SAFETY EFFICACY CONFIDENCE LEVELS FOR

PEDESTRIAN & BICYCLE TREATMENTS

2018

FEHR & PEERS

This review presents comments and evaluation based only on our own perspectives and experience. Our purpose is to propose a framework for the evaluation of design guidelines, but not to supplant our evaluation for that of the reader. Before adopting any of the design guidelines, the reader should first evaluate it using the reader's own well-informed judgment.

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introduction

Introduction

As standards for the design of pedestrian- and bicycle-friendly intersections and streets continue to evolve, guidelines such as those published by the National Association of City Transportation Officials (NACTO) are increasingly becoming the state of the practice. This paper seeks to provide context for the safety efficacy of various improvements included in the NACTO Urban Bikeway Design Guide and the Urban Street Design Guide so that practitioners can make more informed decisions on each treatment's appropriate application.

A review of the literature was completed for each treatment to compile key conclusions and findings about crash reduction and other measures of effectiveness (MOEs) related to safety such as yielding behavior or level of user comfort. The summary tables provide information on each treatment's documented benefits and limits of use, based on the reviewed studies. The quality of the studies was also documented for context on the sample size and the consistency of results.

Treatments are organized into three categories based on the confidence of their documented safety efficacy – high, medium, and low - results for which are shown below.

Confidence Levels for Documented Safety Efficacy

HIGH	MEDIUM	LOW
› Bicycle Boulevards	› Bend-Out Crossing	› Bend-in Crossing
› Green Pavement	› Bike Boxes	› Combined Bike Lane/ Turn Lane
› Leading Pedestrian Interval	› Buffered Bike Lanes	› Intersection Crossing Markings (Non-green)
› Raised Bicycle Crossing	› Contraflow Bike Lanes	› Through Bike Lane
› Separated Bike Phasing (Traffic Signals)	› Conventional Bike Lanes	› Two-stage Left Turn Box
	› Coordinated Signal Timing	
	› Mixing Zone	
	› One-way Protected Bikeway	
	› Two-way Protected Bikeway	

High Confidence Level

The high confidence level was reserved for devices with studies that include robust safety data and/or consistent findings across multiple studies that show a reduction in collisions. In the absence of documented crash reductions, some devices in this category had no evidence of a negative safety impact and provide an objective safety benefit that would lead to a strong positive recommendation for the treatment, such as bicycle signals. The Federal Highway Administration (FHWA) cites that this treatment can reduce the bicycle crash rate by up to 45 percent,[14] and a published case study in Davis, California saw reductions from 16 bicycle and motor vehicle collisions before installation to 2 vehicle-only collisions after implementation.[15] A video-based study in multiple cities found that there were high levels of compliance at intersections with separated phasing compared to other bicycle treatments.[16] While there are a limited number of published studies for this treatment, the available research consistently shows positive safety results which leads to a high confidence level. In this confidence category, specific areas of caution are also included in the final conclusions and may apply when research is lacking.

Medium Confidence Level

Devices were assigned to the medium confidence level when there were gaps in the research but ultimately no significant safety concerns. Many devices in the medium level have documented crash reductions but they may be referenced from a limited number of studies or there may be several nuances that aren't well understood. For example, studies consistently show positive safety impacts for bend-out crossings at unsignalized crossings across the minor street;[13,18] however, additional research is needed to better understand certain situations such as the offset distance for bend-out crossings, the efficacy of bend-out crossings at signalized intersections, and the general efficacy for bend-out crossings in the United States.

Low Confidence Level

The low confidence level category was assigned based on the quality of available data, or for devices for which there are limited if any studies. Studies in this category may not have documented the study sites well enough to fully understand the context of the results, such as an FHWA study for the bend-in crossing. This study aggregated data for bend-in crossings from multiple case studies and results were compared across cases where the device was applied on its own versus cases where the device was applied with other bicycle treatments; however, those other treatments are not documented nor are other site characteristics that may have contributed to the results. The study showed an increase in the absolute number of bicycle crashes per year;[9] however, the data was not controlled for volumes. In general, the low confidence level represents devices for which research is inconclusive or incomplete.

high confidence level

High Confidence Level

The high confidence level was reserved for devices with studies that include robust safety data and/or consistent findings across multiple studies that show a reduction in collisions. In the absence of documented crash reductions, some devices in this category had no evidence of a negative safety impact and provide an objective safety benefit that would lead to a strong positive recommendation for the treatment, such as bicycle signals. The Federal Highway Administration (FHWA) cites that this treatment can reduce the bicycle crash rate by up to 45 percent,[14] and a published case study in Davis, California saw reductions from 16 bicycle and motor vehicle collisions before installation to 2 vehicle-only collisions after implementation.[15] A video-based study in multiple cities found that there were high levels of compliance at intersections with separated phasing compared to other bicycle treatments.[16] While there are a limited number of published studies for this treatment, the available research consistently shows positive safety results which leads to a high confidence level. In this confidence category, specific areas of caution are also included in the final conclusions and may apply when research is lacking.

Bicycle Boulevards

MUTCD STATUS: Allowable[a]

Claims

› Results in reduced vehicle speeds and less through traffic

› Signs and marking raise awareness of the designated routes and encourage people to properly position themselves in the roadway

Quantification of Benefits

Traffic Calming Measures: Studies show documented volume reductions of 5% to 44% and speed reductions of 1% to 23%.[1]

Shared lane markings: Studies show increase in distance between parked cars and cyclists of 8 inches, increase in distance between passing cars and cyclists of over 2 feet.[2]

Documented Crash Reduction

Results show that collision rates on Berkeley's bicycle boulevards are 50% to 88% lower than those on parallel, adjacent arterial routes.[3]

A study of bicycle injuries in Vancouver and Toronto, Canada found that local streets designated as bicycle routes experience a 51% lower risk of injury compared to major streets with on-street parking and no bicycle facilities.[4]

A later published version of the same study shows that traffic diverters on local streets were associated with about a 96% reduction in injury risk compared to roadways with no on-street bicycle facilities. It also found that at intersections, speeds of less than 30km/h (19 mph) were associated with a 48% reduction in injury risk compared to speeds of 30 km/h to 50 km/h (31 mph).[5]

Other MOEs

Bicyclists will go out of their way to ride on bicycle boulevards and women prefer riding on bicycle boulevards to busier streets with bike lanes.[6]

Areas of Caution

The effect of traffic calming on local streets on the relationship between relative risk of injury on local streets compared to major streets was inconclusive in the Canada study.[4]

Gaps in Research: Research is lacking on appropriate signage and traffic calming to ensure safety along the bicycle boulevard.

Study Details

Sample Size:[b] Medium

Notes on Quality/ Consistency of Results: The difference in collision rates is highly statistically significant in the Berkeley study. The study controls for bicyclist volumes, indicating that the results cannot be easily refuted by self-selection or safety in numbers. The Canadian study interviewed injured cyclists from hospital records, which included injuries caused by all kinds of collisions, not just those involving vehicles.

Conclusion

Although this is based on two studies, the results and claims are considered reasonable, especially based on established research for traffic calming devices and shared lane markings. Bicycle boulevards, as local streets with reduced vehicle speeds, have a recognized safety efficacy when compared to major roads.

Recommended for:

› *Local streets parallel to arterials with high levels of on-street parking and no bicycle facilities*

› *Use with volume reduction measures such as diverters*

Not Yet Recommended for:

› *Streets outside of residential areas*

Green Pavement

MUTCD STATUS: Allowable through interim approval (IA-14[7])

Claims

› Increases visibility of cyclists, raises motorist and bicyclists awareness to potential areas of conflict

› Increases bicyclist comfort through clearly delineated space

› Increases motorist yielding behavior

› Helps reduce bicycle conflicts with turning motorists

Quantification of Benefits

In one study, 98.5% of motorists yielded to bicycles after green paint was applied, compared to 86.7% before.[11]

Documented Crash Reduction

10% decrease in collisions at signalized intersections with one colored marked bike crossing.[8]

Average annual total crashes, which included vehicle-only collisions, decreased by 12% on average for all applications of green pavement including along an entire corridor, only at conflict points, and except at conflict points.[9]

Rate of conflicts decreased from 0.95 to 0.59 conflicts per 100 bicyclists after colored pavement was added to conflict zones.[10]

Other MOEs

FHWA interim approval notes that bicyclists and motorists both have a positive impression of the effect of green pavement.[7]

In the Copenhagen study, all intersections with 3 legs experienced a decrease in collisions, regardless of whether one or two colored crossings were marked.[8]

Areas of Caution

In the Copenhagen study, intersections with 4 legs had mixed results – marking one colored crossing resulted in a decrease in collisions, however marking 2 or 4 crossings resulted in an increase in collisions.[8]

A documented collision increase of 23% and 60% for markings of two and four colored cycle crossings, respectively, was reported in the Copenhagen study. This increase was primarily rear-end collisions among motor vehicles and accidents with red-light driving vehicles.8

Bicycle crashes, not adjusted for volumes, increased at 25 study sites by 39% on average for all applications of green pavement. This included applications along an entire corridor, only at conflict points, and except at conflict points.[9]

Gaps in Research: Discouragement of illegal parking in bike lane and specific thresholds for efficacy of green pavement such as vehicle volumes.

Study Details

Sample Size:[b] Large

Notes on Quality/ Consistency of Results: Some studies (where noted) did not adjust for volumes.

Conclusion

The increase in bicycle crashes indicated in the FHWA Crash Report is inconclusive since it is not adjusted for volumes. Removing that result, all other studies indicate positive results which mainly applies to applications at weaving zones or conflict points other than through an intersection. More study of green markings through intersections is needed in the US based on the results of the Copenhagen study, which suggests that there may be an upper limit to the efficacy of colored pavement at 4-legged signalized intersections where 2 or more colored crossings are marked. Additional research is needed to determine the potential cause for this result, which may be due to higher vehicle volumes or the size of the intersection rather than the number of marked bike crossings alone.

<u>Recommended for:</u>

› *Weaving zones such as the extension of a bike lane across a dedicated turn lane*

› *Focused use at smaller signalized intersections, such as marking the extension of bike lanes through a three-legged signalized intersection or to highlight one heavy bicycle crossing movement through a four-legged intersection with relatively low vehicle volumes*

<u>Not Yet Recommended for:</u>

› *The only treatment at large signalized intersections. Additional protection may be needed at intersections with high vehicle volumes and long crossing distances.*

Leading Pedestrian Interval

MUTCD STATUS: Allowable

Claims

› LPIs increase the visibility of crossing pedestrians and give them priority within the intersection.

› LPIs have been shown to reduce pedestrian-vehicle collisions as much as 60% at treated intersections.

› LPIs typically require adjustments to existing signal timing that are relatively low cost compared to other countermeasures.

Quantifications of Benefits

Refer to "Documented Crash Reduction"

Documented Crash Reduction

According to a 2010 study, a crash reduction of 46.2% to 71.3% can be expected with the installation of LPIs; however, due to limitations of the study (there were sites with limited crashes in the before/after period), it is typically appropriate to assume a crash reduction of 58.7%.[42]

In 2016, NCHRP 498, Application of Pedestrian Crossing Treatments for Streets and Highways, was published and documented a 59% statistically significant reduction in pedestrian-vehicle crashes with a corresponding Crash Modification Factor (CMF) of 0.41.[43]

Other MOEs

None found.

Areas of Caution

None.

Gaps in Research: Research has not clearly identified reasons for the reduction in vehicle-pedestrian crashes following the installation of LPIS; however, it seems reasonable that the crash reduction can be attributed to increased visibility of crossing pedestrians.

Study Details

Sample Size:[b] Small

Notes on Quality/ Consistency of Results: The primary study used in identifying the expected crash reduction due to LPIs[42] examined 10 intersections in State College, Pennsylvania. Although this study only included data from one city at ten intersections, the study's methods were robust enough for the authors of NCHRP 498 to identify a Crash Modification Factor for LPIs.

Conclusion

The research on Leading Pedestrian Intervals is amongst the highest-quality available for pedestrian and bicycle treatments.

Recommended for:

› *Signalized intersections where high turning traffic volumes conflict with pedestrians in the crosswalk.*

Not Yet Recommended for:

› *N/A*

Raised Bicycle Crossing

NOTE: Device not included in NACTO
APPROVAL STATUS: Not a traffic control device so no MUTCD restriction on its use

Claims

› Provides traffic calming for automobiles and can slow bicyclists

Quantification of Benefits

A Scandinavian study from 1998 reported a 40% reduction in vehicle turning speeds at crossings that were raised 12 cm (4.7 inches).[13]

The Scandinavian study found that the number of conflicts involving motorists was reduced by about 60%.[13]

Documented Crash Reduction

One Dutch study in 2011 reported a statistically significant 51% reduction in risk of a collision with the presence of raised crossings on minor side streets.[12]

A study in Sweden found an approximate 30% reduction in risk of a collision with a raised bicycle crossing on the minor approach compared to a conventional bicycle crossing (with curb cuts and ramps).[13]

Other MOEs

None found.

Areas of Caution

The study in Sweden found a 13% increase in speed for bicyclists using the elevated crossings compared to the non-elevated crossings.[13]

Gaps in Research: Existing research is in the context of the Netherlands and Sweden and is lacking for US cities. Appropriate situations in US where raised crossings are effective at reducing crashes, specifically on minor roadways when paired with "bend-out" design.

Study Details

Sample Size:[b] Large

Notes on Quality/ Consistency of Results: The Dutch study chose non-signalized intersections where the major road with a speed limit of approximately 30 mph crosses a minor road. Seven municipalities were studied. Intersections were chosen based on high vehicle and bicycle volumes. The Swedish study chose intersections along one-way cycle tracks on major streets with the elevated crossing across the minor street.

Conclusion

Available studies show high efficacy at unsignalized intersections on the minor cross street. Practitioners should use caution when implementing since current research is based in non-US cities.

Recommended for:

Lower-volume side streets or driveways, especially when paired with the "bend-out" design

Unsignalized intersections

Not Yet Recommended For:

Signalized intersections

Major roadways

High conflicting turning movements

Separated Bike Phasing (Traffic Signals)

MUTCD STATUS: Allowable through interim approval (IA-16[14])

Claims

› Increases convenience and safety of bicycling

› Discourages red light running by bicyclists

Quantification of Benefits

Refer to "Documented Crash Reduction"

Documented Crash Reduction

FHWA cites results that a bicycle signal can "reduce the overall number of bicycle crashes, or reduce the bicycle crash rate up to 45 percent where bicycle volumes concurrently increase."[14]

At a study intersection in Davis, CA, collisions were reduced from 16 bicycle and motor vehicle collisions prior to the installation of bicycle signal heads to 2 vehicle-only collisions after implementation of bicycle signal heads. The data collection period both before and after was a two-year period.[15]

Other MOEs

77-93% compliance with bicycle signal by bicyclists; 84-92% compliance by motorists to left-turn signal across protected bike lane.[16]

Areas of Caution

FHWA interim approval prohibits bicycle signals for any movement where bicycles share a lane with motorized vehicles.[14]

FHWA interim approval also prohibits an all-bicycle "scramble" phase.[14]

Gaps in Research: Further research needed on crash reduction effectiveness and effect on operations[17]

Study Details

Sample Size:[b] Medium

Notes on Quality/ Consistency of Results: Limited published research.

Conclusion

Results of available research consistently report a positive safety effect and reduction in collisions. Specific signal phasing was not well documented in these publications, and further research is needed to understand the operational effects and for potential safety effects of an all-bicycle "scramble" phase.

Recommended for:

› *Facilitating unusual or unexpected arrangements of bicycle movement through complex intersections, conflict areas, or signal control*

› *Protected bike lanes through intersections with high conflicting turn volumes*

Not Yet Recommended for:

› *Intersections with a shared through/right turn lane or low conflicting turning volumes*

medium confidence level

Medium Confidence Level

Devices were assigned to the medium confidence level when there were gaps in the research but ultimately no significant safety concerns. Many devices in the medium level have documented crash reductions but they may be referenced from a limited number of studies or there may be several nuances that aren't well understood. For example, studies consistently show positive safety impacts for bend-out crossings at unsignalized crossings across the minor street;[13,18] however, additional research is needed to better understand certain situations such as the offset distance for bend-out crossings, the efficacy of bend-out crossings at signalized intersections, and the general efficacy for bend-out crossings in the United States.

Bend-Out Crossing

NOTE: Device not included in NACTO
APPROVAL STATUS: Not a traffic control device so no MUTCD restriction on its use[g]

Claims

› Provides space for vehicle queueing

› Provides space for right-turning vehicles to turn before encountering bicycle conflicts

Quantification of Benefits

Refer to "Documented Crash Reduction".

Documented Crash Reduction

A Netherlands study found that cyclists were 45% less likely to be involved in a collision where the bicyclist has the right-of-way and where vehicles are leaving or entering the side street at unsignalized intersections where a protected bikeway approach was deflected 2 to 5 m (6.5 to 16 ft) away from the main roadway; compared to locations with a bike lane (no physical separation) without deflection or no bicycle facility.[12]

Other MOEs

None found.

Areas of Caution

The Netherlands study reported variations in the effect on collisions when the distance of deflection for the protected bikeway approach was greater than 5 m (16.5 ft) and less than 2 m (6.5 ft), although these results were not considered statistically significant. For example, at unsignalized intersections where the protected bikeway approach was deflected more than 5 m (16 ft) away from the main roadway, cyclists were only 7% less likely to be involved in a collision compared to locations with a bike lane (no physical separation) with no deflection or no bicycle facility. At locations with a deflection of 0 to 2 m (0 to 6.5 ft), the safety result was counterproductive and cyclists were 3% more likely to be involved in a collision.[12]

Similarly, a separate Scandinavian study found an increase in collision risk of 40% at signalized intersections when a cycle path is introduced that is separated approx. 4.5 m (15 ft) from the roadway.[18]

Gaps in Research: Effect of vehicle volumes, speeds, raised crossings or changes in signal timing on safety efficacy at signalized intersections. Effect of raised crossings on bend-outs in general, including unsignalized intersections.

Study Details

Sample Size:[b] Large

Notes on Quality/ Consistency of Results: All research completed in non-US cities. The Netherlands study (Schepers et. al) included seven municipalities with study intersections at major roadways crossing a minor roadway at a non-signalized location, chosen based on high numbers of motor vehicle traffic and bicycle traffic. Raised crossings are commonly used in northern Europe and Scandinavia and the details of the study are not clear whether all, some, or none of the studied "bend-outs" were raised. The Scandinavia study (Garder et al.) studied 18 towns in Sweden, Finland, and Norway; differences in intersection designs and context not available in study. Additional research is needed, especially at signalized intersections.

Conclusion

Recommend with caution. Research is limited on this emerging area of design and existing research is focused in non-US cities.

Recommended for:

› *Unsignalized intersections, especially across lower-volume side streets or driveways. Special consideration for the offset of the path should be taken as it relates to placement within the zone where vehicles would be expected to accelerate after making their turn.*

› *Achieving a higher level of perceived user comfort*

Not Yet Recommended for:

› *Side streets and/or intersections with high conflicting turning volumes*

Bike Boxes

MUTCD STATUS: Allowable through interim approval (IA-18[19])

Claims

- Helps prevent "right-hook" conflicts with turning vehicles at the start of green
- Reduces vehicle encroachment into crosswalk
- Improves visibility of bicyclists
- Facilitates left turn positioning for bicyclists during red signal (applicable only for bike boxes that extend across a lane from which left-turns are allowed)
- Provides priority for bicyclists at signalized bicycle boulevard crossings of major streets

Quantifications of Benefits

64.4% reduction in observed right turn conflicts (near misses) per cyclist[20]

Reduction in motorist crosswalk encroachment frequency from 25% to 6.3% with color and 18.5% to 6% without color[20]

Reduction in cyclist crosswalk encroachment frequency from 13% to 16% with color and 10% to 13% without color[20,21]

An Austin study found an increase in number of cyclists leaving first from the intersection from 32% to 71% and from 54% to 64%21. A higher number of cyclists left the intersection first at the crossing of a major roadway where the bike lane ends and transitions to a shared lane on the opposite side of the intersection compared to the crossing of a minor roadway with a bike lane on the receiving leg of the intersection (32% to 71% compared to 54% to 64%).[21]

Documented Crash Reduction

None found. Refer to "Areas of Caution" for documented crash increase.

Other MOEs

42% of motorists and 77% bicyclists felt the intersection was safer with the bike boxes versus more dangerous[20]

Increase in cyclists stopping in bike box with green paint added (58.4% to 91.8%, 36.4% to 49.3%, and 65.8% to 74.6%)[20, 21]

Increase in usage of bike box from 36.4% to 58.4% at major roadway crossing where bike lane ends and transitions to a shared lane on far side of intersection compared to a minor roadway crossing with a bike lane on far side of intersection[21]

Areas of Caution

Increase in motorist encroachment into bike box after installation compared to encroachment into crosswalk before installation (26.8% compared to 23.2%)[20]

Lower efficacy during "stale" green (increase in right-hook collisions at 36% of study intersections when bike box was added, 88% of which occurred during the stale green phases)[22]

Reduction in right turn conflicts may be less significant at locations with heavy right turning traffic[i] due to right turns on red[21]

Gaps in Research: Facilitating transition from right side bike lane to left side bike lane during red for left turns.

Study Details

Sample Size:[b] Small

Notes on Quality/ Consistency of Results: None

Conclusion

Recommend with caution especially at signalized intersections with high instances of conflicts during "stale" green. While bike boxes can help with crosswalk encroachment, research shows that they do not eliminate encroachment into the bike box itself.

Recommended for:

- *Situations where the majority of right turn conflicts are at the start of green (such as side-street approaches where most bicyclists will arrive on red)*
- *Locations with high levels of crosswalk encroachment*
- *Locations where bike lane on intersection approach transitions to shared lane on receiving leg of intersection*

Not Yet Recommended for:

- *Locations with high instances of conflicts during "stale" green*
- *Facilitating bicyclist left turns*
- *Locations with heavy "right turn on red" movements*

Buffered Bike Lane

MUTCD STATUS: Allowable[k]

Claims

› Encourages bicyclists to ride outside of the door zone when buffer is between parking lane and bicycle lane

› Provides greater space for bicycling without making the bike lane appear so wide that it might be mistaken for a travel lane or parking lane

› Encourages bicycling by contributing to the perception of safety among users of the bicycle network

Quantification of Benefits

No quantitative data found.

Documented Crash Reduction

None found.

Other MOEs

90% of cyclists preferred a buffered bike lane to a standard lane[23]

70% of cyclists surveyed indicated they would go out of their way to ride on a buffered bike lane over a standard bike lane[23].

58% of cyclists felt that driver behavior is safer and calmer with buffered bike lane[23]

Areas of Caution

For intersections along the buffered bike lane without a right-turn lane, motorists' turning actions were inconsistent; over 33% of right-turning motorists moved into the buffered bike lane to make the turn.

Intersections along the buffered bike lane also pose challenges for left-turning bicyclists. A portion of left-turning bicyclists completed the movement as a two-stage turn while just over 50% of bicyclists turned from the left motor vehicle lane.[23]

Gaps in Research: Appropriate accommodation at intersections; effect of buffer on bicyclist placement within lane.

Study Details

Sample Size: Small

Notes on Quality/ Consistency of Results: None

Conclusion

Although the first two claims are not readily backed by data, they are considered reasonable claims based on typical applications of buffered bike lanes. Buffered bike lanes are expected to contribute to a positive perception and improve comfort, however without crash reduction data it is unclear the point at which they are no longer comfortable. Use caution when implementing on higher volume, higher speed roadways where more protection may be warranted. The design of the buffered bike lane at intersections should reflect a city's preferred approach to motorists' turning movements and associated yielding. Appropriate signage should be utilized to improve motorist comprehension at these locations.

Recommended for:

› *Roadways where standard bike lanes do not provide acceptable perceptions of safety/comfort but protected bike lanes may not be warranted or are cost prohibitive*

› *Use with skip stripe pattern at intersections similar to a standard bike lane to encourage motorists to move into the bike lane during right turns, with potential for clarifying signage to educate users on appropriate use*

Not Yet Recommended for:

› *Roadways with extra-wide travel lanes or bike lanes*

› *Corridors where conflicts at intersections are the focus for improvement*

› *Use with striped bend-in design (no skip striping) at intersections where vehicles yield to through bicycles during a right turn movement*

Contraflow Bike Lanes

MUTCD STATUS: Allowable[m]

Claims

› Reduces dangerous wrong-way riding

› Decreases sidewalk riding

› Allows bicyclists to use safer, less trafficked streets

› Quantification of Benefits

› Refer to "Documented Crash Reduction".

Documented Crash Reduction

A study based in Australia compiled a literature review of international studies for contra-flow cycling and found that overall collision risk for cyclists was reduced on quiet one-way streets (85th percentile speeds 25mph or less) after accommodating contra-flow cycling with signing and striping.[24]

Other MOEs

Based on contraflow bike lanes implemented in Cambridge, MA on low-volume roadways (less than 2,000 vehicles per day), these roadways experienced reduced wrong-way riding and decreased sidewalk riding.[44]

Areas of Caution

In Massachusetts, the contraflow bike lanes have experienced some bicyclists traveling in the bike lane in the wrong direction.[44]

Gaps in Research: Role of intersection safety and crash reduction over extended period of time in the US.

Study Details

Sample Size:[b] Small

Notes on Quality/ Consistency of Results: All conclusive collision-based studies are from non-US cities.

Conclusion

Based on available studies, contraflow bike lanes may be appropriate on low-volume roadways with key destinations where bicyclists ride in the wrong direction. Their safety efficacy, however, has not been studied in the US.

Recommended for:

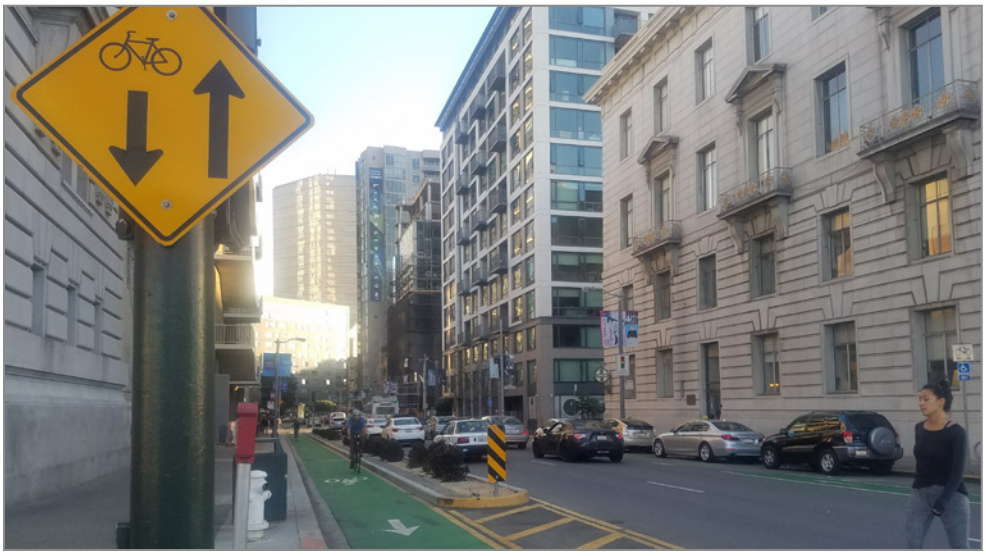
› *One-way streets where traffic volumes and speeds are low, and the lane provides an improved travel experience over a high-volume, high-speed alternative route*

› *One-way corridors that are short and provide direct access to a high-use destination*

Not Yet Recommended for:

› *Roadways with many driveways, alleys, or intersecting streets on the side of the proposed contraflow lane*

› *Implementation on higher volume, higher speed roadways as signing and striping alone (without a physical barrier)*



Conventional Bike Lane

MUTCD STATUS: Allowable

Claims

- Increases bicyclist comfort and confidence on busy streets
- Creates separation between bicyclists and automobiles
- Increases predictability of bicyclist and motorist positioning and intersection
- Increases total capacities of streets carrying bicycle and motor vehicle traffic

Quantification of Benefits

Refer to "Documented Crash Reduction".

Documented Crash Reduction

The 2010 Highway Safety Manual (HSM) reports that providing dedicated bicycle lanes in urban areas "appears to reduce bicycle-vehicle crashes and total crash on roadway segments". However, the magnitude of crash reduction is not certain.

Select studies reported a decrease in collisions from 5% to 53% as a result of bicycle lane installation.[4, 25, 26, 27] One study in New York concluded no difference in collisions after accounting for collisions at mid-block and intersection locations.[28]

A Davis study found that bicycle lanes did typically decrease collisions related to bicyclists exiting driveways, motorists exiting driveways, bicyclists on the wrong side of the street, motorists overtaking bicyclists, and motorists making improper rights.[27]

The New York study found a decrease in total midblock crashes (all modes) of 5.6% associated with installation of bike lanes[28]

Other MOEs

One study indicated that bike lanes were safer for bicyclists than wide curb lanes because the bicyclists positioned themselves better within the space to avoid obstacles, such as open car doors.[29]

Bike lanes have been found to provide more consistent separation between bicyclists and passing motorists than shared travel lanes. The presence of the bike lane stripe has also been shown from research to result in fewer erratic motor vehicle driver maneuvers, more predictable bicyclist riding behavior, and enhanced comfort levels for both motorists and bicyclists.[30]

Areas of Caution

The Davis study found a higher frequency of crashes (10 bicycle-vehicle collisions versus 4) related to bicyclists making improper left turns on streets with bike lanes compared to similar streets without bike lanes.[27]

A Copenhagen study found that the best estimate for safety effects of bicycle lanes in urban areas was an increase of 5% in crashes overall (intersections and mid-block). Corrections for changes in volumes were made.[31.]

The New York study found an increase of 5.7% in total crashes (all modes) and 28% in bicycle crashes at intersections associated with the installation of bike lanes, however these increases were not considered statistically significant[28]

According to the HSM, certain bicycle-vehicle crashes may be unaffected by bike lanes: (1) failure to stop or yield by a bicyclist at a controlled intersection; (2) failure to stop or yield by a driver at a controlled intersection; or (3) improper vehicle left turn

Gaps in Research: None identified

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Conventional Bike Lane

MUTCD STATUS: Allowable

Study Details

Sample Size:[b] Large

Notes on Quality/ Consistency of Results: The New York study did not adjust for changes in bicyclist volumes.

Conclusion

Based on available studies, bike lanes are effective for predictable positioning and generally for collision reductions, however results are unclear at intersections. Additional thought may be required for bicycle turning movements and protection from vehicle turning movements, and used alone they may not attract "interested but concerned" riders on multi-lane roads.

Recommended for:

- *Providing a more comfortable alternative than shared lanes on non-local streets*
- *Locations where bicyclist positioning is important such as wide curb lanes or on-street parking*

Not Yet Recommended for:

- *High-volume, high-speed streets where buffered or protected bike lanes may provide a higher level of user comfort*
- *Improved safety at intersections*
- *Corridors with high volumes or instances of bicyclist left turns at intersections*

Coordinated Signal Timing

MUTCD STATUS: Allowable

Claims

- Reduces number of stops along a corridor for bicycles
- Provides for a continuous flow of traffic at the targeted speed
- Provides for platooning of bicyclists along the corridor

Quantifications of Benefits

Refer to "Documented Crash Reduction".

Documented Crash Reduction

Total collisions on Valencia Street in San Francisco decreased by 20%, however the results were not statistically significant.[32]

Other MOEs

Signal timing changes (not specifically bicycle coordination) have been shown to reduce pedestrian and bicyclists injury by 37%[33]

Areas of Caution

Conclusive studies of the safety efficacy of bicycle signal coordination were not found.

Gaps in Research: Effect of coordinated signal timing for bicycles on bicycle-related collisions

Study Details

Sample Size:[b] Small

Notes on Quality/ Consistency of Results: While there are multiple case studies on pedbikesafe.org, results are inconclusive. In some cases data was collected over a short period of time (one year).

Conclusion

While the claims are considered reasonable based on typical results of vehicle-oriented applications of coordinated signal timing, there are no conclusive results related to safety efficacy for bicyclists. Coordinated signal timing for bicyclists is expected to contribute to a positive perception and improved comfort related to reduced delay, however without crash data it is unclear for which situations they are ineffective in reducing collisions.

Recommended for:

- *Locations with high frequency of bicyclists running red lights*
- *Corridors where reduced bicycle delay or improved comfort is a priority*

Not Yet Recommended for:

- *Improved safety related to turning conflicts at intersections*
- *The sole purpose of providing improved safety or protection for cyclists along a corridor*

Mixing Zone

MUTCD STATUS: Allowable[q]

Claims

› Encourages bicyclists and vehicles to negotiate the space within the turn lane in advance of the intersection

Quantification of Benefits

Refer to "Documented Crash Reduction".

Documented Crash Reduction

Annual bicycle crashes decreased from 2.1 to 0 when a mixing zone was applied on its own.[9]

Annual total crashes (including vehicle-vehicle conflicts) decreased by 14% when a mixing zone was applied with other design elements.[9]

Other MOEs

A mixing zone with yield entry markings had 93% compliance with intended use by turning vehicles in one study, which was the highest level of compliance by vehicles in that study.[16] On the other hand, only 63% of observed bicyclists used the mixing zone correctly when a car was present. This was based on a single intersection.

Areas of Caution

Bicycle crashes increased by 31% when a mixing zone was applied with other design elements, the specifics of which were not called out. These collisions were not adjusted for volumes.[9]

Bicyclists and motorists exhibited lower compliance at mixing zones with sharrow markings and green skip coloring than mixing zones with post-restricted entry/through bike lanes and mixing zones with yield entry markings. However, only a single intersection was analyzed in each case.[16]

Gaps in Research: Appropriate contexts for safety efficacy of mixing zones.

Study Details

Sample Size:[b] Medium

Notes on Quality/ Consistency of Results: Collision results were not adjusted for bicycle volumes. The FHWA study did not document the specific locations/ context of the studies.

Conclusion

Practitioners should use caution, as specific cases are not well researched and locations were not well documented in the FHWA study.

Recommended for:

› *Locations with low right turning volumes*

Not Yet Recommended for:

› *Locations with high right turning volumes*

One-Way Protected Bikeway (Cycle Track)

MUTCD STATUS: Not a traffic control device, so no MUTCD restriction on its use[s]

Claims

- Dedicates and protects space for bicyclists in order to improve perceived comfort and safety
- Eliminates risk and fear of collisions with over-taking vehicles
- Reduces risk of dooring compared to a bike lane and eliminates the risk of a doored bicyclist being hit by a vehicle

Quantification of Benefits

None found.

Documented Crash Reduction

Studies found did not clearly distinguish between one-way and two-way facilities. Refer to two-way cycle track summary sheet for available comparisons between one-way and two-way.

Other MOEs

A review of available research in 2013 indicated that one-way cycle tracks are generally safer at intersections than two-way and that, when effective intersection treatments are employed, constructing cycle tracks on busy streets reduces collisions and injuries.[34]

Areas of Caution

One 2008 study from Denmark found that crash reductions along cycle track segments were outweighed by crashes at intersections.[31]

A 2013 review concluded that crash reduction effects have not been well examined.[34]

Gaps in Research:
Research is lacking on appropriate applications of specific intersection designs including measurements of user comfort and perception.

Study Details

Sample Size:[b] Medium

Notes on Quality/ Consistency of Results:
The Vancouver/Toronto study notes that injury risk at intersections were inconclusive because most sites did not apply the cycle track through the intersection, only between intersections. Existing research is conflicting. In many cases there were a small number of overall crashes, leading to a small change in crashes appearing noteworthy. There were many studies with a lack of complete data sets and differences in design that may impact the safety of the facility, particularly at intersections.

Conclusion

Existing research is conflicting, and appropriate intersection design is critical to improving safety along protected bikeways. Refer to intersection designs such as bend-ins, bend-outs, separated bike phasing, and mixing zones to understand safety implications. Also refer to two-way cycle tracks for relative safety implications compared to one-way cycle tracks.

Recommended for:

- *Locations with a high level of mid-block crashes*
- *Accommodating bicyclists along major roadways*

Two-Way Protected Bikeway (Cycle Track)

MUTCD STATUS: Not a traffic control device, so no MUTCD restriction on its use[u]

Claims

› Protects space for bicyclists by improving perceived comfort and safety

› Reduces risk of dooring and eliminates risk of doored cyclist being hit by moving vehicle

› On one-way streets, reduces out of direction travel (by providing contraflow movement)

Quantification of Benefits

Refer to "Documented Crash Reduction".

Documented Crash Reduction

A 2011 study of Montreal, Canada a reduction in risk of injury of 28% for two-way cycle tracks compared with reference streets (streets without bicycle facilities but that are considered alternative bicycling routes).[35]

A study in Washington DC found no significant change in number of bicycle collisions per cyclist after the installation of a two-way cycle track on a two-way street.[36]

Other MOEs

Cyclists felt that riding on the two-way cycle track in Washington D.C. was much safer and easier, and that they would go out of their way to ride on the cycle track compared to other streets.[36,v]

Areas of Caution

Bidirectional separated bike lanes may exhibit higher crash rates than one-way separated bike lanes or other facilities.[12,37]

An unpublished study in Finland found that two-way cycle tracks had an increased crash risk compared to riding in the street.[34]

Gaps in Research: Efficacy of specific intersection designs for two-way protected bike lanes, also bicycle entry and exit design and reductions in dooring.

Study Details

Sample Size:[b] Medium

Notes on Quality/ Consistency of Results: The 2011 Montreal study has been criticized for a number of reasons, including that the reference streets are dissimilar from the study streets.[38] The Washington D.C. study compared collisions based on 1 year of collision data after installation, which may not provide conclusive information for the collision patterns on the corridor.[36]

Conclusion

Existing research is conflicting. While there is no research for the reduction of out-of-direction travel on one-way streets, it is believed to be a reasonable claim. However, this may not outweigh the safety implications for driveways and intersections. Design of the intersections is the most critical for safety since drivers won't expect cyclists in both directions, and the efficacy of specific intersection designs for two-way protected bike lanes is not well studied.

Recommended for:

› *One-way streets with few driveways and intersections where one-way protected bike lanes are not feasible*

› *One-way streets with driveways and intersections where dedicated bicycle signal phasing is feasible*

Not Yet Recommended for:

› *Two-way streets*

› *Locations where one-way protected bike lanes are feasible and provide desirable levels of bicyclist accessibility*

low confidence level

Low Confidence Level

The low confidence level category was assigned based on the quality of available data, or for devices for which there are limited if any studies. Studies in this category may not have documented the study sites well enough to fully understand the context of the results, such as an FHWA study for the bend-in crossing. This study aggregated data for bend-in crossings from multiple case studies and results were compared across cases where the device was applied on its own versus cases where the device was applied with other bicycle treatments; however, those other treatments are not documented nor are other site characteristics that may have contributed to the results. The study showed an increase in the absolute number of bicycle crashes per year;[9] however, the data was not controlled for volumes. In general, the low confidence level represents devices for which research is inconclusive or incomplete.

Bend-in Crossing

APPROVAL STATUS: Not a traffic control device so no MUTCD restriction on its use[x]

Claims
› Promotes visibility in advance of the intersection

Quantification of Benefits
Refer to "Documented Crash Reduction".

Documented Crash Reduction
18.4% reduction in total collisions for all road users (including vehicle-vehicle) when a bend-in crossing was applied on its own.[9]

Other MOEs
None found.

Areas of Caution
Bicycle collisions, not adjusted for volumes, increased from .45 to 3 per year when a bend-in was applied on its own and from 1 to 2.2 per year with other treatments.[9]

Gaps in Research: Appropriate contexts for bend-in treatment; Comparison of two-way and one-way protected bikeways.

Study Details
Sample Size:[b] Small

Notes on Quality/ Consistency of Results: Studies were not adjusted for changes in bicycle volumes.

Conclusion
Results are inconclusive since they weren't adjusted for volumes and the specific sites aren't well documented in the FHWA study.

Recommended for:

› *Adapting protected bikeways to the standard bike lane striping at intersections with use of soft-hit posts or delineators within the striped buffer*

Not Recommended for:

› *Use without raised element (striping only)*

› *High conflicting turning volumes*

› *Locations where user comfort is a high priority*

Combined Bike Lane/Turn Lane

NOTE: Refers to shared-lane markings only (rather than a striped bike lane)
MUTCD STATUS: Allowable[z]

Claims

- Preserve positive guidance for bicyclists in a situation where the bike lane would otherwise be dropped
- Maintains bicyclist comfort and priority in absence of dedicated bicycle through lane
- Guides bicyclists to ride in turning lane, which tends to have lower speed traffic than adjacent through lane (allows higher speed through traffic to pass unimpeded)
- Reduces risk of "right-hook" collisions at intersections

Quantification of Benefits

Refer to "Documented Crash Reduction".

Documented Crash Reduction

One study evaluated crash reduction rates for combined bike lane and through-right turn lanes and right turn lanes in New Zealand and Australia. The results for the two cities evaluated were in conflict. In Adelaide, collisions increased by about 40 percent in both combined bike lane/travel lane scenarios, whereas in Christchurch, collisions decreased by 40 percent for shared through-right turn lanes and 3 percent for exclusive right-turn lanes with bicycles. The study accounted for changes in volumes before and after implementation of the device.[39]

Other MOEs

None found.

Areas of Caution

Striping of bike lane within right turn lane is disallowed by MUTCD.

Gaps in Research: Reduction in "right hook" collisions, yielding efficacy, and reduction in vehicle speeds.

Study Details

Sample Size:[b] Small

Notes on Quality/ Consistency of Results: None

Conclusion

Research is conflicting. While there may be merits of this as an alternative to no treatments, it is likely not safer than a dedicated facility. The crash benefit cannot be quantified at this time (the available data does not strongly support it increasing or decreasing).

Recommended for:

- *Locations with speeds of 35 mph or lower where space doesn't allow for a dedicated facility*

Not Recommended for:

- *Crash reduction*
- *Striping a bike lane within a turn lane of sub-standard width (not allowed by MUTCD)*
- *Locations where there is adequate space to stripe a bike lane*
- *Locations where an off-street transition is a viable alternative*

Intersection Crossing Markings (Non-Green)

MUTCD STATUS: Allowable[bb]

Claims

› Raises awareness for both bicyclists and motor vehicles to potential conflicts

› Makes bicycle movements more predictable

› Increases the visibility of bicyclists

› Reduces conflicts between bicyclists and turning motorists

Quantification of Benefits

None found.

Documented Crash Reduction

None found.

Other MOEs

Sharrow treatment (no dotted lines) may have highest comprehension among roadway users when compared to dashed white markings or colored pavement in conflict zones[40]

Areas of Caution

When compared to use of green in conflict zones, non-green crossing markings are not widely studied

Gaps in Research: Examples of safety efficacy and user comfort with non-green, MUTCD-compliant bike lane extensions through conflict zones

Study Details

Sample Size:[b] Small

Notes on Quality/ Consistency of Results: Study was based on a computer simulation rather than field tests

Conclusion

Safety efficacy for effects on collisions has not been studied.

Recommended for:

› *Bike positioning where there are no conflicts (through an intersection with a dedicated right turn)*

Not Yet Recommended for:

› *Substitute to green striping in conflict zones where bicycles are a priority*

› *High-conflict areas*

[bb] Bike lane extensions through intersections can include standard bicycle lane arrows, bicycle symbols, or pavement word markings

Through Bike Lane

MUTCD STATUS: Allowable[dd]

Claims

- Reduces conflicts between turning motorists and bicycle through traffic
- Leads to more predictable bicyclist and motorist travel movements
- Alerts motorists to expect and yield to merging bicycle traffic
- Signifies the appropriate location for motorists to safely merge across the bike lane into the turn lane

Quantification of Benefits

None found.

Documented Crash Reduction

None found.

Other MOEs

High correct lane use by turning vehicles (87%) and through bicyclists (91%) when entry to the turning lane was restricted by posts at one intersection.[16] Lower compliance for both user groups resulted with unrestricted entry into the turn lane. This was based on a single intersection for each treatment.

Areas of Caution

Correct lane use decreased from 87% to 66% by turning motorists for unrestricted entry compared to restricted entry with soft-hit posts.[16]

Gaps in Research: Effect of through bike lanes on the frequency of bicycle-vehicle collisions

Study Details

Sample Size:[b] Small

Notes on Quality/ Consistency of Results: None found

Conclusion

Safety efficacy is unclear for applications with unrestricted entry. The research suggests that without the use of soft-hit posts to restrict entry to the turn lane, vehicle merging location may be unpredictable or inconsistent.

Recommended for:

- *Locations where the merging location can be controlled by on-street parking or soft-hit posts*
- *Maintaining a separate bike facility at an intersection where volumes warrant a dedicated right turn lane*

Not Recommended for:

- *Locations where bicycle safety and comfort are a high priority and separated bicycle phasing is feasible*

Two-Stage Left Turn Boxes

MUTCD STATUS: Subject to experimentation[41]

Claims

- Improves bicyclist ability to safely and comfortably make left turns
- Provides a formal queuing space for bicyclists making a two-stage turn
- Reduces turning conflicts between bicyclists and motor vehicles
- Prevents conflicts arising from bicyclists queuing in a bike lane or crosswalk
- Separates turning bicyclists from through bicyclists

Quantifications of Benefits

None found.

Documented Crash Reduction

None found.

Other MOEs

None found.

Areas of Caution

In theory, a two-stage left turn box does provide basic infrastructure for bicyclists to make left turns and it does seem reasonable that this maneuver would be more comfortable than weaving across multiple travel lanes to access a left turn lane. In addition to a lack of research regarding safety, reduced vehicle-bicyclist conflicts and reduced bicyclist-pedestrian conflicts, no research is available regarding how well understood and utilized two-stage left turn boxes are.

Gaps in Research: Safety of two-stage turn boxes including assessment of change in bicyclist-vehicle and bicyclist-pedestrian conflicts, understanding and utilization of two-stage left turn boxes by bicyclists (including geometric and traffic control design elements that maximize two-stage left turn box use).

Study Details

Sample Size: No studies available

Notes on Quality/ Consistency of Results: None

Conclusion

Safety efficacy has not been adequately studied.

Recommended for:

- *Providing basic accommodations for left-turning bicyclists along protected bike lanes/cycle tracks or bike lanes on streets with either several travel lanes or high travel speeds (agencies should be cautioned as to the limited availability of efficacy studies)*

Not Yet Recommended for:

- *Locations where accessing a left-turn lane is generally easy and comfortable for bicyclists including well designed shared roadways such as bicycle boulevards and bike lanes on streets with two travel lanes (each direction) and low travel speeds (25-30 MPH or less)*

Conclusion

In order to feel confident in the overall application and effect of several of these treatments, there is a need for more rigorous safety studies. Such studies would allow for inclusion of more of these devices in the Highway Safety Manual and therefore a better quantification of benefits and costs. More rigorous quantification would also likely support bicycle safety projects competing more effectively for limited safety funds. Using standardized data collection protocols for as many projects as possible, especially the collection of bicycle volumes before and after project implementation, would be one key factor to help advance the state of research for bicycle treatments. Consistent, standardized data collection and additional studies of bicycle infrastructure treatments would improve guidance for transportation professionals and facilitate safer facility designs.

footnotes & references

Footnotes

[a] MUTCD refers to shared lane markings and bike route signs only: Shared Lane Marking, Section 9C.07, 2014 MUTCD; Bicycle Guide Signs, Section 9B.20, 2014 MUTCD, Bicycle Route Signs, Section 9B.21, 2014 MUTCD

[b] Small = 1-2 cities, Medium = 3-5 cities, Large = >5 cities

[g] No restrictions as long as MUTCD-compliant signing and striping is used and the design is compatible with relevant geometric guidelines

[i] Study described right turn volume as "heavy" although no value was given. The approach volume was 450 vph in the AM and 350 vph in the PM.

[m] Marking For Bicycle Lanes – Contraflow Bicycle Lanes, Section 9C.04

[q] This measure is allowed through the use of MUTCD-compliant striping for combined right turn/bike lanes. (See Combined Bike Lane/Turn Lane for more information)

[s] Guidance for this treatment can be found in FHWA's Separated Bike Lane Planning and Design Guide and CROW, the Dutch Design Manual for Bicycle Traffic

[u] Guidance for this treatment can be found in FHWA's Separated Bike Lane Planning and Design Guide and CROW, the Dutch Design Manual for Bicycle Traffic

[v] No quantitative results for this survey were found in the study

[x] Although no specific examples are included, this measure could be implemented using MUTCD compliant striping and HCM compliant curb geometries

[z] https://www.fhwa.dot.gov/environment/bicycle_pedestrian/guidance/mutcd/index.cfm, http://mutcd.fhwa.dot.gov/knowledge/faqs/faq_part9.htm#mkgsq11

Bicycle Lane Line Extensions through Intersections, Section 9C.04, 3B.08, and 3B.20, MUTCD 2014; http://mutcd.fhwa.dot.gov/knowledge/faqs/faq_part9.htm#mkgsq7. See also: http://mutcd.fhwa.dot.gov/resources/policy/tcdstatusmemo/index.htm

[dd] Bicycle Lane Treatment at Right Turn Only Lanes, Section 9C.04 and Figures 9C-1, 9C-4, 9C-5, Optional Use of Bicycle Signal Faces, Section 4D.104(CA), CA MUTCD 2014

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