chicane lengths only about half as long as the reverse curve method presented in this paper. This confirms that the reverse curve method prescribes a path that cars can follow safely.

In the UK, the Transportation Research Laboratory has also studied the relationship between chicane design and speed (*9*). There, chicane geometry was reduced to a single parameter—path angle—which implies a constant ratio F/L for a given speed, consistent with the shift taper formula. However, the field data does not match the fitted relationship well, perhaps because the study does not account for how fastest path tendencies can make a vehicle path's taper angle differ considerably from the road's taper angle.

Table 2. Tendency for Through Cars to Pass by a Car Waiting to Turn Left at Informal Flares

Approach	Half-road width (ft)	Approach description	n	% Passing
Rt 138 NB at Neponset Valley Pkwy, Milton	21	18 ft travel lane and 3 ft shoulder. Top of a T-junction, unsignalized.	62	95
Faneuil St EB at Brooks St, Boston	18	Parking allowed but unoccupied. Top of a T-junction, unsignalized.	100	87
Heath St WB at Shiller, Boston	17	Parking occupied 15 ft from stop line. Top of a T-junction, signalized.	135	87
Parker St SB at Ruggles, Boston	17	Parking occupied 20 ft from stop line. Four-leg crossroads, signalized.	51	75

Note: NB = northbound; EB = eastbound; WB = westbound; SB = southbound.

The authors were able to find only one set of speed measurements involving median island chicanes on two-lane roads in the U.S.A., for N 68th Street south of Shea Boulevard in Scottsdale, Arizona. Speed was measured between two median island chicanes that are 330 ft apart. After installation, mean speed between the two islands fell from 29.7 mph to 26.6 mph northbound, and from 29.4 mph to 26.0 mph southbound. The proposed method estimates speed at the chicane heading northbound and southbound to be 20.3 mph and 17.8 mph, respectively, which is roughly 7.3 mph slower than observed mean speeds. Part of the discrepancy is because speed was measured midway between chicanes, while the proposed method predicts speed at the chicane. Another likely reason is that these islands have flush curbs, which likely leads to smaller vehicle-curb offsets and therefore a larger path radius than predicted using offsets determined by Equations 3 and 4.

Informal Flares

On roads with one lane per direction, a car waiting to turn left at an intersection will block the through lane unless there is a way for through traffic to get by. While this functionality can be provided by adding an auxiliary lane—a treatment called a flare—it can also be provided without marking an auxiliary lane if the approach roadway is wide enough, a treatment we call an "informal flare." Informal flares are extremely common. For example, through traffic will typically use a parking lane, bike lane, or shoulder, if available, to bypass a waiting left-turner. When analyzing intersection capacity on such an approach, traffic engineers have long known to model it as if there was an auxiliary left-turn lane, because otherwise standard capacity analysis methods will assume that every left-turning vehicle blocks the approach. Nevertheless, to the authors' knowledge, this configuration or functionality has not previously been named or analyzed.

This informal flare concept was first developed and analyzed by the study team in conjunction with a project that proposed replacing formal turn lanes with informal flares to create space for bike lanes; the study includes a simulation video illustrating informal flare function (*10*). It also turns out that informal flares are crucial in designs involving crossing islands, because intersections often have space for left-turn lanes or crossing islands, but not both; and where it is important to prevent left-turning cars from backing up through traffic—as is often the case on road diet projects—auxiliary left-turn lanes are often chosen instead of crossing islands, to the detriment of crossing safety, without considering that it might be possible to have the functionality of both, using an informal flare.

To examine the relationship between informal flare functionality and half-road width, field measurements were made at four sites in the Boston area with informal flares. Half-road width ranged from 17 ft to 21 ft (Table 2). At the first and third listed sites, the road authority had already put in place treatments to facilitate informal flare function—at the first, the travel lane was flared from 12 ft to 18 ft (by shrinking the shoulder from 9 ft to 3 ft), and at the third, a No Parking restriction was in place to keep the parking lane clear for through vehicles to use. The unit of observation was a through vehicle which, approaching the intersection, faced a vehicle queued to turn left ahead of it, and faced no other obstruction; the question was what fraction of those vehicles passed through without waiting for the left-turning vehicle to clear.

Results shown in the table indicate a strong though less than 100% tendency for vehicles to pass without waiting for the left-turning vehicle to clear. The flare function is strongest with the wider roadway, as one would expect. Even down to a half-road width of 17 ft, there is still a strong flare function. On the first three approaches, the tendency to pass was near 100% for vehicles arriving more than 5 s after the left-turning vehicle; with a time lag that long, drivers had time to recognize the situation and smoothly swerve around the waiting cars. Through cars that immediately followed a left-turning car, on the other hand, were often stuck behind it when it stopped to wait for a gap in opposing traffic; some then swerved around the waiting car, while others waited until it cleared.

Based on these results, an informal flare with at least 18 ft width will prevent most left-turning vehicles from creating a bottleneck at unsignalized intersections, and therefore avoids any lasting effect on traffic capacity. Where turning cars enter a median opening and queue with an oblique heading, informal flare functionality can be inferred if there is a 10 ft wide "gate" between the rear right corner of the queued car and the nearest obstruction (e.g., a corner curb) on the right.

An example of using an informal flare as part of a road diet is shown in Figure 7, a proposed striping plan for a road diet on Tremont Street in Boston. Because of two recent deaths at pedestrian crossings, it was highly desirable to provide both a road diet and crossing islands; at the same time, because a road diet would confine traffic to a single lane in each direction, it was important to prevent left-turning cars from blocking through traffic. Bike lanes and parking restrictions at the corner bulbouts provide the space needed for informal flare function.

It is worth noting that while corner bulbouts—a device that shortens pedestrian crossings and lowers speed for right turns—are part of the proposed design for the 60 ft wide road shown in Figure 7, on narrower roads it may not be possible for intersections to have corner bulbouts as well as crossing islands. Given a choice, crossing islands are clearly superior for pedestrian safety and, unlike corner bulbouts, also contribute to safety by helping limit the speed of through traffic and left-turning traffic.

A device that may improve informal flare function is curb continuation lines, also called "shadow lines," drawn through median openings, as pictured in Figure 8. This striping, commonly used on Florida highways and on Dutch streets, may facilitate drivers advancing deeper into a median opening by providing a visible boundary of the travel lane. Geometric analysis of different positions where a left-turning car may stop indicates that for every foot a queued car extends deeper into a median break, an additional 0.3–0.4 ft becomes available for through traffic to bypass the left-turning car (*11*).

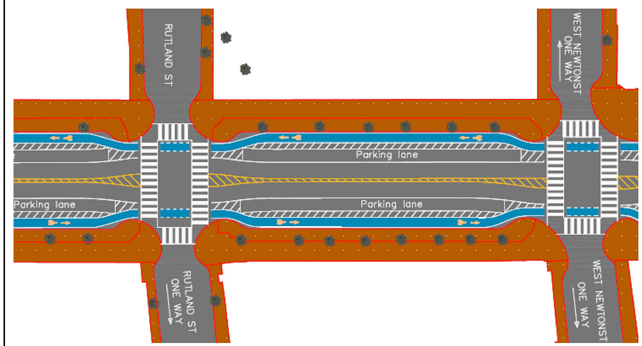

Figure 7. Road diet plan for Tremont Street, with bike lanes and parking restrictions at the corner bulbouts contributing to informal flares.

Feasibility of Fitting Crossing Island Chicanes into U.S. Intersections

On narrow collector and minor arterial streets that are common in older cities, is there sufficient space to provide crossing islands that provide speed control through a chicane effect? This section describes a geometric study of the feasibility of fitting crossing island chicanes into the intersection of a two-lane collector road and local street of limited width. The research questions were

Figure 8. Curb continuation lanes through median openings, Perry, FL (left) and Delft, NL.

whether crossing islands in such a context would still accommodate large turning vehicles and allow through vehicles to bypass a queued left-turner, how great a parking loss they would involve, and how the intersection would perform on other dimensions of safety and user convenience.

The through street was assumed to have a 60 ft ROW and either 10 ft sidewalks, leaving 40 ft curb-to-curb, or 8 ft sidewalks, leaving 44 ft curb-to-curb, with a travel lane and a parking lane in each direction, like many collectors in pre-1920 neighborhoods in the Boston area. Collectors whose paved width is 40 ft usually have no bike facilities; those with 44 ft of pavement typically have bike lanes. A third scenario assumes a 44 ft paved width, a single parking lane, and a pair of unidirectional cycle tracks (protected bike lanes). The local street was assumed to have a 40 ft ROW and 7 ft sidewalks, like most local streets in the Boston area, leaving 26 ft of pavement between curbs. Local streets of this dimension sometimes operate two-way, but more often are one-way so that cars can park on both sides of the street without blocking traffic.

The large vehicle whose turns have to be accommodated was taken to be AutoDesk's S-BUS-36, a conventional school bus 35.8 ft long with capacity for 65 passengers. The design passenger car is 17.06 ft long and 6.365 ft wide, which is a bit smaller than the (unrealistically large) AASHTO design passenger car which is 19 ft long and 7 ft wide.

To facilitate wide turns, crosswalks across the major street—with their corresponding crossing islands—are set back from the intersection. This makes crossing distances shorter, but also makes the crossings out of line with the sidewalks. To protect pedestrian convenience, designs ensured that the heading of a through-going pedestrian would not deviate by more than 45° from a straight line.

Corner radii were minimized to maximize pedestrian space in the corner, subject to the need to accommodate large vehicle right turns. This led to a 10 ft corner radius in each scenario. To shorten the length of curb ramps, and thus make more of the sidewalk available as walking path, curb reveal at the crosswalk ramps is limited to 3 in. for the major street curb and 1 in. for the minor street curb; with the standard ratio of 1 ft of length per inch rise, curb ramps are, respectively, 3 ft and 1 ft long. Where the sidewalk is only 7 ft wide, the 1 in. curb at the minor street crossing allows the curb ramp to be direct, in contrast to the commonly used apex ramp, which forces pedestrians into the intersection. Low curb reveals also allow an intersection to accommodate vehicles larger than the design vehicle by overrunning the curbs.

Crossing islands are 6 ft wide and 20 ft long with a cutout for the walking path, and have 4 in. curbs so that they can be overrun by occasional large turning vehicles such as home removals vans.

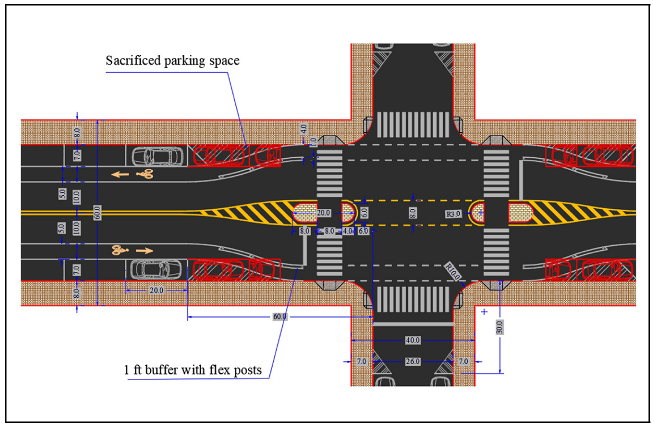

Figure 9. Plan with 44 ft roadway and bike lanes.
Note: Dimensions are in ft.

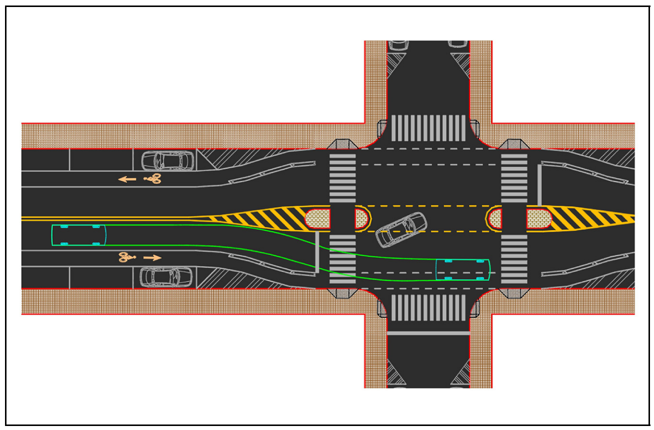

Figure 10. Informal flare analysis.

Figure 9 shows the plan for one of the scenarios, a 44 ft road with conventional bike lanes. The number of parking spaces lost is 1.6 per corner, calculated at 20 ft per space and assuming that, regardless of layout, no parking is allowed within 30 ft of the intersecting street's curb line.

The informal flare analysis is shown in Figure 10. The left-turning car is positioned with its front corner 2 ft back of the continuation line of the median curb, along a left-turn trajectory. The track of a through car passes behind it with ample space, though it encroaches on the bike crossing. This means that facing both a queued left-turning car and a bike about to enter the intersection, a through driver will have to pause for a few seconds to let the bike pass the pinch point.

The pedestrian path analysis is shown in Figure 11. Compared with the no-island scenario, maximum pedestrian exposure is reduced from 48 ft to 19 ft when crossing the major street, and from 30 ft to 27 ft when crossing the minor street. As a result of the setback, total pedestrian path length crossing the major street increases by

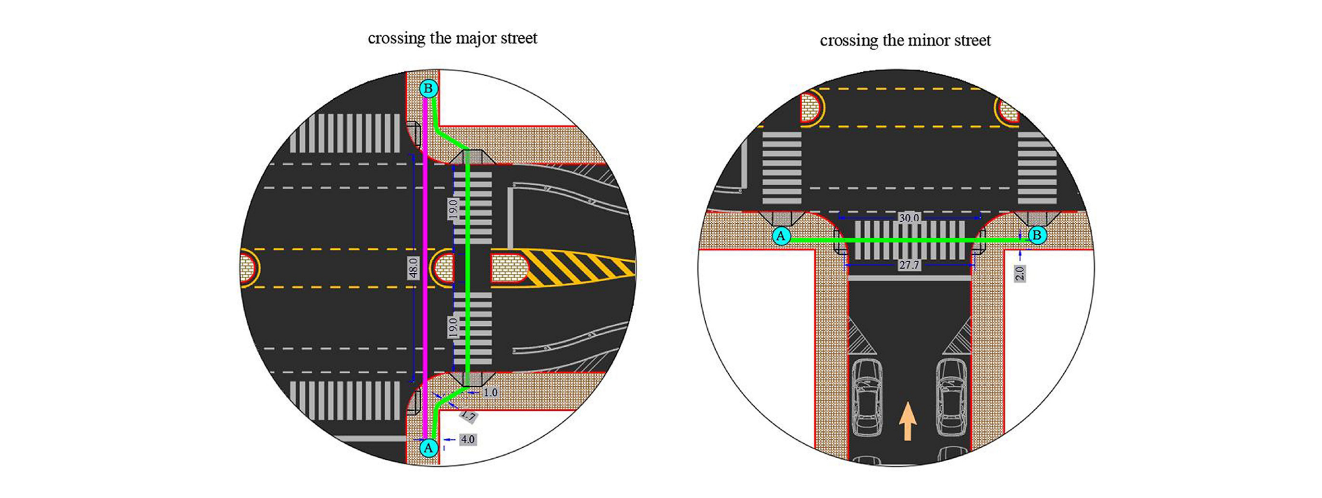

Figure 11. Pedestrian path analysis.

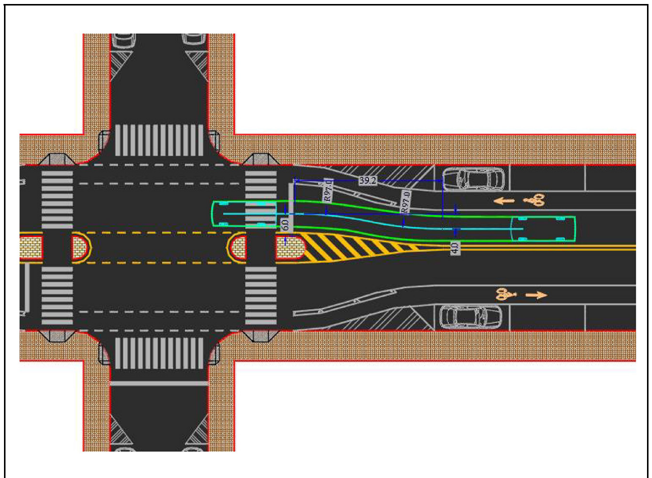

Figure 12. Fastest path/speed control analysis.

7.3 ft (less than 2 s of walking time), while it is unchanged crossing the minor street.

Analysis of the fastest path/speed control for through traffic is shown in Figure 12. With a conventional bike lane and lacking any vertical separator, drivers will encroach on the bike lane to flatten their curve, making it impossible for a chicane to provide speed control while also making it safe for a bike and car to operate next to one another. Adding a few flexposts on the bike lane line where the parking lane ends solves this dilemma. The fastest path analysis assumes a car comes within 2 ft of the first flexpost and within 3 ft of the crossing island, and finds the path radius to be 97 ft, which, from Figure 3, corresponds to a mean speed of 20 mph. For speed control, it is sufficient to add flexposts on the approach legs only, leaving the departure legs free of vertical elements so that large vehicles can more easily complete their turns.

The analysis of left-turn threat is shown in Figure 13. For left turns from the major street, indicated by green lines, the fastest path turning radius is reduced from 65 ft, which a driver can negotiate at 18.5 mph (Figure 3), to 20 ft, corresponding to a turn speed of 11 mph. In the no-island layout, a car or truck can pass the crosswalk at an oblique angle, creating blind spots caused by the vehicle's A-pillar, while with the island, a car passes the crosswalk at a right angle, with ideal visibility. For cars turning left from the minor street, indicated by purple lines, in the no-island layout, such a car threatens pedestrians everywhere in a 46 ft crossing, and might choose an unexpected path to pass a pedestrian in way that is frightening; with an island, the turning vehicle's path is severely restricted, with a sharp turn that limits speeds and that crosses the pedestrian path at a right angle, threatening a pedestrian for only 19 ft.

Finally, analysis of the large vehicle turn is shown in Figure 14, showing that a conventional school bus can turn left or right from either street without its wheels tracking over any curbs and without its body hitting the flexposts that separate the bike lane on the approach leg. For the right turns, the body of the bus tracks over a bit of the crossing island. By limiting the height of the island's curbs to 4 in. and limiting the height of the corner curbs, occasional large vehicles such as moving vans can make turns by overrunning the median islands, corner curbs, or both.

Plans for the other two collector cross-section scenarios—40 ft roadway with no bike facilities and 44 ft roadway with cycle tracks and only one parking lane—are shown in Figures 15 and 16. The same set of geometric analyses was conducted for those scenarios, as well as for

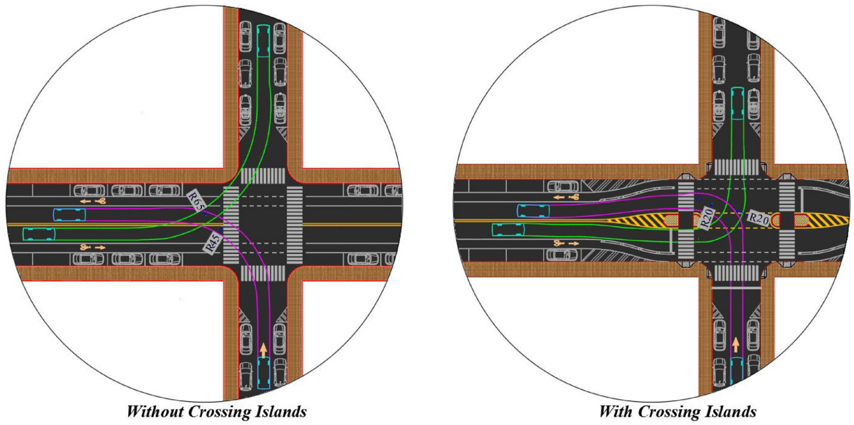

Figure 13. Left-turn threat analysis.

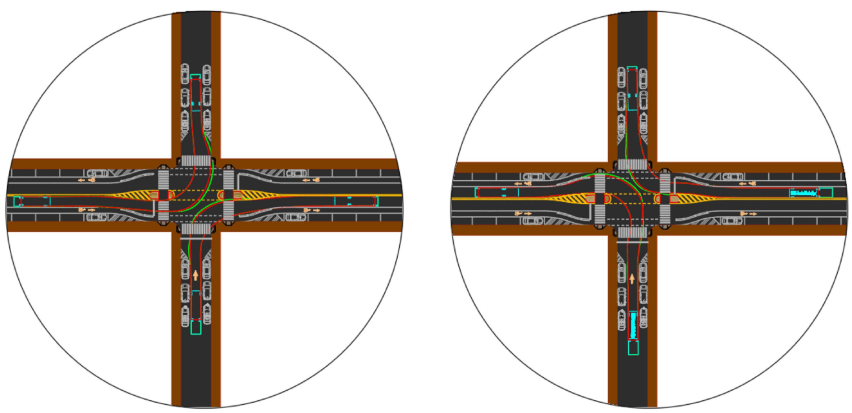

Figure 14. Large vehicle turn analysis.

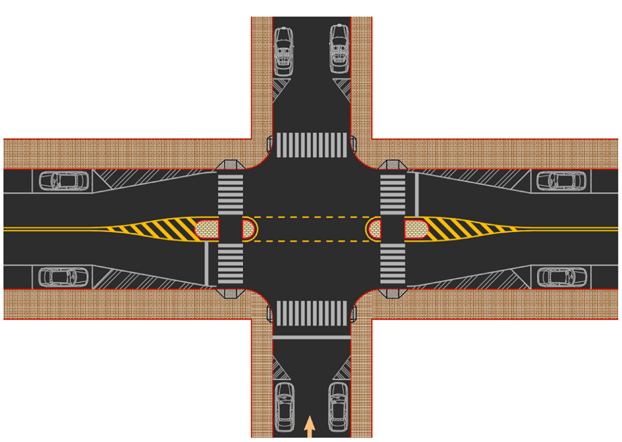

Figure 15. Plan for the 40 ft roadway scenario with no bicycling facility.

a base scenario without crossing islands (*12*). An evaluation summary for the three scenarios is given in Table 3. In all three scenarios, the crossing island design accommodates large vehicle turns, prevents queued left-turning vehicles from blocking through traffic, and allows for continuous bicycling facilities, while providing substantial speed control and pedestrian safety benefits.

Conclusions

Crossing islands at unsignalized intersections, in addition to their pedestrian crossing safety benefits, can also serve as speed control devices, at least on two-lane roads. A method has been developed for designing reverse curve chicanes on two-lane collector and minor arterial roads that indicates the vehicle path radius needed to achieve a target speed, the vehicle path offset that can be expected

Table 3. Evaluation Summary for the Three Collector Cross-Section Scenarios

Collector layout	40 ft roadway, no bike lanes	44 ft roadway with bike lanes	44 ft roadway with cycle tracks
Thru vehicle path radius (ft)	97	97	97
Thru vehicle average speed (predicted) at crosswalk (mph)	20	20	20
Left turn from major street path radius: with versus without crossing island (ft)	20 versus 65	20 versus 65	20 versus 55
Left turn from major street speed (predicted): with versus without crossing island (mph)	11 versus 18.5	11 versus 18.5	11 versus 17.25
Pedestrian exposure crossing major street: with versus without crossing island (ft)	17 versus 44	19 versus 48	19 versus 48
Pedestrian exposure crossing minor street: with versus without crossing island (ft)	27.7 versus 30	27.7 versus 30	27.7 versus 30
Increase in pedestrian path length along major street (ft)	5.7	7.3	7.3
Pedestrian path maximum deviation (heading) (°)	45	45	45
S-BUS-36 can make all right and left turns without overrunning curbs	Yes	Yes	Yes
Informal flare—thru cars can pass while a car waits to turn left	Yes	Yes	Yes
Number of omitted parking spaces per corner	1.5	1.6	2.5
Bicycle facilities	None	Bike lane continues	Protected bike lane continues

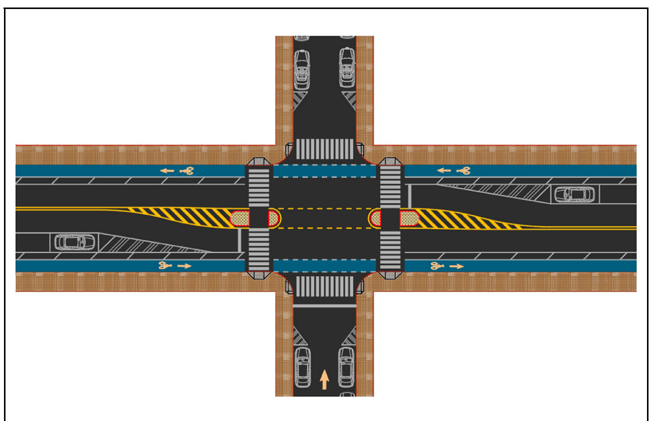

Figure 16. Plan for the 44 ft roadway with cycle tracks.

based on lane width and island geometry, and the resulting chicane length—and thus, parking setback—needed. The speed–radius relationship accounts for the increased willingness of drivers to experience lateral forces at lower speeds, a relationship to which this study has offered new data that confirms previous studies. Using crossing island chicanes, a city authority can enable its busy two-lane roads to achieve safe speed targets that previously were unachievable because those roads were not amenable to traffic calming devices such as speed humps, while at the same time improving crossing safety and making crossings accessible to children and people with low walking speed.

A geometric analysis has shown that crossing islands can fit into intersections even on roads with ROW as narrow as 60 ft. Using set-back crossings creates space to accommodate wide vehicle turns and reduces pedestrian exposure and overall crossing length without forcing undue deviation in the pedestrian path. Using informal flares, left-turn blockage can be largely prevented without replacing crossing islands with auxiliary left-turn lanes. Curb continuation striping can help enhance the informal flare functions by facilitating queued left turners to stop deeper in the median break. Compared with intersections without crossing islands, the threat from left-turning vehicles is greatly reduced because they are forced to turn with a sharper radius and narrowly confined path that passes the crosswalk at a right angle. On wider roads reduced from four lanes to two by a road diet, corner bulbouts also contribute to shorter crossings and lower turn speeds. Intersections with this kind of design, common in many European countries, have the potential to transform many busy two-lane roads, and many four-lane roads amenable to a road diet, into no longer being used as speedways and no longer being neighborhood barriers.

Several questions raised by this study are worthy of further research. At informal flares involving a bike lane, how do motorists and cyclists actually behave when there is a conflict (both want to be in the same space at the same time)? Will pedestrians behave as expected (i.e., use the marked crosswalk) if crosswalks are moved further from the center of an intersection and therefore out of line with the sidewalk? Will informal flares behave as intended, that is with through vehicles passing around cars waiting to turn left? How does informal flare function relate to left-turn queue length, and thus indirectly to left-turning volume and opposing through volume? How do vertical flexposts alter driver path choice—do drivers shy further from them than from raised curbs or less? Do curb continuation lines at median breaks actually induce motorists waiting to turn left to queue deeper into the opening? Also, data from additional sites and with greater variety in road geometry would be desirable to understand better how vehicle path and vehicle speed relate to road geometry at chicanes.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: PF, MT, SS; data collection: MT, SS, JJ, ZS, YA, PF; analysis and interpretation of results: PF, MT, SS, JJ, ZS, YA, PF; draft manuscript preparation: PF, MT, SS, JJ, YA. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The Helen and William Mazer Foundation provided partial support for this research.

References

1. Bertulis, T., and D. M. Dulaski. Driver Approach Speed and Its Impact on Driver Yielding to Pedestrian Behavior at Unsignalized Crosswalks. *Transportation Research Record*, 2014. 2464: 46–51.
2. New York City Department of Transportation. *NYC Study Don't Cut Corners: LEFT TURN Pedestrian & Bicyclist Crash Study*. New York City Department of Transportation, New York, 2016.
3. Zegeer, C., C. Lyon, R. Srinivasan, B. Persaud, B. Lan, S. Smith, D. Carter, N. J. Thirsk, J. Zegeer, E. Ferguson, and R. van Houten. Development of Crash Modification Factors for Uncontrolled Pedestrian Crossing Treatments. *Transportation Research Record*, 2017. 2636: 1–8.
4. AASHTO. *Guide for the Planning, Design, and Operation of Pedestrian Facilities*. AASHTO, Washington, D.C., 2004.
5. AASHTO. *A Policy on Geometric Design of Highways and Streets*. AASHTO, Washington, D.C., 2011.
6. Rodegerdts, L. A., J. Bansen, C. Tiesler, J. Knudsen, E. Myers, M. Johnson, M. Moule, B. Persaud, C. Lyon, S. Hallmark, H. Isebrands, R. B. Crown, B. Guichet, and A. O'Brien. *Roundabouts: An Informational Guide*, 2nd ed. NCHRP report 672. TRB, Washington, D.C., 2010.
7. Ahac, S., T. Džambas, and V. Dragčević. Review of Fastest Path Procedures for Single-Lane Roundabouts. *Proc., 4th International Conference on Road and Rail Infrastructure*, Šibenik, Croatia, 2016.
8. Kjemptrup, K. *Speed Reducing Measures*. Danish Secretariate of Road Standards, Denmark, 1988.
9. Sayer, I. A., D. I. Parry, and J. K. Barker. *Traffic Calming: An Assessment of Selected On-Road Chicane Schemes*. Report 313. Transportation Research Laboratory, 1998.
10. Furth, P. G., Z. H. Sha, and S. Rauwolf. Bike Lanes for Longwood Avenue (Video). https://www.youtube.com/watch?v=rzqrHcMTliw&t=211s.
11. Shekari, S. *Design Treatments for Increasing Traffic Capacity in Road Diet Projects*. MS thesis, Northeastern University, Boston, MA, 2019.
12. Furth, P. G. and M. Tahmasebi. Safer Intersection Design Using Crossing Islands. http://www.northeastern.edu/peter.furth/safer-intersection-design-using-crossing-islands/.