Beacon Street
Roadway & Streetscape Improvements
Somerville, Massachusetts
MassDOT File No. 607209

Design Exception Report

Prepared by Design Consultants, Inc.

July 2012
Revised August 2, 2012
Revised December 10, 2012

Design Consultants, Inc.
CIVIL ENGINEERS and LAND SURVEYORS
120 Middlesex Avenue, Suite 20
Somerville, MA 02145
617-776-3350p 617-776-7710f

massDOT
Massachusetts Department of Transportation
Highway Division

Executive Summary

The Beacon Street Roadway and Streetscape Improvements Project in Somerville will reconstruct 1.1 miles of roadway, from Oxford Street to the Somerville/Cambridge city line.

Beacon Street is an urban arterial with an existing roadway width of approximately 44 feet within a 66 foot City layout. Existing sidewalks are 10 feet wide. The posted speed limit is 30 mph along the corridor. Abutting land use is a dense mix of commercial and residential with parking provided along both sides throughout most of the project area.

The proposed design currently includes full depth reconstruction of the entire roadway and sidewalks. Full depth reconstruction is necessitated by previous utility work, proposed utility work and the condition of the existing bituminous asphalt along Beacon Street. However, the potential to mill/overlay the roadway, rather than full depth reconstruction, is still being evaluated.

The roadway cross section from Oxford Street to Museum Street and from Park Street to Washington Street includes 10’ sidewalk, 6’ cycle track, 11’ travel lane, 13’ travel lane (including 2’ shoulder), a 7’ parking lane, a 9’ cycle cycle track and a 10’ sidewalk.

The roadway cross section from Museum Street to Park Street includes 10’ sidewalk, 7’ parking lane, 5’ bike lane, 11’ travel lane, 11’ travel lane, a 5’ bike lane and a 5’sidewalk.

The roadway cross section from Washington Street to the Somerville/Cambridge city line includes 10’ sidewalk, 7’ parking lane, 5’ bike lane, 11’ travel lane, 11’ travel lane, a 5’ bike lane, 7’ parking lane and a 10’sidewalk.

There are approximately 100 utility poles located along Beacon Street, most of which are between 6” and 12” from the face of curb. In most locations, sanitary sewer and water lines are located on one or both sides of the utility poles. The intent of the roadway cross sections in areas where there is no cycle track is to approximately maintain the curb line, reducing as much as is feasible, the need to relocate utility poles.

The Federal Highway Association and MassDOT recognize 13 controlling criteria from the AASHTO Policy on Geometric Design of Highways and Streets which if not met, require formal approval of design exceptions.

The proposed project does not meet two of the controlling criteria, namely Shoulder Width and Horizontal Clearance. The minimum shoulder width is not met between Oxford Street and Washington Street in the southbound direction, where a 2’ shoulder is provided between the travel and parking lane. The minimum 18” horizontal clearance is not met between Washington Street and the Somerville/Cambridge city line. The existing curbline along this portion of Beacon Street is to be approximately maintained, resulting in the existing utility pole clearances (6” to 12” from face of curb) remaining. These clearances are between the parking lane and curb.

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1. Existing Conditions

The existing project area and its relation to the surrounding roadway system is shown on Figure 1-1. The following is a description of the project area roadways noted on the plan.

Figure 1-1: Study Area

Beacon Street is an urban arterial that runs northwest from the Cambridge city line to Somerville Avenue. The Beacon Street project area extends from the bridge abutment at Oxford Street to Dickinson Street, a distance of approximately 1.1 miles. The existing roadway width is approximately 44 feet within a 66 foot City layout. Existing sidewalks are approximately 10 feet wide. The posted speed limit is 30 mph along the corridor. Abutting land use is a dense mix of commercial and residential with parking provided along both sides throughout most of the project area.

The roadway pavement is in poor condition. From Oxford Street in the northwest to the city line in the southeast the pavement is a series of patches, potholes, failing trench repairs, lateral and longitudinal cracks, shoving, heaving and rutting.

The sidewalks are substantial in width, however are in poor condition and have non-compliant cross slopes in many cases. While there are sections of new sidewalk, much of the sidewalk is very old with cracks, settlement and heaved sections. Additionally throughout the project there are frequent, poorly constructed bituminous concrete pavement patches.

The pedestrian ramps throughout the corridor are in poor condition and not ADA compliant. Additionally in numerous locations pedestrian ramps do not exist at all.

Utility poles exist on both sides of the street with clearances generally less than 18 inches from face of curb, most utility poles are located at or slightly behind the back of curb.

Beacon Street has been in operation as currently constituted for over one-hundred and fifty years. As such the profile and alignment is fixed by the development that occurred during that time. Fortunately, the arterial is in an area of gentle topography, hence vertical and horizontal alignment is acceptable. The vertical alignment ranges from ¾% to 2%. The horizontal alignment for all intent and purpose is straight with several minor angle points.

With regard to traffic, Beacon Street operates as one travel lane in each direction with areas of metered and 2 hour parking permitted along both sides. A variable 4 foot-wide bicycle lane is provided along both sides of the Beacon Street. Traffic signalization is provided at several locations along the corridor to control vehicular traffic and/or provide for pedestrian crossings. The intersections of Beacon Street/Washington Street and Beacon Street/Park Street/Scott Street are fully signalized. The intersections of Buckingham Street/Cooney Street and Museum Street/Kent Street provide pedestrian actuated traffic signals. There is a lack of turn lanes or protected movements at Washington Street and signal equipment is antiquated, resulting in significant back-ups and delays. Traffic and pedestrian signal equipment do not conform to MUTCD and ADA standards.

The existing typical section for Beacon Street provides for one travel lane, a bicycle lane and parking (about 22 feet) in each direction. Field observations and intersection count data indicate that pedestrian and bicycle activity is high.

Following are descriptions of the Beacon Street study area intersections.

Beacon Street/Sacramento Street

Beacon Street at Sacramento Street is 44 feet wide providing for one travel lane in each direction, a bicycle lane and parking on both sides. A pedestrian crosswalk is provided on Beacon Street as Star Market is located on the northeast corner of the intersection and a pedestrian connection is located along Sacramento Street to Somerville Avenue.

Sacramento Street is one-way eastbound from Massachusetts Avenue to Carver Street where it turns northerly and becomes two-way to its intersection with Beacon Street where it is stop sign controlled. The northern leg of Sacramento Street borders the Star Market parking lot and comes to an end at the railroad tracks running behind the supermarket. A pedestrian underpass provides access to the other side of the tracks and Somerville Avenue. This connection is critical for pedestrians to access the bus routes along the west end of Somerville Avenue where no bus stops exist. Pedestrians must use this link to access public transportation. Star Market is located on the northeast corner of the intersection and deliveries utilize the north leg of Sacramento Street.

Beacon Street/Kent Street/Museum Street

This intersection is located approximately 900 feet northwest of the Beacon Street/Park Street intersection and is controlled by flashing traffic signals which provide a Beacon Street pedestrian crossing by displaying red/yellow indications to all approaches during pedestrian actuation. Beacon Street north of this intersection is 44 feet wide providing one lane in each direction with bicycle lanes and parking on both sides. Beacon Street south of this intersection to the Scott/Park Street intersection is 42’ wide providing one lane in each direction with bicycle lanes and parking on both sides and a sidewalk on the east side only. Abutting land use is a dense mix of commercial, retail and residential.

Museum Street travels north-south from Hammond Street to Beacon Street. Museum Street is 24 feet wide providing one lane in each direction with parking along both sides and is controlled by a flashing red indication at its intersection with Beacon Street.

Kent Street is 16 feet wide travelling from Beacon Street to its dead end terminus. Kent Street is also controlled with a flashing red indication and a stop sign.

This pedestrian actuated intersection is provided to protect pedestrians that must cross Beacon Street as no sidewalk is provided along the south side of Beacon Street between Museum Street and Scott Street.

All traffic signal equipment is antiquated and not up to current MUTCD and ADA standards.

Beacon Street/Park Street/Scott Street

This four legged signalized intersection is located 0.2 miles west of the Beacon Street/Washington Street intersection. Park Street is a major north-south link between Beacon Street and Somerville Avenue. Park Street is 33 feet wide providing one lane in each direction with parking along both sides. Scott Street travels one-way from Holden Street to its intersection with Beacon Street. Scott Street is 33 feet wide and provides parking along both sides. A reverse counterflow (southerly) bike lane is provided on Scott Street from Beacon Street to Bryant Street in Cambridge.

Beacon Street south of this location is 44 feet wide providing one travel lane in each direction with parking allowed along the south side near the intersection. Beacon Street north of this intersection to the Kent/Museum Street intersection is 42' wide providing one lane in each direction with bicycle lanes and parking on both sides and a sidewalk on the east side only. Traffic signal control at this intersection consists of 2-phase vehicle control with an exclusive pedestrian phase.

Beacon Street/Washington Street

Washington Street intersects Beacon Street just north of the Somerville/Cambridge city line forming a 4-legged signalized intersection. Washington Street travels east-west from Somerville Avenue to the City of Cambridge where it becomes Kirkland Street. Beacon Street is 44 feet wide providing one travel lane in each direction with parking along both sides. Washington Street is 40 feet wide and also provides one lane in each direction with parking along both sides. Traffic control consists of pre-timed, two-phase control with an exclusive pedestrian phase. The Washington Street northbound left turn movement is significant and creates back-ups on Washington Street as there is no separate turn lane or protected movement. Existing sidewalk ramps and pedestrian signal equipment do not comply with the current MUTCD and ADA standards. Abutting land use is commercial and residential.

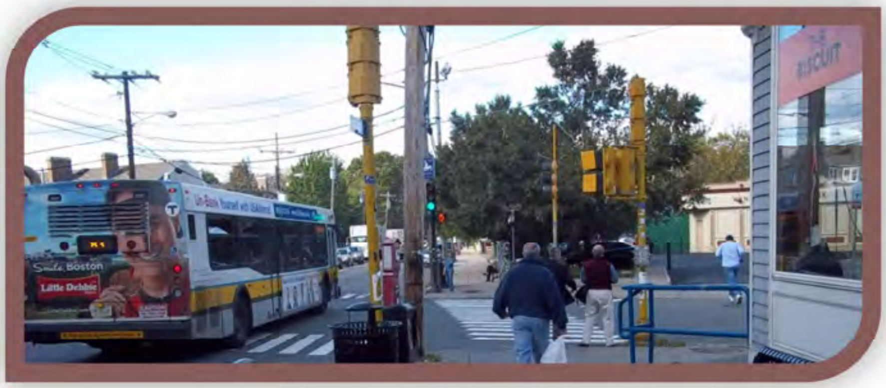
Beacon Street/Buckingham Street/Cooney Street

Buckingham Street and Cooney Street intersect Beacon Street approximately 1,000 feet east of the Beacon Street/Washington Street intersection. The two side streets are offset by approximately 65 feet. Buckingham Street is 26 feet wide travelling north-south from Beacon Street to Dimick Street. Cooney Street is 20 feet wide travelling one-way southbound from Beacon Street to Line Street. A signalized pedestrian crossing is provided on Beacon Street between Buckingham and Cooney Streets. The traffic signals provide flashing green for Beacon Street and flashing red for Buckingham Street. The traffic control equipment is antiquated and not up to current MUTCD and ADA standards.

Transit Service

The following identifies current Bus Routes along or crossing Beacon Street.

- MBTA Route 83 – connecting Ridge Avenue to Central Square in Cambridge via Porter Square. This route travels along the Beacon Street corridor project from the Cambridge city line to Park Street then on to Somerville Avenue. The route directly serves the project corridor.
- MBTA Route 86 – connecting Sullivan Square and Cleveland Circle via Harvard Square in Cambridge. This route crosses the corridor at the intersection of Washington



Street/Beacon Street with near-side stops along Washington Street (located back from the intersection). This is the busiest location along the route acting as a hub location.

- MBTA Route 87 – connecting Arlington Center and Lechmere Station via Somerville Avenue. This route does not directly cross the project but given the close proximity of Somerville Avenue and Beacon Street on the westerly end of the project limits, the existing pedestrian connection at Sacramento Street was made to improve pedestrian access to this bus route.

All of these routes terminate or intersect with a major multimodal hub such as Sullivan Station (Orange Line), Lechmere Station (Blue Line), Harvard Square (Red Line) or the Porter Square station (Red Line and Commuter Rail). Hence the project leverages these other modes of transportation by enhancing bus stop location and size, handicapped accessibility, bicycle racks and safety. Actual bus service on Beacon Street is only from Park Street to the Cambridge line.

2. Design Exception Report Checklist

The MassDOT Design Exception Report Checklist has been completed and is included in the following section.

DESIGN EXCEPTION REPORT
CHECKLIST

City/Town: Somerville **Project File No.:** 607209

Facility: Beacon Street **Fed. Aid Proj. No.:** ______

I. Project Description

A. Type of Work Proposed

- ☑ Full Depth Reconstruction
- ☐ Reclamation
- ☐ New Construction
- ☑ Resurfacing/Box Widening
- ☐ NHS Bridge Replacement/Rehabilitation
- ☐ Other ______

B. Purpose of Project

- ☑ Safety Improvement
- ☐ Additional Capacity
- ☐ Describe if Other: ______
- ☐ Maintenance
- ☐ Other

C. Footprint Road Project? ☐ YES ☑ NO

II. Indicate Controlling Criteria, as defined by Project Development and Design Guide, requiring a Design Exception. (See worksheet ATTACHMENT A).

A. Roadway and Bridge Criteria

- ☐ Design Speed
- ☐ Lane Width
- ☑ Shoulder Width
- ☐ Horizontal Alignment
- ☐ Vertical Alignment
- ☐ Grades
- ☐ Stopping Sight Distance
- ☐ Cross Slope
- ☐ Superelevation
- ☑ Horizontal Clearance

B. Bridge Only Criteria

- ☐ Width
- ☐ Structural Capacity
- ☐ Vertical Clearance

III. Description of Facility

A. Functional Classification

- ☐ Urban Freeway
- ☑ Urban Arterial
- ☐ Urban Collector
- ☐ Urban Local
- ☐ Rural Freeway
- ☐ Rural Arterial
- ☐ Rural Collector
- ☐ Rural Local

DESIGN EXCEPTION REPORT
CHECKLIST

City/Town: Somerville **Project File No.:** 607209

(Description of Facility cont'd)

B. NHS

☐ Yes ☑ No

C. General Description of Project Area

☐ Undeveloped ☑ Residential
☑ Commercial ☐ Industrial
☐ Scenic ☐ Historic
☐ Describe if Other: ______

D. Traffic Volume

ADT (Current)	12,500	T (Peak Hour)	4%
ADT (Design Year)	13,750	T (Avg. Day)	5%
K	7.70%	DHV	1,050
D	60%	DDHV	630

E. Speed

Posted	30 MPH	85th Percentile	30 - 35 MPH
Observed		Existing Design Speed	35 MPH

F. Lane and Shoulder Width

Existing

Lane Width 10.5 Right Shoulder 0 Left Shoulder 0

Attach a Typical Section (8 1/2" x11") depicting existing dimensions and proposed cross-sections. Include R.O.W lines.

G. Right of Way

☐ State Highway ☐ County
☑ City/Town

Average Width 66

DESIGN EXCEPTION REPORT
CHECKLIST

City/Town: Somerville **Project File No.:** 607209

(Description of Facility cont'd)

H. Crash Data

The crash rate shall be calculated based on the latest three years of crash data available. Crash rates should be calculated for roadway segments based on Hundred Million Vehicle Miles traveled (HMVM) as follows:

$$HMVM = (A \times 100{,}000{,}000)/(ADT \times D \times L)$$

A = number of total crashes at the study location during a given period
ADT = Average Daily Traffic
D = number of days in the study period
L = length of study location in miles

Attach additional tables and diagrams as necessary to accurately communicate the crash history within the project limits.

Provide a detailed narrative that summarizes available data and draws a conclusion as to the expected effectiveness of any proposed improvements.

I. Environmental Factors

Attach a brief discussion of the natural, cultural, historic or other environmental constraints associated with the proposed project. All of the following must be addressed: wetland/floodplain, trees, parkland, endangered species, cultural, historic, archaeological, etc.

V. Summary of Impacts

Complete the attached spreadsheet titled Summary of Impacts (ATTACHMENT B). A separate spreadsheet is required for each of the controlling criteria for which a design exception is requested.

Attach photographs that illustrate existing features important to the proposed design.

VI. Recommendation

By drawing from all of the above information, attach a narrative documenting that reasonable engineering judgement was used to justify the proposed design.

DESIGN EXCEPTION REPORT
CHECKLIST

City/Town: Somerville **Project File No.:** 607209

VII. Certification of Design Exception Report (Engineering Directive E-99-002)

I have reviewed this document as it relates to the proposed design and have determined the design to be safe for public health and welfare in conformity with accepted engineering standards.

Signature and P.E. Stamp of Principal or Chief Engineer of firm preparing report:

Name

President DCI

Title

12/10/12

Date

COMMONWEALTH OF MASSACHUSETTS
35844
DAVID
GIAN-GRANDE
REGISTERED

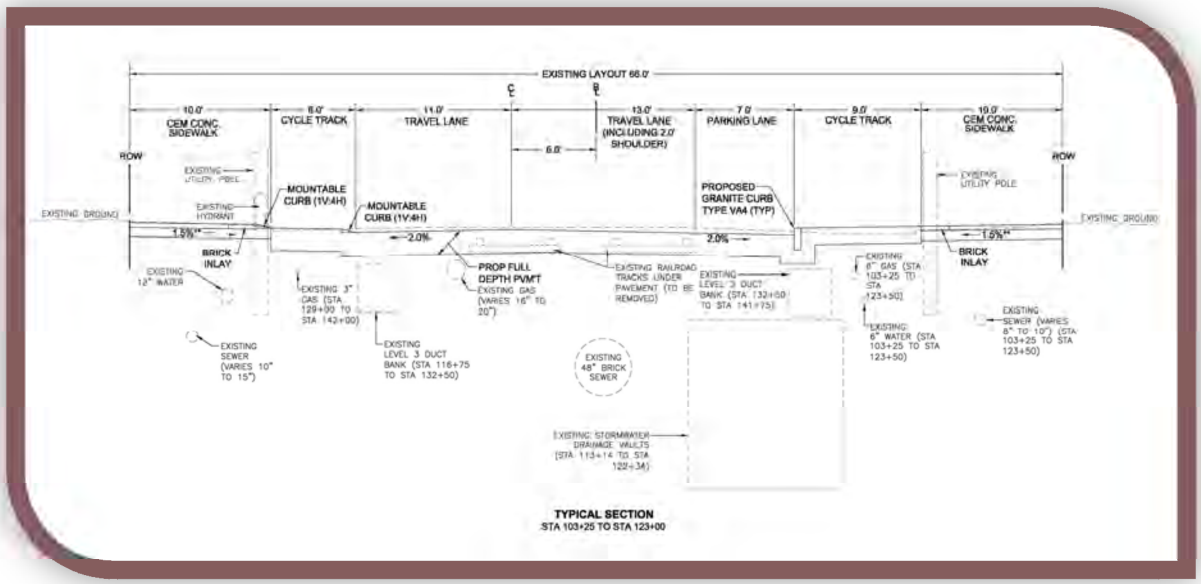
3. Typical Sections

The Proposed Typical Sections

The proposed typical sections within the available 66 foot-wide road right of way have been developed to provide an improved level of safety and mobility for bicycles while maintaining acceptable levels of service for all other travel modes, including on-street parking (refer to Beacon Street Study Report, July 2012, prepared for the City of Somerville). These typical sections are shown and described as follows:

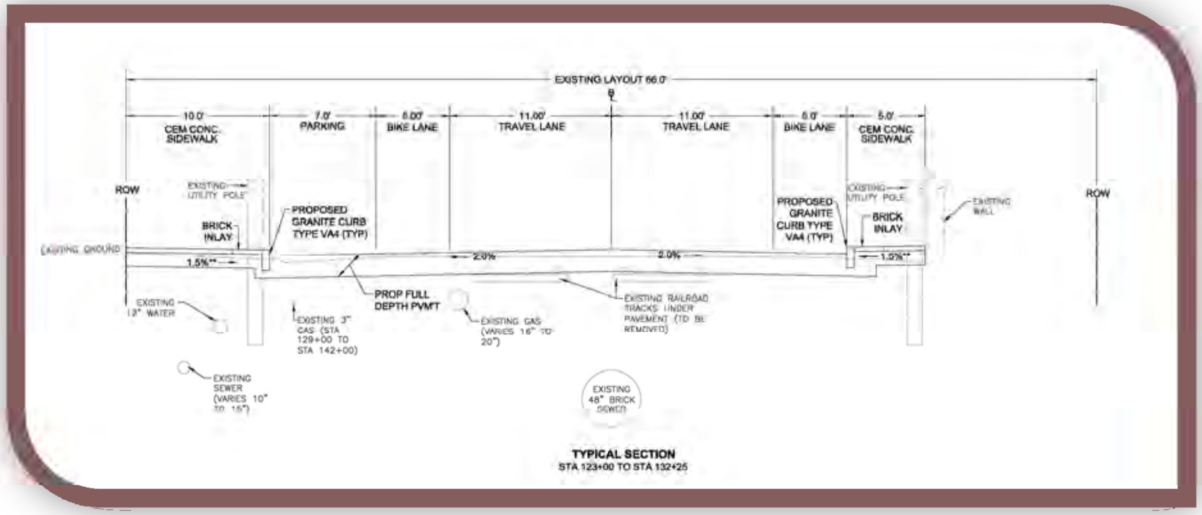
Oxford Street to Museum Street (Sta 103+25 to Sta 123+00)

A 6 foot-wide cycle track with 1v:4h mountable curbing is proposed on the northeast side of the roadway and a 9 foot wide cycle track is proposed on the southwest side of the roadway, each adjacent to a 10 foot-wide concrete sidewalk. On-street parking (7 feet in width) will be maintained on the southwest side only. This results in an 11 foot-wide northbound travel lane and a 13 foot-wide southbound travel lane.



Museum Place to Park/Scott Streets (Sta 123+00 to Sta 132+25)

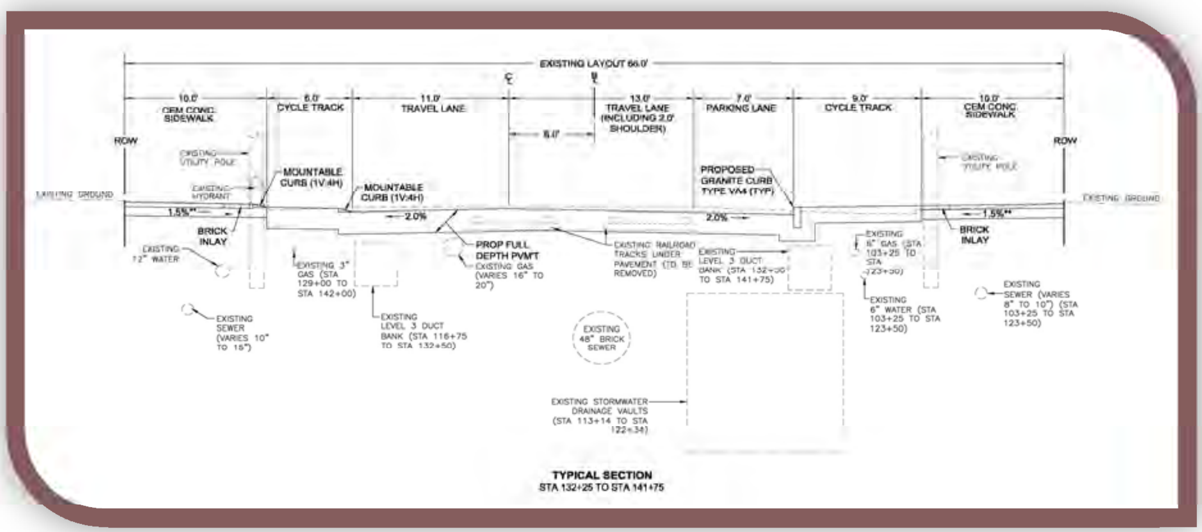
A 5 foot-wide bike lane is proposed adjacent to an 11 foot-wide travel lane in both directions. The existing 10 foot sidewalk and on-street parking (7 feet in width) will be maintained on the northeast side. A new 5 foot-wide sidewalk will be added on the southwest side while maintaining the existing adjacent wall structure at the back of sidewalk.



TYPICAL SECTION
STA 123+00 TO STA 132+25

Park/Scott Street to Washington Street (Sta 132+25 to Sta 141+75)

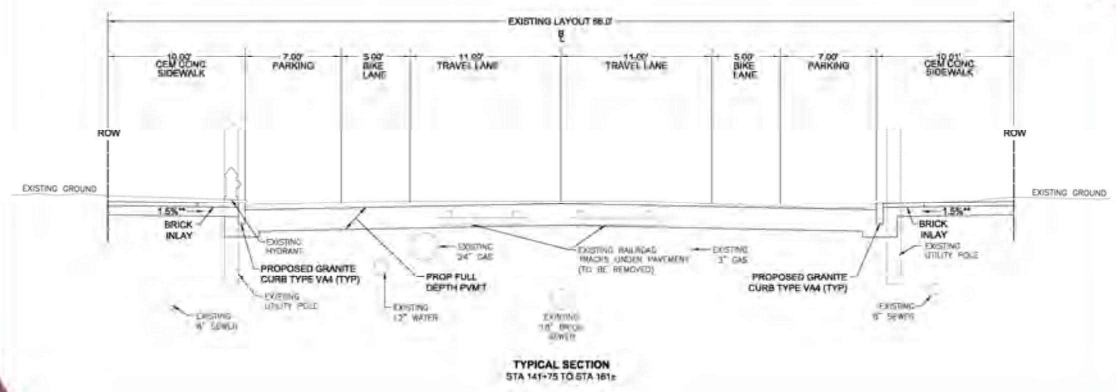
A 6 foot-wide cycle track with 1v:4h mountable curbing is proposed on the northeast side of the roadway and a 9 foot wide cycle track is proposed on the southwest side of the roadway, each adjacent to a 10 foot-wide concrete sidewalk. On-street parking (7 feet in width) will be maintained on the southwest side only. This results in an 11 foot-wide northbound travel lane and a 13 foot-wide southbound travel lane.



TYPICAL SECTION
STA 132+25 TO STA 141+75

Washington Street to Cambridge City Limit (Sta 141+75 to Sta 161+00)

A 5 foot-wide bike lane is proposed adjacent to an 11 foot-wide travel lane in both directions. The existing 10 foot-wide sidewalk and on-street parking (7 feet in width) will be maintained on both sides of the street.



4. Supplemental Narrative

Through careful consideration of all the constraints placed on a project of this type, and in concert with the City of Somerville, the following design exceptions are requested:

Shoulder Width

The 2006 Project Development and Design Guide calls for minimum 4-foot shoulders for all arterials and collectors because of the value they provide bicycle and pedestrian accommodation, and motor vehicle safety.

ATTACHMENT B
DESIGN EXCEPTION REPORT
SUMMARY OF IMPACTS

Provide a summary of the incremental impacts associated with the Desirable, Minimum and Proposed design. Include impacts of incremental designs.

A separate Summary of Impacts sheet shall be prepared for each controlling criteria element that does not meet the minimum specified.

CONTROLLING CRITERIA: Shoulder Width

SUMMARY OF IMPACTS

INSERT VALUE IN THIS COLUMN	WETLANDS (SF)	TREES (EA)	PARKLANDS (SF)	STONE WALLS (LF)	SALT MARSH (SF)	ADDITIONAL UTILITIES ($)	ROW ($)	CONST. COST ($)	TOTAL COST ($)
DESIRABLE 10 FT	N/A	149	N/A	600	N/A	$2 - 4M	PROHIBITIVE	$6-8M	PROHIBITIVE
MINIMUM 4 FT	N/A	0	N/A	0	N/A	$0	$0	$5.8M	$5.8M
ALTERNATIVE 1 5 FT BIKE LANE ALTERNATIVE	N/A	14	N/A	0	N/A	$2 - 4M	$0	$6M	$8-10M
RECOMMENDED 6 FT NB 2 FT SB	N/A	14	N/A	0	N/A	$0.25 - 0.5M	$0	$6M	$6M

Preview of Attachment B-1 – Summary of Impacts for the Shoulder Width Controlling Criteria - Full size attachment at the end of the report

Proposed improvements along Beacon Street from Oxford Street to Museum Street and from Park Street to Washington Street provide for separate bicycle accommodation (cycle tracks) off the roadway while maintaining the existing pedestrian sidewalk. In the northbound direction, the proposed design contains a 6 foot wide cycle track that is adjacent to the 11 foot wide travel lane. The cycle track is separated from the travel lane by a 3-inch mountable curb (sloped at 1V:4H). As such, the cycle track will be available for vehicular use in emergency situations. In the southbound direction, a 7 foot wide parking lane will be separated from an 11 foot wide travel lane with a 2 foot wide shoulder. Bicycles will be accommodated on a 9 foot wide cycle track that is located on the outside of the parking lane, and separated from the parking with 6-inch vertical granite curbing. On both sides of Beacon Street, 10 foot wide sidewalks are located adjacent to the proposed cycle tracks. Increasing the shoulder widths within the existing right of way while maintaining the cycle track and lane widths would require many of the existing utility poles to be relocated. In most locations along Beacon Street, the utility poles are located very close to or in between the water and sewer lines. Therefore, relocating the utility poles would also require replacement of portions of the sanitary sewer lines and water mains. This would result in a very high cost of utility pole relocation and would reduce the width of the existing pedestrian sidewalks.

Alternative Analysis

DESIRABLE ALTERNATIVE (10 ft shoulder width)

Chapter 5 of the MassDOT Project Development and Design Guide, recommends a 4-12 ft shoulder for urban arterials. In past iterations of the manual, desirable width for urban arterial shoulders was 10 ft. Assuming that the desirable shoulder is 10 ft, the following section would be required, 8ft sidewalks, 7 ft parking lanes, 10 ft shoulders providing bicycle accommodations and 11 ft travel lanes.

The necessary Right of Way (R.O.W.) for the 10 ft shoulder width is at least 72 ft, with only 66 ft available along Beacon Street. Hence, acquisition of 6 additional feet of R.O.W. would be required in this dense urban environment. With buildings at or close to the R.O.W. line, the R.O.W. cost would be prohibitively high. Additionally, 105 utility poles would require relocation into a space that already contains water and sewer mains. The cost to relocate the poles, water and sewer mains is estimated at $10 million +/-. This alternative is not feasible from a cost perspective, or impact to the community.

MINIMUM ALTERNATIVE (4.0 ft shoulder width/similar to existing)

Chapter 5 of the MassDOT Project Development and Design Guide requires 4 ft as a minimum width of shoulder: "Minimum 4-foot shoulders are recommended for all arterials and collectors because of the value they provide for bicycle and pedestrian (particularly in rural areas) accommodation, and motor vehicle safety." This arrangement is further described in the MassDOT Project Development and Design Guide as a Case 2 condition. The Case 2 condition is a partial sharing for bicycles and motor vehicles and is not considered as full bicycle lanes.

The alternative does not provide an adequate balance of accommodations between cyclists and motor vehicles. With 11,000 to 13,000 vpd in addition to 500 cyclists per day, modal equity is critical. The available accident data involving bicycles for this 1.1-mile stretch of Beacon Street indicated 34 accidents in a 3 year period from 2009-2011. The bicycle crash rate for the corridor is significant at 56.4 crashes per million miles travelled which is approximately equal to the national average of 37.1 per million kilometers or 58 per million miles.[1] Based on discussions with cyclists in the area, it is also believed that bicycle ridership is suppressed due to the poor condition of the roadway and overall rideability. When the new surface is completed it is anticipated that an increased bicycle use will occur. Additionally, it is widely recognized that accidents are directly related to utilization or ridership. Hence, it is anticipated that accidents will increase significantly putting the accident rate above the national average. Increasing the ridership without enhancing safety is not recommended.

ATLTERNATIVE 1 (5 ft Bike Lane Alternative)

According to AASHTO "Guide for the Development of Bicycle Facilities, 2012 4th Edition", Bicycle lanes that are adjacent to on-street parking are recommended to be 5 ft (1.5m) wide. The section provided would allow the full implementation of an exclusive bike lane. In order to accomplish this, they would consist of 9-foot sidewalks, 7 foot parking lanes, 5-foot bike lanes, and 11-foot travel lanes. This would equal a curb-to-curb section of 46 feet, a 2 feet larger than existing. Moving the curb by 2 feet would require the relocation of up to 100 utility poles and the relocation of much of the sewer and water mains that are presently squeezed into the modest sidewalk areas. The estimated cost to perform this work would be $2 to $4 million and potentially delay in the schedule for 1 year.

RECOMMENDED ALTERNATIVE (cycle track / 6 ft shoulder NB, 2 ft shoulder SB, station 103+25 to station 123+00, Station 132+25 to station 141+75)

The section that has been requested by the City and Community includes the removal of on-street parking north bound and maintaining parking south bound. The full section will be: 10 ft sidewalks on each side, a 6 ft one-way cycle track in the NB direction (separated from the vehicular travel lane by a 3-inch mountable curb), a11 ft NB travel lane, a 13.0 ft SB travel lane (including a 2.0 shoulder south bound), a 7 ft parking lane on the south bound side, and a 9 ft cycle track (separated from the parking lane with 6 inch vertical granite curbing). It is assumed that the 6 ft cycle track in the NB direction will also serve as a useable shoulder, as needed. This section totals 46 ft, however that is from face of utility pole to face of utility pole vs. face of curb to face of curb for alternative 1. The significance of which means no relocations of utility poles for the length of the cycle track. The cycle track would occur in the area where both sidewalks have water and sewer. A result of not having to move poles in this area alleviates the need to relocate subsurface utilities and saves $2-4 million.

Additionally, the benefits of this Alternative are as follows:

1. Maintaining 10 ft sidewalks for pedestrian use.

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[1] TRB Publications Index: Survey of North American Bicycle Commuters.

2. Enhanced perception of safety which results in increased bicycle ridership and a reduction of motor vehicle travel (all reports indicate a 10-20% increase ridership).

3. The recommended section can be constructed within the R.O.W. with limited impact on private and public utilities. In the cycle track section the utility pole relocation is minimal.

STUDY DATA SYNOPSIS

The results of the Trafitec study that was presented by District 4 are not consistent with the literature we have seen on the safety of cycle tracks, so we were surprised with the results. To understand the methodology used in the referenced reports, we read through the report entitled “Bicycle Tracks and Lanes: A Before-After Study”, a copy of this report is included with this report. Reading the report sheds light on how the high percentages were determined as well as the irrelevancy of those results.

The methodology of calculating the accident results in “Bicycle Tracks and Lanes: A Before-After Study” is as follows. The report attempted to develop equations and models that could be used to predict future accident results. A known result of installed cycle tracks is that motor vehicle traffic decreases while bicycle traffic increases. The models include several “correction factors” used to calibrate the models to the observed existing accident data prior to the installation of the cycle tracks. These correction factors were then applied to the decreased motor vehicle traffic and increased bicycle traffic to develop an “Expected After” crash result. The comparison of this theoretical “Expected After” result was then compared to the actual observed crash results (after cycle tracks were installed) and this comparison is what is reported in the study. This number is only a comparison between a predicted model value and the actual observed value. A much more appropriate comparison would be to compare the crash results from before the installation of the cycle tracks to the crash results after the installation of the cycle tracks. This is the comparison that most readers of the Trafitec report believe is being reported, but this is not the case. Below is the comparison of the crash results from before the installation of the cycle tracks to the crash results after the installation of the cycle tracks. This information is taken directly from the “Bicycle Tracks and Lanes: A Before-After Study”.

		Observed Before	Observed After	Safety Effect (percent)
Single Vehicle Crash	All Crashes	170	142	-16.5
	MV	134	111	-17.2
	BM	36	31	-13.9
Rear-End Crash	All Crashes	718	584	-18.7
	MV and MV	517	483	-6.6
	MV and BM	173	57	-67.1
	BM and BM	28	44	57.1
Frontal Crash	All Crashes	77	92	19.5
Right-Turn Crash	All Crashes	160	397	148.1
	MV and turning MV	47	73	55.3
	Turning MV and BM	81	282	248.1

	Turning MV and Ped	25	32	28.0
	Turning BM	7	10	42.9
Left-Turn Crash	All Crashes	614	589	-4.1
	MV and turning MV	334	334	0.0
	Turning MV and BM	120	161	34.2
	Turning MV and Ped	65	47	-27.7
	Turning BM	95	47	-50.5
Right-Angle Crash	All Crashes	575	522	-9.2
Crash with Parked MV	All Crashes	217	142	-34.6
	MV and parked MV	123	96	-22.0
	BM and parked MV	94	46	-51.1
Crash with Pedestrian from Right	All Crashes	296	244	-17.6
	MV and Ped	228	140	-38.6
	BM and Ped	68	104	52.9
Crash with Pedestrian from Left	All Crashes	123	85	-30.9
	MV and Ped	111	68	-38.7
	BM and Ped	12	17	41.7
Crash with Entering or Exiting Bus Passenger		5	73	1360.0
Other Pedestrian Crashes		32	41	28.1

As can be seen when actual crash rates are compared, most crash rates are reduced with the installation of cycle tracks. The crashes which are not reduced are the vehicular right turn movements and crashes at bus stops. These two type of crashes are well documents as being a concern with cycle tracks and cycle track designs need to be carefully thought out so that accidents are reduced, not increased.

The right turn vehicular movement crash can be remediated by restricting right hand on red turns at signalized intersections, by providing sight triangles at minor streets (20') and at driveways (10') and by introducing signage that alerts motor vehicle operators that they must yield to bicycles on the cycle track. The type of signage could be a variant of MUTCD R1-5, 1-5a as seen here[2]. In its report[3], Alta Planning + Design concluded that increased visibility and protected signal phases are important to protect both vehicle and bicycles at signalized intersections.

MassDOT pointed out the conflict with the bus stops in the District 4 comments dated June 1, 2012. The response to this comment was that DCI and the City proposed to remove or relocate the two southbound stops. The two remaining northbound bus stops are a nearside stop at Park Street and a far side stop at Washington Street. The intent at these two locations is to bring the cycle track to grade and transition to traditional bike lanes prior to the boarding and

[2] Urban Bikeway Design Guide, National Association of City Transportation Officials, April 2011 Edition.
[3] Cycle Tracks, Lessons Learned, Alta Planning + Design, February 2009.

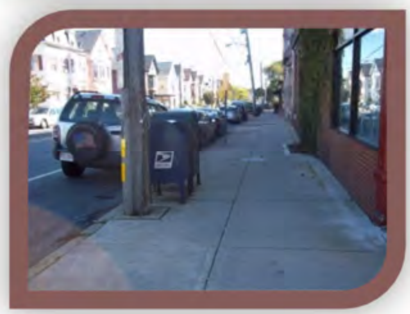
alighting area. The Alta Planning + Design report concluded that "Signage or markings should instruct bicyclists to yield to disembarking passengers".

Minimum Horizontal Clearance

The 2006 Project Development and Design Guide recommends a minimum 18 inches beyond face of curb for vertical roadway elements (on lower speed streets) such as trees, utility poles and fire hydrants.

There are approximately 100 utility poles along Beacon Street. The locations of these poles vary from tight to the back of the existing curbing to 12" from the back of the curbing.

The intent of the project is to maintain the curb line in those areas where bike lanes are proposed (Washington Street to the Somerville/Cambridge city line). In these locations, the existing utility pole clearances will remain approximately as they currently are. Some of the existing utility poles are located too close to the existing curbing to allow for new curbing to be placed and will be "shifted" (moved laterally up to 18"). "Shifting" the poles is less costly than relocating the poles as the wires on the poles can remain on the pole during a "shift". Proposed utility pole clearances that match or slightly exceed the existing condition (but are still less than 18 inches) are considered to be acceptable since they will continue to be adjacent to parking lanes versus travel lanes. Increasing the horizontal clearances to 18 inches from Washington Street to the Somerville/Cambridge city line would result in greatly increased project costs and in slightly narrower sidewalks.



5. Supplemental Crash Data

To identify vehicle crash trends along Beacon Street and at the study area intersections, accident data was obtained from available Somerville Police records for January 2009 to April 2012. A record of the accident data is presented in Appendix C of the Functional Design Report.

Crash rates for intersections are calculated based upon the number of crashes at an intersection and the volume of traffic travelling through an intersection on a daily basis. The MassDOT average crash rates are based upon the average number of crashes occurring per million vehicles entering signalized and unsignalized intersections. The average crash rates for MassDOT District 4 are 0.78 and 0.59 for signalized and unsignalized intersections, respectively.

Based upon the reviewed accident data and the recent April 2012 traffic counts, DCI has calculated the following crash rates for the study area intersections. As indicated in Table 4.1 the signalized intersections of Beacon Street/Washington Street and Beacon Street/Park Street had the highest 3-year accident totals (32 and 19 respectively). The resulting crash rates of 1.13 and 0.94 are significantly higher than the District 4 average of 0.78, indicative of a safety concern. The unsignalized and pedestrian actuated intersection crossing locations shown on Table 4.1 show fewer accidents with resulting crash rates that are at or below the District 4 average of 0.59.

Although no individual unsignalized intersection showed a high crash rate, a total of 187 crashes over a 3-year period occurred along the 1.1 mile stretch of roadway, with numerous closely spaced intersections, poor pavement conditions, mid-block pedestrian/bike related crashes as well as parked vehicles. This translates to a crash rate of 11.9 per million vehicles-miles of travel for the roadway segment; much higher than the latest available state-wide average crash rate of 3.72 in the year 2009 for Urban Minor Arterials.

MassDOT intersection and segment crash rate worksheets are provided in Appendix C of the Functional Design Report.

Table 6-1: Intersection Crash Data

Location	Number of Crashes	Crash Rate *
Beacon Street/Oxford Street	7	0.56
Beacon Street/Sacramento Street	8	**0.64**
Beacon Street/Museum Street/Kent Street	4	0.28
Beacon Street/Park Street/Scott Street	19	**0.94**
Beacon Street/Washington Street	32	**1.13**
Beacon Street/Buckingham Street/Cooney Street	4	0.25

* - Based on 2012 peak hour counts and 3 year accident data provided by the City of Somerville

Note - All other unsignalized intersections experience 3 accidents or less during the three-year period.

Bicycle-related Crashes

The 3-year crash data was summarized by accident type and shown in the following Table 4.2. The data shows a significant portion of accidents were bicycle-related at 18.2 % , consistent with the higher bicycle volumes relative to motorized-vehicle traffic.

Table 6-2 Crashes by Accident Type

Type	2009	2010	2011	Total (%)
Bicycle Involvement	10	12	12	34 (18.2 %)
Pedestrian Involvement	7	2	9	18 (9.6 %)
Hit and Run	9	10	9	28 (15.0 %)
Motorized Vehicles Only	35	47	23	105 (56.1 %)
Other	0	2	0	2 (1.1 %)
TOTAL	61	73	53	187 (100 %)

* - Based upon 3 year accident data provided by the City of Somerville

Attachment A

Controlling Criteria

DESIGN EXCEPTION REPORT

ATTACHMENT A
CONTROLLING CRITERIA

City/Town: Somerville **Project File No.:** 607209

Design Speed

Refer to Guidebook, Exhibit 3-7

Desirable	35
Minimum	25
Posted	30
Proposed	35

☐ Design Exception Required.

Lane Width

Refer to Guidebook, Exhibit 5-14

Desirable	12
Minimum	11
Proposed	11

☐ Design Exception Required.

Shoulder Width

Refer to Guidebook, Exhibit 5-12 (see note 3)

	Right		Left
Desirable	10	Desirable	10
Minimum	4	Minimum	4
Proposed	2	Proposed	6*

Right: ☑ Design Exception Required.

Left: ☐ Design Exception Required.

* assumes that a 6 ft cycle track, separated by a 3 inch mountable curb is useable shoulder, as needed

Horizontal Alignment

Refer to Guidebook, Exhibit 4-8 and 4-9

Minimum	300
Proposed	n/a

PI Sta.		PI Sta.		PI Sta.		PI Sta.	
Radius		Radius		Radius		Radius	

☐ Design Exception Required.

Refer to Guidebook, Chapter 4, Section 4.2 (Compound Curves).

Check all compound curves. The radius of the tighter curve should be no less than 50 percent of the flatter curve.

☐ Design Exception Required.

DESIGN EXCEPTION REPORT

ATTACHMENT A
CONTROLLING CRITERIA

City/Town: Somerville **Project File No.:** 607209

(Horizontal Alignment cont'd)

Length of Curve.
Lmin = 30 V (freeways)
Lmin = 15 V (other major highways)
V = Design Speed
☐ Design Exception Required.

Vertical Alignment

For Crest Vertical Curves, refer to Guidebook, Exhibit 4-26

Minimum 19
Proposed 33

PVI Sta.	151+32	PVI Sta.	150+30	PVI Sta.	124+89	PVI Sta.	131+25
K	33	K	43	K	55	K	63

☐ Design Exception Required.

For sag curves, refer to Guidebook, Exhibit 4-27

Minimum 37
Proposed 46

PVI Sta.	110+24	PVI Sta.	136+12	PVI Sta.	109+76	PVI Sta.	135+38
K	46	K	47	K	58	K	81

☐ Design Exception Required.

Grades

Refer to Guidebook, Exhibit 4-21
Maximum 8
Proposed 2.25
☐ Design Exception Required.

Stopping Sight Distance

Refer to Guidebook, Exhibit 3-7
Minimum 200
Desirable 200
Proposed 665
☐ Design Exception Required.

DESIGN EXCEPTION REPORT

ATTACHMENT A
CONTROLLING CRITERIA

City/Town: Somerville **Project File No.:** 607209

(Stopping Sight Distance cont'd)

Refer to Guidebook Section 3.7 and Exhibit 4-5 (SSD Middle Ordinate)

Minimum 100

Desirable 100

☐ Design Exception Required.

Cross Slope

Refer to Guidebook, Section 5.5.2

Bit Conc. 0.020

Cem Conc. 0.016

Proposed 0.02

☐ Design Exception Required.

Superelevation

Refer to Guidebook Section 4.2. Check required values for superelevation rates, transitioning, runoff, banking, etc. for all lanes and shoulders.

☐ Design Exception Required.

Horizontal Clearance

Refer to AASHTO A Policy on Geometric Design of Highways and Streets.

Minimum 18 inches beyond face of curb.

☑ Design Exception Required.

Bridge Only Criteria

Lane and Shoulder Width

Refer to AASHTO A Policy on Geometric Design of Highways and Streets.

☐ Design Exception Required.

Structural Capacity

Refer to Chapter 3 of MassHighway Bridge Manual.

☐ Design Exception Required.

Vertical Clearance

Refer to Guidebook, Exhibit 4-28

Minimum ______

Proposed ______

☐ Design Exception Required.

Attachment B

Summary of Impacts

ATTACHMENT B
DESIGN EXCEPTION REPORT
SUMMARY OF IMPACTS

Provide a summary of the incremental impacts associated with the Desirable, Minimum and Proposed design. Include impacts of incremental designs.

A separate Summary of Impacts sheet shall be prepared for each controlling criteria element that does not meet the minimum specified.

CONTROLLING CRITERIA: Shoulder Width

SUMMARY OF IMPACTS

INSERT VALUE IN THIS COLUMN	**WETLANDS (SF)**	**TREES (EA)**	**PARKLANDS (SF)**	**STONE WALLS (LF)**	**SALT MARSH (SF)**	**ADDITIONAL UTILITIES ($)**	**ROW ($)**	**CONST. COST ($)**	**TOTAL COST ($)**
DESIRABLE 10 FT	N/A	149	N/A	600	N/A	$2 - 4M	PROHIBITIVE	$6-8M	PROHIBITIVE
MINIMUM 4 FT	N/A	0	N/A	0	N/A	$0	$0	$5.8M	$5.8M
ALTERNATIVE 1 5 FT BIKE LANE ALTERNATIVE	N/A	14	N/A	0	N/A	$2 - 4M	$0	$6M	$8-10M
RECOMMENDED 6 FT NB 2 FT SB	N/A	14	N/A	0	N/A	$0.25 - 0.5M	$0	$6M	$6M

NOTE: Attach a narrative detailing the impacts of each alternative.

NOTE: Columns and rows may need to be added to address additional incremental designs or impacts

ATTACHMENT B
DESIGN EXCEPTION REPORT
SUMMARY OF IMPACTS

Provide a summary of the incremental impacts associated with the Desirable, Minimum and Proposed design. Include impacts of incremental designs.

A separate Summary of Impacts sheet shall be prepared for each controlling criteria element that does not meet the minimum specified.

CONTROLLING CRITERIA: Horizontal Clearance (other than "clear zone")

SUMMARY OF IMPACTS

INSERT VALUE IN THIS COLUMN	WETLANDS (SF)	TREES (EA)	PARKLANDS (SF)	STONE WALLS (LF)	SALT MARSH (SF)	ROW ($)	CONST. COST ($)	TOTAL COST ($)
DESIRABLE	-	10	-	-	-	-	$600,000	$600,000
MINIMUM (18")	-	10	-	-	-	-	$600,000	$600,000
ALTERNATIVE 1								
ALTERNATIVE 2								
RECOMMENDED (6"-12")	-	-	-	-	-	-	$0	$0

NOTE: Attach a narrative detailing the impacts of each alternative.

NOTE: Columns and rows may need to be added to address additional incremental designs or impacts

Cycle Track Papers

Bicycle Tracks and Lanes: a Before-After Study

Risk of Injury for Bicycling on Cycle Tracks versus In the Street

Bicycle Tracks and Lanes: a Before-After Study

Initial Submission Date: 1 August 2007
Submission Date of Revised Paper: 7 November 2007

Word count: 5,184 words + 2 figures + 6 tables

Author:
Søren Underlien Jensen
Member of TRB Committee on Bicycle Transportation

Trafitec ApS
Research Park Scion-DTU
Diplomvej 376
2800 Kongens Lyngby
Denmark

Tel.: (+45) 25246732
Fax: (+45) 88708090
Email: suj@trafitec.dk

ABSTRACT

This paper presents a before-after crash, injury and traffic study of constructing bicycle tracks and marking bicycle lanes in Copenhagen, Denmark. Corrections factors for changes in traffic volumes and crash / injury trends are included using a general comparison group in this non-experimental observational study. Analysis of long-term crash trends points towards no significant abnormal crash counts in the before period. The safety effects of bicycle tracks in urban areas are an increase of about 10 percent in both crashes and injuries. The safety effects of bicycle lanes in urban areas are an increase of 5 percent in crashes and 15 percent in injuries. Bicyclists' safety has worsened on roads, where bicycle facilities have been implemented. Design of bicycle facilities and parking conditions for motor vehicles clearly seems to have safety implications, especially at intersections. The study has revealed a few points in relation to this. Construction of bicycle tracks resulted in a 20 percent increase in bicycle / moped traffic mileage and a decrease of 10 percent in motor vehicle traffic mileage, whereas marking of bicycle lanes resulted in a 5 percent increase in bicycle / moped traffic mileage and a decrease of 1 percent in motor vehicle traffic mileage. The changes in traffic do result in health benefits due to more physical activity, less air pollution and less traffic noise. The positive benefits may well be much higher than the negative consequences caused by new safety problems.

INTRODUCTION

The traditional Danish bicycle track with a curb to the carriageway and a curb to the sidewalk is depictured in Figure 1 along with a bicycle lane. The first bicycle tracks in Denmark were introduced in Copenhagen as early as 1910. Since then about 8,000 km of bicycle tracks and paths with a dividing verge to the carriageway have been constructed so about every ninth km of road have these bicycle facilities in rural and urban areas in Denmark.

FIGURE 1 Photos of bicycle track (left) and bicycle lane (right).

Many studies of bicycle tracks have been undertaken in Northern Europe. A meta-analysis of 11 studies shows a reduction of 4 percent in crashes, and the crash reduction is almost the same for pedestrians, bicyclists and motorists respectively (*1*). Danish results show that construction of bicycle facilities leads to fewer and less severe crashes in rural areas, but more crashes in urban areas primarily due to increasing crash rates at intersections (*2*). Studies show that constructing bicycle tracks and paths increase bicycle traffic volumes (*1*).

Three studies of marking bicycle lanes in urban areas indicate an increase in crashes of about 10 percent primarily due to more crashes at intersections (*3-5*). No reliable studies of bicycle lanes impact on traffic volumes have been found.

The before-after traffic, crash and injury study, which is presented in the following, includes construction of one-way bicycle tracks on both road sides along 20.6 km of road and marking of one-way bicycle lanes on both road sides along 5.6 km of road in Copenhagen, Denmark. These bicycle tracks were constructed during the years 1978-2003 and the bicycle lanes were marked 1988-2002. The width of bicycle tracks are about 2-2.5 meters, whereas bicycle lanes are about 1.5-2 meters. The volume of motor vehicles 6-18 o'clock on a weekday on the studied roads varies from 5,000 to 28,000 and the corresponding volumes of bicyclists are 1,000-17,000. A Danish report describes the study in detail (*6*).

SECOND-BEST METHODOLOGY

Randomized experiments (*7*), where the experimental units like roads are randomized to treatment like bicycle lanes, are often viewed as the best way to study road safety effects. In our case, a randomized experiment has not been undertaken.

The safety effects of bicycle facilities are therefore studied using an observational study methodology. The Empirical Bayes method (*8*) is viewed by many as the best of the non-experimental observational methods. The Empirical Bayes method accounts for three major possible biases in before-after crash studies; regression-to-the-mean effects, crash trends and traffic volumes.

However, the Empirical Bayes method has not been used in this study. One thing is that using this method includes a very time-consuming effort to calculate many crash models, which is needed in this case because the bicycle facilities have been applied over a long period, and hence many different before and after periods are part of the study. Such crash models include relationships between crashes / injuries and traffic volumes for different types of intersections and road links.

A second but much more important thing is that some of the roads, where bicycle facilities have been applied, are the most trafficked in Copenhagen in terms of bicyclists and pedestrians. The crash models that need to be developed if the Empirical Bayes method were to be used could be of the kind shown in general in Formula 2 and 3 later in this paper. Such crash models are relatively reliable to use in order to predict the number of crashes, if traffic volumes on the road or at the intersection, where you wish to predict crash figures, are pretty normal compared to the traffic volumes that the crash models are based upon. In the Copenhagen case, many of the studied roads / intersections are in the far end of the traffic volume axis, i.e. much trafficked, and we are therefore close to or outside the boundaries of the possible crash models' valid area. The prediction of crash figures for these much trafficked roads / intersections are unreliable, because the beta figures of the crash models becomes crucial for the prediction, and these beta figures change from model to model primarily due to uncertainty, because the models are based on a relatively low number of roads / intersections. The prediction results for regression-to-the-mean effects and figures for expected crashes and consequently safety effects will therefore be relatively unreliable, because most of the crashes in this study actually take place on the much trafficked roads.

Instead a stepwise methodology is used. First, a general comparison group is used to account for crash trends. Second, changes in traffic volumes are taken into account. And third, an analysis of long-term crash trends is made in order to check for abnormally high or low crash counts, i.e. regression-to-the-mean, in the before period. It was chosen to use equally long before and after periods, which for the individual studied roads was of 1-5 years duration. The expected number of crashes in the after period is calculated based on a formula, here shown in the general form:

$$(1) \quad A_{Expected} = A_{Before} \cdot C_{Trend} \cdot C_{Traffic} \cdot C_{RTM} ,$$

where $A_{Expected}$ is the number of crashes / injuries expected to occur in the after period if bicycle facilities were not applied, A_{Before} is the number of crashes / injuries that occurred in the before period, C_{Trend}, $C_{Traffic}$ and C_{RTM} are correction factors for crash trends, traffic volumes and regression-to-the-mean respectively.

The study of bicycle facilities is part of project including studies of reconstructions, markings, signal-control and traffic calming schemes in the City of Copenhagen. A major effort was made in order to register all physical changes to the road network in the period 1976-2004. Several hundred schemes were identified.

Several intersections and links had undergone more than one reconstruction or other scheme. Only "clean" schemes are studied, meaning that the roads, where bicycle facilities have been applied, no other scheme has been implemented in before and after periods and in the year(s), when the bicycle facility was applied.

Unchanged roads with known developments in traffic volumes were used to set up a general comparison group. The Copenhagen Police District covers the entire area of the City of Copenhagen, and there is no indication that crashes are registered differently in one city quarter compared to another. The general comparison group consists of 110 km of roads with 170 locations, where motor vehicle and bicycle / moped traffic is counted yearly or every fourth to sixth year. A total of 24,369 crashes and 8,648 injuries occurred on the 110 km of roads in the period 1976-2004.

Since a general comparison group has been chosen instead of a matched comparison group, an effort was made in order to avoid consequences of larger differences between general comparison group and treated roads, where bicycle facilities were applied. Trends for different types of crashes and injuries of the general comparison group were compared. Trends for intersection and link crashes are very similar, and hence no need for sub-grouping. However, trends for different crash / injury severities and transport modes exhibit rather different developments. It was found reasonable to describe trends by 7 crash sub-comparison groups and 5 injury sub-comparison groups. These sub-groups are defined in Table 1.

TABLE 1 Definition of 12 Sub-comparison Groups (in Brackets: Number of Crashes / Injuries 1976-2004)

	Bicycle/moped [a]	Pedestrian [b]	Motor vehicle [c]
Crashes with killed / severe injuries	1 (2,197)	2 (1,445)	3 (1,584)
Crashes with minor injuries and no killed / severe injuries	4 (1,289)	5 (1,228)	
Property damage only crashes	6 (3,316)		7 (13,310)
Killed and severe injuries	8 (2,235)	9 (1,477)	10 (1,907)
Minor injuries	11 (1,359)	12 (1,670)	

[a] Crashes involving cyclists / moped riders and injuries in these crashes,
[b] Crashes between pedestrians and motor vehicles and injuries in these crashes,
[c] Crashes only with motor vehicles involved and injuries in these crashes.

So the correction factor C_{Trend} is actually 12 different correction factors, which is the number of crashes / injuries in the sub-comparison group in the after period divided by the number of crashes / injuries in the sub-comparison group in the before period. The individual correction factor, e.g. $C_{Trend,1}$, is then multiplied with the same sub-group of crashes, which occurred on the treated road in the before period, $A_{Before,1}$, as part of Formula 1.

The correction factor $C_{Traffic}$ is based on changes in traffic volumes on the treated road and in the general comparison group. The relationship between traffic flow and crashes / injuries is non-linear. Danish crash prediction models for links (Formula 2) and intersections (Formula 3) are most often of the following kinds:

$$(2) \quad E(\mu)=\alpha \cdot N^{\beta},$$

$$(3) \quad E(\mu)=\alpha \cdot N_{pri}^{\beta_1} \cdot N_{sec}^{\beta_2},$$

where $E(\mu)$ is the predicted number of crashes / injuries, N is the motor vehicle daily flow on the link, N_{pri} and N_{sec} are the incoming motor vehicle daily flow from primary and secondary directions at intersections, and α, β, β_1 and β_2 are estimated parameters. β is often close to 0.7, and β_1 and β_2 are often close to 0.5 in the many models that have been developed during the last decades in Denmark, whereas α varies between the different types of roads and intersections (*9-16*). Figures for α varies, because the level of safety depends on the type of road and intersection. In this case, incoming bicycle / moped flow is also known, and here the sparse number of crash prediction models indicate that bicycle / moped flow only influence the number of crashes involving cyclists and moped riders. Formula 2 and 3 are then used to set up formulas for $C_{Traffic}$:

$$(4)\quad C_{Traffic,pmv,link} = \left(\frac{\dfrac{MV_{after}}{MV_{before}}}{\dfrac{MV_{CG,after}}{MV_{CG,before}}} \right)^{0.7},$$

$$(5)\quad C_{Traffic,bike,link} = \left(\frac{\dfrac{MV_{after}}{MV_{before}}}{\dfrac{MV_{CG,after}}{MV_{CG,before}}} \right)^{0.7} \cdot \left(\frac{\dfrac{BM_{after}}{BM_{before}}}{\dfrac{BM_{CG,after}}{BM_{CG,before}}} \right)^{0.7},$$

$$(6)\quad C_{Traffic,pmv,intersection} = \left(\frac{\dfrac{MV_{pri,after}}{MV_{pri,before}}}{\dfrac{MV_{CG,after}}{MV_{CG,before}}} \right)^{0.5} \cdot \left(\frac{\dfrac{MV_{sec,after}}{MV_{sec,before}}}{\dfrac{MV_{CG,after}}{MV_{CG,before}}} \right)^{0.5},$$

$$(7)\quad C_{Traffic,bike,intersection} = \left(\frac{\dfrac{MV_{pri,after}}{MV_{pri,before}}}{\dfrac{MV_{CG,after}}{MV_{CG,before}}} \right)^{0.5} \cdot \left(\frac{\dfrac{MV_{sec,after}}{MV_{sec,before}}}{\dfrac{MV_{CG,after}}{MV_{CG,before}}} \right)^{0.5} \cdot \left(\frac{\dfrac{BM_{pri,after}}{BM_{pri,before}}}{\dfrac{BM_{CG,after}}{BM_{CG,before}}} \right)^{0.5} \cdot \left(\frac{\dfrac{BM_{sec,after}}{BM_{sec,before}}}{\dfrac{BM_{CG,after}}{BM_{CG,before}}} \right)^{0.5},$$

where $C_{Traffic,\ pmv}$ is the traffic correction factor for pedestrian and motor vehicle crashes / injuries (see Table 1), $C_{Traffic,\ bike}$ is the traffic correction factor for bicycle-moped crashes / injuries, MV, MV_{pri} and MV_{sec} are motor vehicle daily flow at the treated site on link, primary and secondary direction respectively, BM, BM_{pri} and BM_{sec} are bicycle-moped daily flow at the treated site on link, primary and secondary direction respectively, and MV_{CG} and BM_{CG} are motor vehicle flow and bicycle-moped flow in the comparison group respectively.

Flow data from before and after periods are used, hence, increases and decreases in traffic volumes from before to after are accounted for. The change from before to after in motor vehicle traffic varied from -26 percent to +29 percent, however, most treated roads experienced a minor decrease. Similar the change in bicycle-moped traffic was between -28 percent and +90 percent, most treated roads experienced a larger increase. However, Formula 6 and 7 have been used for the intersections, where traffic volumes for side streets are known.

Traffic volumes are known for only about a tenth of the intersections. The rest of the intersections (minor side streets) have been treated as links using Formula 4 and 5.

The analysis of long-term crash trends is made in order to check for abnormally high crash counts, i.e. regression-to-the-mean, in the before period. The analysis is made using a before-before period, which is a 5-year period 8 to 12 years before applying bicycle facilities. The before-before period is chosen because it most often will be prior to an eventual black spot identification period or other type of systematic crash investigation period that may have lead to applying bicycle facilities. This before-before period is then used to calculate an expected number of crashes and injuries in the before period of the treated roads by making corrections for crash trends and traffic volumes:

$$A_{Expected,Before} = A_{Before\text{-}Before} \cdot C_{Trend} \cdot C_{Traffic}$$

The C_{RTM} correction factor is then calculated as the expected number of crashes in the before period divided by the observed number of crashes in the before period, and likewise for injuries. However, because not all treated roads can undergo this type of analysis, the C_{RTM} is set to be the same for all treated roads and is only used, if there are statistically significant differences between the expected and observed numbers of crashes and injuries in the before period.

Of the 23 roads, where bicycle tracks were constructed, it is possible to make this calculation for 9 roads, and the calculation was possible for 5 of 10 roads, where bicycle lanes were marked. Several roads have been excluded of this analysis because they have been changed by other schemes in the period between 12 years before the bicycle facility was applied and the before period. Some roads have been excluded of the analysis because crash records only are available back to 1976.

TABLE 2 Expected and Observed Crashes and Injuries in the Before-Before and Before Period, where Bicycle Tracks and Bicycle Lanes have been Applied

		Observed BEFORE-BEFORE	Expected BEFORE	Observed BEFORE	Change in safety (percent)	
					Best estimate	95% CI [a]
Bicycle tracks	All crashes	686	460	484	-3 [b]	-21 ; +20 [b]
	All injuries	211	128	140	+10	-13 ; +38
Bicycle lanes	All crashes	411	333	337	+1	-12 ; +18
	All injuries	111	89	84	-7	-31 ; +25

[a] 95% confidence interval, [b] inhomogeneous i.e. results of random effects model.

The results of the analyses of long-term accident trends, which are shown in Table 2, indicate no general abnormally high or low crash counts, i.e. regression-to-the-mean effects, in the before period. Meta-analyses have been used to calculate best estimates for safety changes and related confidence intervals. Table 2 shows that the best estimate for the change in safety, where bicycle lanes have been marked, is an increase of 1 percent (+1) in crashes. This means that the observed number of crashes in the before period is 1 percent higher than expected. The 95% confidence interval for bicycle lanes, all crashes, is between a fall of 12 percent (-12) and an increase of 18 percent (+18), meaning that the best estimate of a change in safety is within this interval with 95% certainty. A glance on the confidence intervals in Table 2 reveals that all intervals include 0 or no change, which means that none of the best estimates are statistically significant different from 0. In other words, Table 2 indicate no abnormally high or low crash counts in the before period. Results from breakdowns into different accident / injury severities and transport modes do neither indicate abnormal crash counts in the before period. The general correction factors for regression-to-the-mean effects are then set to 1.

Due to major differences in correction factors for crash trends and traffic volumes and that the bicycle facilities have been applied over a long time span it is founded reasonable to use meta-analysis rather than simple sums of crashes and injuries in order to describe best estimates for safety effects and the variance of these effects. The meta-analysis methodology used is described by Elvik (*17*). Fixed effects models have been used for homogeneous mean effects, i.e. only random variation in estimated effects. Random effects models are adopted to heterogeneous mean effects.

Effects on traffic volumes are simply estimated by taking the traffic development in the general comparison group into account. Hence, no traffic model has been used. Parallel streets to the treated roads have been checked for major construction works in the before and after periods, however, no such construction works have been identified.

RESULTS OF BEFORE-AFTER CRASH AND INJURY STUDY

Bicycle Tracks

The construction of bicycle tracks has resulted in a slight drop in the number of crashes and injuries on road links between intersections of 10 and 4 percent respectively, see Table 3. The two figures may be found in Table 3 in the "Links" rows and the "Best estimate" column. In the confidence interval column it may be seen that none of these safety effects on the links are statistically significant, because the intervals include 0 or no change. At intersections on the other hand, the number of crashes and injuries has risen statistically significant by 18 percent. A decline in road safety at intersections has undoubtedly taken place after the construction of bicycle tracks. If figures for links are combined with those for intersections, an increase of about 10 percent in crashes and injuries has taken place.

The safety effects of the various bicycle track projects are statistically significant different in some cases, hence heterogeneous safety effects. The safety effects mentioned above are therefore not general. The reason for this is that the crash composition and road design are different on those individual streets, where bicycle tracks have been constructed. Some road designs with bicycle tracks are safer than others.

The decline in road safety arises, because more pedestrians and bicyclists / moped riders are injured at intersections. There are statistically significant increases in injuries at intersections of 30 and 24 percent respectively for these two road user groups. No major changes in injuries have occurred to motorists.

The increase in injuries to women is 18 percent, whereas there is only a small rise in injuries to men of just 1 percent. The increase in injuries is especially large among females under 20 years of age on foot and bicycle, as well as female pedestrians over the age of 64. On the other hand, there is a considerable fall in injuries among older bicyclists and children in cars of both sexes. The figures for men and women and four age groups have been rescaled in order to account for different trends in the general comparison group.

TABLE 3 Safety Effects of Bicycle Tracks

		Observed BEFORE	Expected AFTER	Observed AFTER	Safety effect (percent)	
					Best estimate	95% CI [a]
Crashes	All	2,987	2,663	2,911	+10 [b]	-2 ; +23 [b]
	Injury	1,313	784	875	+12	+2 ; +23
	Property damage only	1,674	1,879	2,036	+6 [b]	-8 ; +22 [b]
Injuries	All	1,476	857	937	+9	+0 ; +19
	Fatal	25	19	22	+10	-1 ; +23
	Severe	757	606	665		
	Minor	694	231	250	+8 [b]	-17 ; +40 [b]
Intersections	All crashes	2,010	1,840	2,171	+18 [b]	+6 ; +32 [b]
	All injuries	938	541	636	+18	+6 ; +31
Links	All crashes	977	823	740	-10 [b]	-26 ; +10 [b]
	All injuries	538	316	301	-4	-17 ; +12
Pedestrians, all injuries	Total	469	271	315	+19	+2 ; +38
	At intersections	267	154	197	+30	+7 ; +57
	On links	202	117	118	+7	-16 ; +35
Bicyclists and moped riders, all injuries	Total	574	369	406	+10	-4 ; +26
	At intersections	353	230	285	+24	+5 ; +46
	On links	221	139	121	-13	-32 ; +10
Motorists, all injuries	Total	433	217	216	+4 [b]	-24 ; +43 [b]
	At intersections	318	157	154	-3 [b]	-32 ; +39 [b]
	On links	115	60	62	-1 [b]	-28 ; +37 [b]

[a] 95% confidence interval, [b] inhomogeneous i.e. results of random effects model.

The crash composition has changed markedly after the construction of bicycle tracks. Table 4 shows that the construction of bicycle tracks resulted in three statistically significant gains in road safety. Rear-end crashes where motor vehicles hit bicycles / mopeds from behind have fallen by 63 percent due to the traffic separation. Crashes with left-turning bicycles / mopeds have fallen by 41 percent and crashes with bicycles / mopeds against parked motor vehicles have decreased by 38 percent.

These safety gains were more than outweighed by new safety problems, where the number of crashes has risen statistically significant. Rear-end crashes where a bicycle / moped hit another bicycle / moped from behind has risen by 120 percent. Crashes with right-turning vehicles have risen by 140 percent. All kinds of right-turn crashes have increased in numbers. Crashes with left-turning motor vehicles against bicycles / mopeds have risen by 48 percent. Lastly, crashes between bicycles / mopeds and pedestrians or entering / exiting bus passengers have also risen significantly.

Prohibiting parking is one reason why the construction of bicycle tracks brings about more crashes and injuries. Prohibiting parking on a road with a bicycle track results in motor vehicles being parked on minor side streets and consequently more turning traffic, especially at right of way regulated intersections. The construction of bicycle tracks and prohibition of parking resulted in an increase in crashes and injuries at intersections of 42 and 52 percent respectively. The construction of bicycle tracks combined with permission to park also resulted in an increase in crashes and injuries at intersections but of only 13 and 15 percent respectively. On road links with parking ban, there was a 24 percent increase in crashes, whereas on links with parking permitted crashes fell by 14 percent. When parking is permitted, there are fewer parking crashes, rear-end crashes and pedestrian crashes. This means that illegally parked motor vehicles causes more crashes than legally parked vehicles. The total width of drive lanes is reduced when parking is permitted, resulting in increased safety for pedestrians when they cross the road.

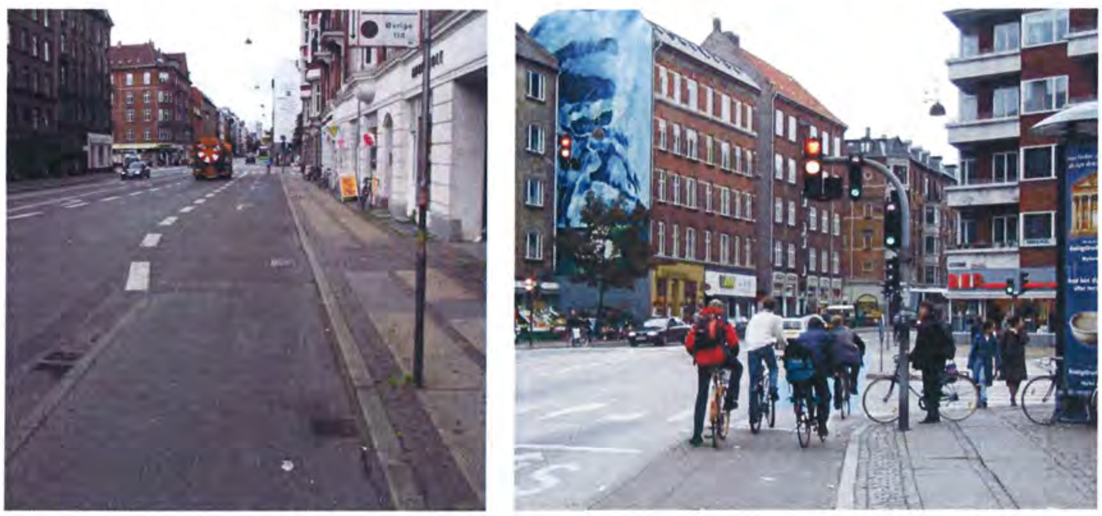
TABLE 4 Effects on Crashes of Bicycle Tracks Divided into 11 Crash Situations

		Observed BEFORE	Expected AFTER	Observed AFTER	Safety effect (percent)	
					Best estimate	95% CI [a]
Single vehicle crash	All crashes	170	151	142	-3	-23 ; +22
	MV [c]	134	127	111	-8	-29 ; +19
	BM [d]	36	23	31	+16	-30 ; +91
Rear-end crash	All crashes	718	674	584	-7 [b]	-22 ; +12 [b]
	MV and MV	517	490	483	+1	-11 ; +15
	MV and BM	173	164	57	-63	-73 ; -49
	BM and BM	28	20	44	+120	+37 ; +253
Frontal crash	All crashes	77	71	92	+34	-2 ; +82
Right-turn crash	All crashes	160	169	397	+140	+98 ; +190
	MV and turning MV	47	41	73	+70	+15 ; +151
	Turning MV and BM	81	104	282	+129 [b]	+57 ; +233 [b]
	Turning MV and Ped [e]	25	20	32	+77	+4 ; +202
	Turning BM	7	4	10	+135	-17 ; +561
Left-turn crash	All crashes	614	548	589	+12 [b]	-7 ; +33 [b]
	MV and turning MV	334	299	334	+9 [b]	-16 ; +40 [b]
	Turning MV and BM	120	119	161	+48 [b]	+4 ; +110 [b]
	Turning MV and Ped	65	45	47	+1	-33 ; +53
	Turning BM	95	85	47	-41	-59 ; -15
Right-angle crash	All crashes	575	536	522	-1	-13 ; +11
Crash with parked MV	All crashes	217	182	142	-21	-36 ; -1
	MV and parked MV	123	105	96	-8	-30 ; +22
	BM and parked MV	94	78	46	-38	-57 ; -11
Crash with pedestrian from right	All crashes	296	220	244	+13	-5 ; +34
	MV and Ped	228	162	140	-10	-28 ; +11
	BM and Ped	68	58	104	+80	+30 ; +148
Crash with pedestrian from left	All crashes	123	83	85	+23 [b]	-25 ; +102 [b]
	MV and Ped	111	75	68	+5 [b]	-38 ; +78 [b]
	BM and Ped	12	9	17	+78	-15 ; +273
Crash with entering or exiting bus passenger		5	4	73	+519	+157 ; +1390
Other pedestrian crashes		32	25	41	+66	+3 ; +167

[a] 95% confidence interval, [b] inhomogeneous i.e. results of random effects model, [c] motor vehicle, [d] bicycle or moped, [e] pedestrian.

Several design features especially at intersections affect the safety effects. At signalized intersections, it has been found that the number of crashes with traffic from entry lanes with a shortened bicycle track ending before a right-turn lane, see Figure 2, fell statistically significant by 30 percent, whereas the number of injuries increased by 19 percent. Another design at signalized intersections is to end the bicycle track at the stop line, i.e. advanced bicycle tracks. This resulted in a statistically significant increase of 25 percent in crashes, whereas injuries only increased by 9 percent. Entry lanes with an advanced bicycle track and no turn lanes for motor vehicles resulted in statistically significant increases of 68 and 67 percent in crashes and injuries respectively. The figures for entry lanes with turn lanes and advanced bicycle track showed a 15 percent increase in crashes and a fall of 5 percent in injuries. A comparison shows that entry lanes with an advanced bicycle track without turn lanes for motor vehicles is the design, which is most unsafe. Shortened bicycle tracks and advanced bicycle tracks with turn lanes for motor vehicles are equally effective as far as safety goes. There is a difference, however, advanced bicycle tracks are best for pedestrians and bicyclists, whereas shortened bicycle tracks are best for motor vehicle occupants. Other results for e.g. non-signalized intersections and bus stops also shows significantly different safety effects for the various designs.

FIGURE 2 Photos of shortened bicycle track (left) and advanced bicycle track (right).



Bicycle Lanes

The marking of bicycle lanes resulted in an increase in crashes of 5 percent and 15 percent more injuries, see Table 5. These increases are not statistically significant. The decline in road safety can be seen both at intersections and on links. The worsening safety occurred especially amongst bicyclists and moped riders, where the increase in injuries is 49 percent.

In line with the study of bicycle tracks, there is a larger increase in injuries among women of 22 percent with the marking of bicycle lanes, whereas the figure for men was only 7 percent. There is a fall in injuries among children under 20 years of age and an increase among those aged 20-34.

TABLE 5 Safety Effects of Bicycle Lanes

		Observed BEFORE	Expected AFTER	Observed AFTER	Safety effect (percent)	
					Best estimate	95% CI [a]
Crashes	All	389	295	311	+5	-10 ; +23
	Injury	95	90	102	+14	-15 ; +52
	Property damage only	294	205	209	+1	-16 ; +21
Injuries	All	106	98	113	+15	-13 ; +52
	Fatal	3	3	0	+22	-15 ; +73
	Severe	72	48	59		
	Minor	31	47	54	+5	-36 ; +73
Intersections	All crashes	327	249	247	0	-16 ; +18
	All injuries	87	82	93	+14	-16 ; +54
Links	All crashes	62	47	64	+30	-9 ; +87
	All injuries	19	16	20	+27	-38 ; +160
Pedestrians, all injuries	Total	29	24	19	-17	-54 ; +49
	At intersections	23	20	18	-8	-51 ; +74
	On links	6	4	1	-53	-91 ; +154
Bicyclists and moped riders, all injuries	Total	41	39	60	+49	-1 ; +126
	At intersections	33	30	47	+57	-1 ; +150
	On links	8	9	13	+27	-48 ; +207
Motorists, all injuries	Total	36	35	34	+12	-34 ; +89
	At intersections	31	32	28	+1	-43 ; +79
	On links	5	3	6	+39 [b]	-98 ; +10753 [b]

[a] 95% confidence interval, [b] inhomogeneous i.e. results of random effects model.

The marking of bicycle lanes has a markedly different effect on the crash composition compared to the construction of bicycle tracks. Bicycle lanes did not apparently lead to an appreciable fall in rear-end crashes between motor vehicle and bicycle / moped or crashes involving left-turning bicycle / moped. Conversely, the marking of bicycle lanes did not apparently lead to an increase in crashes between bicycle/moped and pedestrians or crashes between left-turning motor vehicle and bicycle / moped.

There are however similarities. The number of crashes involving right-turning motor vehicles increased statistically significant by 73 percent with the marking of bicycle lanes. There was also a considerable increase in rear-end crashes between two bicycles / mopeds.

RESULTS OF BEFORE-AFTER TRAFFIC STUDY

The construction of bicycle tracks resulted in a 20 percent increase in bicycle/moped traffic mileage and a decrease of 10 percent in motor vehicle traffic mileage on those roads, where bicycle tracks have been constructed, see Table 6. These effects are statistically significant. A considerable amount of these effects were already visible during the construction period, although the effects increased after road works were completed.

The marking of bicycle lanes resulted in a 5 percent increase in bicycle / moped traffic mileage and a decrease of 1 percent in motor vehicle traffic mileage on those roads, where bicycle lanes have been marked. These effects are not statistically significant.

TABLE 6 Effects on Traffic of Construction of Bicycle Tracks and Marking Bicycle Lanes

		Traffic effect (percent)	
		Best estimate	95% CI [a]
Bicycle tracks	Bicycle / moped traffic mileage	+20	+11 ; +29
	Motor vehicle traffic mileage	-10	-14 ; -6
Bicycle lanes	Bicycle / moped traffic mileage	+5	-4 ; +14
	Motor vehicle traffic mileage	-1	-10 ; +8

[a] 95% confidence interval.

Bicycles comprise over 95 percent of bicycle / moped traffic. The effects are valid for bicycle traffic, but it is not known whether they are valid for moped traffic on its own.

DISCUSSION

The study is based on a second-best methodology. Corrections for changes in traffic volumes and road safety trends have been made. Despite methodological shortcomings, study results show systematic patterns. Several safety and traffic effects are statistically significant. The analyses point towards specific safety gains and flaws for different road user groups, crash situations and road and intersection designs. Overall, there is internal consistency in the changes of safety and traffic volumes, which indicate causality, and the causal direction seems clear.

The bicycle facilities effects on traffic volumes are rather large. We do not know for sure whether these effects are a result of changes of route choice or transport mode choice or both. The magnitude of the changes in traffic volumes on the reconstructed streets, and the traffic volumes on parallel streets, however, do indicate that thousands of travelers in total must have changed their choice of transport mode. We do not know who have shifted mode – children, middle-aged or elderly, women or men, beginners or experienced, etc. Another point is that the reduced motor vehicle traffic volumes may have resulted in traffic operation changes e.g. higher vehicular speed, increased crossing activity by pedestrians outside formal crossings, etc. Due to dramatic shifts, the corrections for changes in traffic volumes in the safety studies can be important to the safety effect findings.

If corrections for traffic volumes were not done at all, the expected number of crashes and injuries in the after period on the roads, where bicycle tracks were constructed, would be 2,758 and 875, respectively. The comparable figures found when corrections for traffic volumes were done, see Table 3, are 2-4 percent lower. This means that corrections for traffic volumes result in a small worsening of the overall safety effect, i.e. the effect would be about 6 percent instead of about 10 percent as shown in Table 3. However if corrections for traffic volumes were not done, the increase in bicycle-moped injuries would be 15 percent instead of the 10 percent when these corrections were done. Here the corrections actually improve the safety effect, because the bicycle traffic has increased. The difference in the safety effects calculated respectively with and without corrections for traffic volumes are rather small. Therefore, the results of the safety studies are not particular sensitive to the method for making corrections for traffic volumes.

Bicycle tracks and bicycle lanes separate bicycle traffic from motor vehicle traffic on links between intersections. Having these bicycle facilities is perceived to be safer and more satisfying by bicyclists compared to a mixed traffic situation (*18*). Seen in this perspective, the results of this study are somewhat controversial. Constructing bicycle tracks and marking bicycle lanes in urban areas resulted in an increase in crashes and injuries of approximately 10 percent in Copenhagen, Denmark. Bicyclists' safety has worsened due to these facilities.

On the other hand, making these bicycle facilities resulted in more cycling and less motor vehicle traffic. This must have contributed to benefits due to more physical activity, less air pollution, less traffic noise, less oil consumption, etc. A recent study shows that an extra pedal cycled kilometer in Copenhagen gives an average gain in health and production solely due to more physical activity of rather more than 5 DKK, which equals about 1 US$ (*19*). The positive benefits may well be much higher than the negative consequences caused by new safety problems. It will be reasonable to sum up costs and benefits in order to identify roadways that are relevant for implementing bicycle facilities.

Design of bicycle facilities clearly seems to have safety implications. The study has revealed a few points in relation to this. However, it remains unclear whether it is possible to design urban bicycle facilities so road safety is improved.

CONCLUSIONS

The main conclusions of the research reported in this paper can be summarized in the following points:

1. A before-after traffic, crash and injury study of constructing bicycle tracks and marking bicycle lanes has been completed taking into account changes in crash trends, traffic volumes and regression-to-the-mean effects in the before period. Bicycle facilities are predominantly made in order to provide bicyclists better travel conditions.

2. The weighted means or best estimates for safety effects of bicycle tracks in urban areas are an increase of about 10 percent in crashes and injuries. This is due to a large increase of 18 percent in intersections, which more than outweigh a small reduction on road links between intersections. Pedestrians, bicyclists and moped riders safety at intersections are significantly worsened. Results vary significantly from road to road.

3. One reason to this heterogeneity in safety effect between roads is that some bicycle track designs are safer than others. Roads with bicycle tracks and parking permitted are safer compared to roads with parking bans. Bicycle tracks than ends at the stop line at signalized intersections with no turn lanes for motor vehicles should be avoided due to major safety problems.

4. The best estimates for safety effects of bicycle lanes in urban areas are an increase of 5 percent in crashes and 15 percent in injuries. Safety is worsened both at intersections and on links. Bicyclists' safety has significantly worsened on the roads, where bicycle lanes have been marked. More detailed traffic and design conditions were not studied in relation to bicycle lanes.

5. The construction of bicycle tracks resulted in a 20 percent increase in bicycle/moped traffic mileage and a decrease of 10 percent in motor vehicle traffic mileage on those roads, where bicycle tracks have been constructed. The marking of bicycle lanes resulted in a 5

percent increase in bicycle/moped traffic mileage and a decrease of 1 percent in motor vehicle traffic mileage on those roads, where bicycle lanes have been marked. This must have contributed to benefits due to more physical activity, less air pollution, less traffic noise, less oil consumption, etc.

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IP Online First, published on February 9, 2011 as 10.1136/ip.2010.028696

Risk of injury for bicycling on cycle tracks versus in the street

Anne C Lusk,[1] Peter G Furth,[2] Patrick Morency,[3,4] Luis F Miranda-Moreno,[5] Walter C Willett,[1,6] Jack T Dennerlein[7,8]

[1]Department of Nutrition, Harvard School of Public Health, Boston, MA USA
[2]Department of Civil and Environmental Engineering, Northeastern University, Boston, MA USA
[3]Direction de santé publique de Montréal, Montréal, Québec, Canada
[4]Département de Médecine Sociale et Préventive, Université de Montréal, Montréal, Québec, Canada
[5]Department of Civil Engineering and Applied Mechanics, McGill University, Montréal, Québec, Canada
[6]Department of Epidemiology, Harvard School of Public Health, Boston, MA, USA
[7]Department of Environmental Health, Harvard School of Public Health, Boston, MA, USA
[8]Department of Orthopaedic Surgery, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, USA

Correspondence to
Dr Anne Lusk, Harvard School of Public Health, 665 Huntington Avenue, Building II, Room 314, Boston, MA 02115, USA; annelusk@hsph.harvard.edu

Accepted 1 December 2010

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ABSTRACT

Most individuals prefer bicycling separated from motor traffic. However, cycle tracks (physically separated bicycle-exclusive paths along roads, as found in The Netherlands) are discouraged in the USA by engineering guidance that suggests that facilities such as cycle tracks are more dangerous than the street. The objective of this study conducted in Montreal (with a longstanding network of cycle tracks) was to compare bicyclist injury rates on cycle tracks versus in the street. For six cycle tracks and comparable reference streets, vehicle/bicycle crashes and health record injury counts were obtained and use counts conducted. The relative risk (RR) of injury on cycle tracks, compared with reference streets, was determined. Overall, 2.5 times as many cyclists rode on cycle tracks compared with reference streets and there were 8.5 injuries and 10.5 crashes per million bicycle-kilometres. The RR of injury on cycle tracks was 0.72 (95% CI 0.60 to 0.85) compared with bicycling in reference streets. These data suggest that the injury risk of bicycling on cycle tracks is less than bicycling in streets. The construction of cycle tracks should not be discouraged.

Bicycling could address obesity, cancer, stroke, diabetes, asthma, mortality and pollution;[1 2] however, the bicycling environment is a limiting factor. The predominant bicycle facilities in The Netherlands and Denmark are cycle tracks, or bicycle paths along streets that are physically separated from motor traffic, bicycle-exclusive and with a parallel sidewalk.[3] Due to the separation from vehicles afforded by 29 000 km of cycle tracks in The Netherlands plus other initiatives,[4] 27% of Dutch trips are by bicycle, 55% are women, and the bicyclist injury rate is 0.14 injured/million km.[5] In the USA, 0.5% of commuters bicycle to work, only 24% of adult cyclists are women,[6] and the injury rate of bicyclists is at least 26 times greater than in The Netherlands.[5] The chief obstacle to bicycling, especially for women,[7] children[8] and seniors[9] is perceived danger of vehicular traffic. This perceived danger from cars appears to be real,[10] as corroborated by survey participants who prefer cycle tracks over roads.[11]

Cycle track construction has been hampered in the USA by engineering guidance in the American Association of State Highway and Transportation Officials (AASHTO) 'Guide for the development of bicycle facilities'[12] which cautions against building two-way paths along, but physically separated from, a parallel road. AASHTO states that sidewalk bikeways are unsafe and implies the same about shared-use paths parallel to roads, listing numerous safety concerns and permitting their use only in special situations. Cycle tracks, which can be one or two-way and resemble shared-use paths, are not mentioned in the AASHTO bike guide. A long-standing, and yet not rigorously proved, philosophy in the USA has suggested instead that 'bicyclists fare best when they behave as, and are treated as, operators of vehicles.'[13] The details about cycle tracks in the Dutch bicycle design manual CROW[3] and crash rate comparisons between the USA and The Netherlands [5] have been dismissed by vehicular cycling proponents,[14] with arguments of non-transferability to the American environment. Cycle tracks have been controversial, especially due to conflicting studies with warnings of increased crash rates.[15] The warnings, which in the USA result in striped bike lanes but not cycle tracks, come without any substantial study of the safety of North American cycle tracks. Using existing crash and injury data from Montreal, Canada, a city with a network of cycle tracks in use for more than 20 years, this study compared bicyclists' injury and crash rates with published data and bicyclists' injury rates on cycle tracks versus in the street.

METHODS

We studied six cycle tracks in Montreal that are two-way on one side of the street. Each cycle track was compared with one or two reference streets without bicycle facilities that were considered alternative bicycling routes. One reference street was a continuation of the street with the cycle track; the remaining streets were parallel to the cycle track with the same cross streets as endpoints and, therefore, subject to approximately the same intersection frequency and cross traffic as the cycle track.

Injury and vehicle/bicycle crash rates per bicycle-kilometre

The injury and crash rates for each cycle track were determined from the emergency medical response (EMR) database [16] and police-recorded vehicle/bicycle crashes and estimated on the cycle tracks per bicycle-km. Automated 24-h bicycle counts on Montreal cycle tracks are available for selected years, with 20–64 days in each sample from May to September. We used linear interpolation between the 2000 and 2008 samples to determine average daily use for the date ranges of the injury and crash counts. Average daily use was converted to annual use by multiplying by 200 'effective days' in the 1 April to 15 November bicycling season (when seasonal cycle tracks are open), recognising that

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bicycle use tends to be less in April, October and November than in the sampled months. Use estimates were converted to bicycle-km by multiplying by segment length and the fraction of the cycle track's length ridden per cyclist. This fraction, which ranged from 0.6 to 0.9, was determined using expert judgement considering the cycle track length and opportunities for turning on and off.

Relative Risk (RR) of injury for cycle tracks

The RR of the cycle track compared with the reference street was estimated using bicyclist counts and injuries from the EMR database.[16] Although injury (EMR) and bicycle/vehicle crash data from police records overlap strongly, the injury data have been shown to be more exhaustive[17] and were available for a longer period. Injury counts were determined for the 1 April to 15 November bicycling season and within 15 m of each street centerline. For comparability with exposure data, it was important to exclude individuals injured at intersections who may have been riding on a cross street; however, the EMR database does not indicate which street the injured cyclist was using. Therefore, using the police crash database we determined for each section studied the fraction of bicycle/vehicle crashes involving cyclists who were riding on cross streets, and reduced injury counts by that fraction.

Historical bicycle counts were available for the cycle tracks but not the reference streets. To obtain an unbiased measure of relative exposure, simultaneous 2 h bicycle counts were conducted at parallel counting sites on each cycle track and its reference street(s). Using a ratio of simultaneous counts eliminates systematic effects on bicycle use such as weather, time and day. The simultaneous counts were made during mild weather commuting hours in 2009.

The RR of injury for each cycle track was calculated as:

$$RR = \frac{\frac{\text{injuries}_{\text{track}}}{\text{bikes}_{\text{track}}}}{\frac{\text{injuries}_{\text{ref}}}{\text{bikes}_{\text{ref}}}}$$

where $\text{injuries}_{\text{track}}$ and $\text{injuries}_{\text{ref}}$ are the count of injuries on the cycle track and reference street(s), respectively, and $\text{bikes}_{\text{track}}$ and $\text{bikes}_{\text{ref}}$ are the corresponding cyclist counts.

Ninety-five percent CI were calculated using the variance of log(ratio) based on a Poisson distribution for incidents. CI that did not include 1 were considered statistically significant. RR for all cycle tracks was calculated similarly using the summed data from all the observations.

Relative danger from vehicular traffic

Reference streets were selected with vehicular traffic danger (volume, speed, heavy vehicles) as similar as possible to their cycle track; however, it was impossible to achieve exact similarity. Therefore, to compare the vehicular traffic danger, we also calculated the ratio of motor vehicle occupant (MVO) injuries on the cycle track street to MVO injuries on the reference street. MVO injury counts are considered a surrogate for traffic danger a bicyclist might face on a given street apart from any treatment.

RESULTS

All six cycle tracks were two-way on one side of the street and separated from traffic by raised medians, parking lanes, or delineator posts. There were 8.5 injuries and 10.5 crashes per million bicycle-km. The Brébeuf and Maisonneuve cycle tracks stand out as safer than the other four (table 1).

Table 1 Injury and vehicle/bicycle crash rates for cycle tracks in Montreal, Quebec*

Cycle track	Configuration	Separation	Length† (km)	Length factor‡	Cyclists/day, 1999–2008 §	Bike-km/year (millions)¶ **	Injuries/year ††	Crashes/year‡‡	Injuries per million bike-km	Crashes per million bike-km
1. Brébeuf (seasonal)	2-Way, 1 side of one-way street, street level	Delineator posts and parking lane	1.0	0.9	5316	0.96	3.9	1.8	*4.1*	*1.9*
2. Rachel	2-Way, 1 side of two-way street, street level	Raised median, delineator posts, parking lane	3.5	0.6	2581	1.08	12.6	17.0	*11.6*	*15.7*
3. Berri	2-Way, 1 side of two-way street, street/sidewalk level	Raised median, delineator posts, and parking lane	1.4	0.8	2778	0.62	7.8	10.2	*12.5*	*16.4*
4. Maisonneuve, w. island (seasonal)	2-Way, 1 side of one-way street, street level	Delineator posts	1.9	0.9	2379	0.81	1.9	2.6	*2.3*	*3.2*
5. Chr Colombe (seasonal)	2-Way, 1 side of two-way street, sidewalk level	Curb and (part) planting strip	3.7	0.7	921	0.48	6.7	9.2	*14.1*	*19.3*
6. René-Levesque	2-Way, 1 side of two-way street, street level	Raised median, delineator posts, parking lane	1.3	0.8	1108	0.23	2.8	3.2	*12.3*	*13.9*
All						4.18	35.7	44.0	***8.5***	***10.5***

*Whole segments of the cycle track were studied and not just intersections.
†Length of the section studied, which may be less that the entire cycle track length for comparability with reference streets.
‡Fraction of the study section's length ridden by a typical rider.
§Average for the May to September period over the period 1999–2008.
¶'Year' is the 7.5 month period (1 April to 15 November) when the seasonal cycle tracks are open.
**Demand is lower in April, October and November and, therefore, bicycle volume for a 'year' is assumed to be 200 times the daily volume.
††Injuries (data source — emergency medical response) between 1 April and 15 November for the period 1 April 1999 to 31 July 2008 divided by 9.53.
‡‡Bicycle–motor vehicle crashes (data source — police reports) between 1 April and 15 November 2002–6, divided by 5.

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Table 2 RR of injury for cycle tracks compared to similar on-street routes for Montreal, Quebec*

Cycle track†	Reference street‡	Limiting cross streets	Length (km)	Cycle track 2-h bike count	Cycle track EMR-reported injuries§	Reference street 2-h bike count	Reference street EMR-reported injuries§	RR (95% CI)¶
1. Brébeuf	**St Denis (N)**	**Rachel – Laurier**	1.0	1193	37	437	32	**0.42 (0.26 to 0.68)**
2. Rachel	Mont Royal	St Urbain – Marquette	3.5	990	120	613	63	1.18 (0.87 to 1.60)
3. Berri	**St Denis (S)**	**Cherrier – Viger**	1.4	763	74	134	27	**0.48 (0.31 to 0.75)**
4. Maisonneuve	**Both**	**Claremont – Wood**	1.9	547	18	176**	18	**0.32 (0.17 to 0.62)**
	Sherbrooke (W)					*129*	14	*0.30*
	Ste Catherine					*47*	4	*0.39*
5. Christophe Colomb	Both	Gouin – Jarry	3.7	407	64	122	19	1.01 (0.61 to 1.68)
	Saint-Hubert					*45*	9	*0.79*
	Christophe Colomb (S)	Villeray – Rosemont	2.3			*77*	10	*1.21*
6. René Levesque	Sherbrooke (E)	Lorimier – St Hubert	1.3	109	27	130	32	1.01 (0.60 to 1.68)
All			15.1	4009	340	1612	191	**0.72 (0.60 to 0.85)**

*Statistically significant comparisons are shown in **bold.**
†All cycle tracks are two-way on one side of the street.
‡An on-street bike route on a parallel street in close proximity of the cycle track.
§Injuries recorded by emergency medical response (EMR) services between 1 April 1999 and 31 July 2008 for the season 1 April to 15 November.
¶95%CI calculated using the variance of log(RR) based on a Poisson distribution.
**For comparisons having two reference streets, the total number of bicyclists is used from both streets.

Compared with bicycling on a reference street, the overall RR of injury on a cycle track was 0.72 (95% CI 0.60 to 0.85); thus, these cycle tracks had a 28% lower injury rate. Three of the cycle tracks exhibited RR less than 0.5, and none showed a significantly greater risk than its reference street. Overall, 2.5 times as many cyclists used the cycle tracks compared with the reference streets (table 2).

The relative danger from vehicular traffic of the cycle tracks compared with their reference streets was close to 1.0 overall, but with a wide range (table 3). Not surprisingly, the Brébeuf and Maisonneuve cycle tracks with lowest crash rate and relative injury risk (tables 1 and 2) also had the lowest relative danger from vehicular traffic (table 3). Yet even for the four cycle tracks on streets with vehicular traffic danger similar to or greater than its reference street, the cycle tracks still had less or a similar risk of injury.

DISCUSSION

Contrary to AASHTO's safety cautions about road-parallel paths and its exclusion of cycle tracks, our results suggest that two-way cycle tracks on one side of the road have either lower or similar injury rates compared with bicycling in the street without bicycle provisions. This lowered risk is also in spite of the less-than-ideal design of the Montreal cycle tracks, such as lacking parking setbacks at intersections, a recommended practice.[18]

While the goal of this study was to consider both one and two-way cycle tracks, all of the Montreal cycle tracks were two-way with half the bicyclists riding in a direction opposite to that of the closest vehicular traffic, a practice not favoured by AASHTO. Although the Montreal cycle tracks were two-way, they had lower or similar risk compared with the road. The Dutch CROW bicycle guidelines suggest that one-way cycle tracks are even safer.[3]

The crash rate for Montreal's cycle tracks (10.5 crashes per million bicycle-km) is low compared with the few and inconsistent crash rates in the literature. When calculated to include only vehicle/bicycle crashes, these rates range from 3.75[5] to 54[19] in the USA and from 46[20] to 67[21] in Canada. The injury rate (8.5 injuries per million bicycle-km) lacks comparable data in the literature, partly because few communities have accessible bicycle-incident ambulance records. Although the Brébeuf and Maisonneuve cycle tracks were safer, the sample of six cycle

Table 3 Relative danger from vehicular traffic*

Cycle track street	Reference street	MVO injuries† Cycle track street	MVO injuries† Reference street	Relative traffic danger of cycle track street (95% CI)‡
1. Brébeuf	**St Denis (N)**	8	90	**0.09 (0.04 to 0.18)**
2. Rachel	Mont Royal	86	69	1.25 (0.91 to 1.73)
3. Berri	St Denis (S)	127	116	1.09 (0.85 to 1.41)
4. Maisonneuve	**Both**	13	59§	**0.22 (0.12 to 0.40)**
	Sherbrooke (W)		*72*	
	Ste Catherine		*46*	
5. Christophe Colomb	**Both**	367	217§	**1.69 (1.43 to 2.00)**
	Saint-Hubert		*268*	
	Christophe Colomb (S)		*166*	
6. René Levesque	Sherbrooke (E)	196	205	0.96 (0.79 to 1.16)
All	All	797	756	1.05 (0.95 to 1.16)

*Statistically significant comparisons are shown in **bold.**
†Injuries to motor vehicle occupants recorded by emergency medical response (EMR) services between 1 January 1999 and 31 July 2008.
‡95% CI calculated using the variance of log(RR) based on a Poisson distribution.
§For comparisons having two reference streets, the average number of injuries of the reference streets is used.
MVO, motor vehicle occupant.

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Table 4 Crash RR from Wachtel and Lewiston[22] data with non-intersection crashes included*

	Sidewalk		Roadway		All		RR, sidewalk versus	
	Riders	Crashes	Riders	Crashes	Riders	Crashes	in-street (95% CI)†	p Value‡
Intersection only§								
All cyclists	**971**	**41**	**2005**	**48**	**2976**	**89**	**1.76 (1.16 to 2.68)**	**0.01**
Bicycling in same direction as closest traffic lane	656	13	1897	43	2553	56	0.87 (0.47 to 1.63)	0.56
All crashes¶								
All cyclists	971	41	2005	79	2976	120	1.07 (0.73 to 1.56)	0.79
Bicycling in same direction as closest traffic lane	**656**	**13**	**1897**	**71**	**2553**	**84**	**0.53 (0.29 to 0.96)**	**0.02**

*Statistically significant comparisons are shown in **bold**.
†95% CI calculated using the variance of log(IRR) based on a Poisson distribution.
‡Significance, calculated using the variance of log(IRR) based on a Poisson distribution (for comparison with original article).
§Authors' original data.
¶Non-intersection crashes amounting to 26% of total crashes added to roadway crashes.

tracks was too small to determine which factors make some safer.

In one of the few comparisons of bicycling in the street versus bicycling on a separated path parallel to the street in the USA, Wachtel and Lewiston[22] determined a relative crash risk of 1.8 for bicycling on sidewalks which had been designated as bikeways, compared with bicycling in the adjacent street in Palo Alto, California. However, their study considered only intersection crashes, omitting non-intersection crashes that include being hit from behind, sideswiped, or struck by a car door. The authors, though, reported that 26% of cyclist—motor vehicle collisions city-wide in Palo Alto were non-intersection crashes. If non-intersection crashes are included to match this 26% proportion, reanalysis of the Wachtel and Lewiston[22] data in the article shows that there is no significant difference in risk between the sidewalk bikeway and the street (table 4). For bicyclists riding in the same direction as traffic, as would be case with one-way cycle tracks, sidewalk bikeways carried only half the risk of the street. Therefore, the Wachtel and Lewiston[22] data, when corrected to include non-intersection crashes, corroborate our findings that separated paths are safer or at least no more dangerous than bicycling in the street. Furthermore, as the most common cause of fatal bicyclist collisions in urban areas is overtaking,[23] it is probable that an analysis accounting for the severity of injury would be still more favourable towards cycle tracks.

Our study considered whole segments of cycle tracks and not just intersections, measured bicycle exposure directly, and included appropriate comparison groups. The study, though, only included analysis of six cycle tracks, all of which were two-way and in the same city, and lacked injury severity data. This research underscores the need for better bicycle counting and injury surveillance and for additional safety studies, particularly of one-way cycle tracks, intersections, injury severity and other factors that affect cycle track safety.

What is already known on this subject

- Individuals, in particular women, children, and seniors, prefer to bicycle separated from motor traffic.
- Cycle tracks (physically-separated bicycle-exclusive paths along roads) exist and continue to be built in The Netherlands where 27% of all trips are by bicycle and 55% of bicycle riders are female.
- Engineering guidance in the United States has discouraged bicycle facilities that resemble cycle tracks, including parallel sidepaths and sidewalk bikeways, suggesting that these facilities and cycle tracks are more dangerous than bicycling in the street.

What this study adds

- Overall, 2 ½ times as many cyclists rode on the cycle tracks compared with the reference streets.
- There were 8.5 injuries and 10.5 crashes per million-bicycle kilometers respectively on cycle tracks compared to published injury rates ranging from 3.75 to 67 for bicycling on streets. The relative risk of injury on the cycle track was 0.72 (95% CI=0,60-0.85) compared with bicycling in the reference streets.
- Cycle tracks lessen, or at least do not increase, crash and injury rates compared to bicycling in the street.

IMPLICATIONS FOR POLICY

Public health and bicycling advocates in the USA have faced a dichotomy, believing from surveys and European experience that cycle tracks encourage more bicycling, yet being warned that they lead to higher crash and injury rates. Our results suggest that cycle tracks lessen, or at least do not increase, crash and injury rates compared with the street. The construction of cycle tracks should not be discouraged.

Acknowledgements The authors would like to thank Kevin Manaugh (McGill University) and Nathalie Valois (Montreal police), who performed the geographical queries to extract data from the crash database, and Qi Sun and Elaine Hoffman for a review of the statistics.

Funding ACL was supported by a Ruth L Kirschstein National Research Service Award, F32 HL083639 from the National Institutes for Health, National Heart, Lung and Blood Institute. LFM-M is supported for data collection by the Natural Sciences and Engineering Research Council of Canada (discovery grant — individual).

Competing interests None.

Ethics approval The Harvard School of Public Health IRB reviewed this protocol and found that approval was not required. The HSPH IRB made an exemption determination.

Contributors PGF had full access to the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. Conception and design: ACL and PGF. Acquisition of data: ACL, PGF, PM and LFM-M. Analysis and interpretation of data: ANL, PGF, PM, LFM-M, WCW and JTD. Drafting of manuscript: ACL, PGF. Critical revision for intellectual content: ACL, PGF, PM, LFM-M, WCW and JTD. Statistical expertise: ACL, PGF, PM, LFM-M, WCW and JTD. Administrative, technical or material support: WCW. Study supervision: PGF, WCW and JTD.

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Provenance and peer review Not commissioned; externally peer reviewed.

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Level-of-Service Calculations

Bicycle Lane Levels-of-Service

Bicycle Lane Levels-of Service

In response to Item 2 under Suggested Actions of the July 18, 2012 letter regarding the original Design Exception Report comments, the Levels-of-Service (LOS) for on-street bicycle lanes and off-street (cycle track) bicycle lanes have been determined based upon Chapter 17 of the Highway Capacity Manual 2010. Bicycle LOS along a roadway link is based the roadway cross-section, the adjacent vehicular volume and vehicular speeds, and the condition of the pavement. To represent the 2032 design year, the recorded 2012 bicycle volumes have been increased 10% for the on-street bicycle lanes, as the rideability of Beacon Street will be improved. The existing bicycle volumes have been increased by 20% for the proposed off-street lanes, as the cycle track will entice more bicyclists to use the Beacon Street corridor.

The roadway link bicycle LOS is based upon Exhibit 17-4 of the HCM 2010.

Table A: Beacon Street Bicycle Level of Service (LOS)

	Alternative 1 Proposed On-Street Bicycle Lane LOS		Recommended Alternative Proposed Off-Street Cycle Track LOS	
Beacon Street Roadway Link	**Northbound**	**Southbound**	**Northbound**	**Southbound**
Oxford St to Kent St	B	C	A	A
Park St to Washington St	D	C	A	A

As indicated in Table A, while the on-street bicycle lanes provide acceptable levels of service, the off-street cycle track alternative provides a much better level of service. This is primarily due to the wider bicycle accommodations provided by the cycle track alternative, and the further separation from motorized vehicles.

A bicycle LOS analysis based on the 2000 Highway Capacity Manual was presented in the previous revision of this Design Exception Report. The results of this updated analysis differ from the previous analysis because the methodologies for computing bicycle LOS have changed significantly from the 2000 and 2010 versions of the Highway Capacity Manual. The updated methodology, based on more recent studies of the many factors affecting bicyclists, considers more variables and places a greater emphasis on the proposed cross-section and less of an emphasis on bicycle volumes.

Bicycle Link LOS calc sheet

Defined in Chapter 17 of the 2010 HCM

Roadway:	Beacon Street
Segment:	Oxford Street to Kent Street (Sta 103+00 - Sta 123+50)
Direction:	NB
Alternative:	6ft cycle track

bicycle LOS score for link ($I_{b,link}$)	**1.890**		(calculated with Equation 17-40)
bicycle link LOS	**A**		(from Exhibit 17-4)
cross-section adjustment factor (F_w)	-2.645		(calculated with Equation 17-41)
motorized vehicle volume adjustment factor (F_v)	2.4112		(calculated with Equation 17-42)
motorized vehicle speed adjustment factor (F_S)	1.0145		(calculated with Equation 17-43)
pavement condition adjustment factor (F_p)	0.3489		(calculated with Equation 17-44)
effective width of outside through lane (W_e)	23	ft	(calculated from Exhibit 17-21)
adjusted midsegment demand flow rate (v_{ma})	465	veh/h	(calculated from Exhibit 17-21)
number of through (vehicle) lanes on the segment in the subject direction of travel (N_{th})	1	lane(s)	
adjusted motorized vehicle running speed (S_{Ra})	31	mi/h	(calculated from Exhibit 17-21)
adjusted percent heavy vehicles in midsegment demand flow rate (P_{HVa})	2	%	(calculated from Exhibit 17-21)
pavement condition rating (P_c)	4.5		(from Exhibit 17-7)

Bicycle Link LOS calc sheet

Defined in Chapter 17 of the 2010 HCM

Roadway:	Beacon Street
Segment:	Oxford Street to Kent Street (Sta 103+00 - Sta 123+50)
Direction:	SB
Alternative:	9ft cycle track

bicycle LOS score for link ($I_{b,link}$)	**-1.472**		(calculated with Equation 17-40)
bicycle link LOS	**A**		(from Exhibit 17-4)
cross-section adjustment factor (F_w)	-6.125		(calculated with Equation 17-41)
motorized vehicle volume adjustment factor (F_v)	2.3473		(calculated with Equation 17-42)
motorized vehicle speed adjustment factor (F_S)	1.1963		(calculated with Equation 17-43)
pavement condition adjustment factor (F_p)	0.3489		(calculated with Equation 17-44)
effective width of outside through lane (W_e)	35	ft	(calculated from Exhibit 17-21)
adjusted midsegment demand flow rate (v_{ma})	410	veh/h	(calculated from Exhibit 17-21)
number of through (vehicle) lanes on the segment in the subject direction of travel (N_{th})	1	lane(s)	
adjusted motorized vehicle running speed (S_{Ra})	31	mi/h	(calculated from Exhibit 17-21)
adjusted percent heavy vehicles in midsegment demand flow rate (P_{HVa})	3	%	(calculated from Exhibit 17-21)
pavement condition rating (P_c)	4.5		(from Exhibit 17-7)

Bicycle Link LOS calc sheet

Defined in Chapter 17 of the 2010 HCM

Roadway:	Beacon Street
Segment:	Park Street to Washington Street (Sta 132+75 - Sta 141+50)
Direction:	NB
Alternative:	6ft cycle track

bicycle LOS score for link ($I_{b,link}$)	**1.986**		(calculated with Equation 17-40)
bicycle link LOS	**A**		(from Exhibit 17-4)
cross-section adjustment factor (F_w)	-2.645		(calculated with Equation 17-41)
motorized vehicle volume adjustment factor (F_v)	2.5072		(calculated with Equation 17-42)
motorized vehicle speed adjustment factor (F_S)	1.0145		(calculated with Equation 17-43)
pavement condition adjustment factor (F_p)	0.3489		(calculated with Equation 17-44)
effective width of outside through lane (W_e)	23	ft	(calculated from Exhibit 17-21)
adjusted midsegment demand flow rate (v_{ma})	562	veh/h	(calculated from Exhibit 17-21)
number of through (vehicle) lanes on the segment in the subject direction of travel (N_{th})	1	lane(s)	
adjusted motorized vehicle running speed (S_{Ra})	31	mi/h	(calculated from Exhibit 17-21)
adjusted percent heavy vehicles in midsegment demand flow rate (P_{HVa})	2	%	(calculated from Exhibit 17-21)
pavement condition rating (P_c)	4.5		(from Exhibit 17-7)

Bicycle Link LOS calc sheet

Defined in Chapter 17 of the 2010 HCM

Roadway:	Beacon Street
Segment:	Park Street to Washington Street (Sta 132+75 - Sta 141+50)
Direction:	SB
Alternative:	9ft cycle track

bicycle LOS score for link ($I_{b,link}$)	**-1.687**		(calculated with Equation 17-40)
bicycle link LOS	**A**		(from Exhibit 17-4)
cross-section adjustment factor (F_w)	-6.125		(calculated with Equation 17-41)
motorized vehicle volume adjustment factor (F_v)	2.4813		(calculated with Equation 17-42)
motorized vehicle speed adjustment factor (F_S)	0.8476		(calculated with Equation 17-43)
pavement condition adjustment factor (F_p)	0.3489		(calculated with Equation 17-44)
effective width of outside through lane (W_e)	35	ft	(calculated from Exhibit 17-21)
adjusted midsegment demand flow rate (v_{ma})	534	veh/h	(calculated from Exhibit 17-21)
number of through (vehicle) lanes on the segment in the subject direction of travel (N_{th})	1	lane(s)	
adjusted motorized vehicle running speed (S_{Ra})	31	mi/h	(calculated from Exhibit 17-21)
adjusted percent heavy vehicles in midsegment demand flow rate (P_{HVa})	1	%	(calculated from Exhibit 17-21)
pavement condition rating (P_c)	4.5		(from Exhibit 17-7)

Bicycle Link LOS calc sheet

Defined in Chapter 17 of the 2010 HCM

Roadway: Beacon Street
Segment: Oxford Street to Kent Street (Sta 103+00 - Sta 123+50)
Direction: NB
Alternative: 5ft bike lane

bicycle LOS score for link ($I_{b,link}$)	**2.672**		(calculated with Equation 17-40)
bicycle link LOS	**B**		(from Exhibit 17-4)
cross-section adjustment factor (F_w)	-1.86245		(calculated with Equation 17-41)
motorized vehicle volume adjustment factor (F_v)	2.4112		(calculated with Equation 17-42)
motorized vehicle speed adjustment factor (F_S)	1.0145		(calculated with Equation 17-43)
pavement condition adjustment factor (F_p)	0.3489		(calculated with Equation 17-44)
effective width of outside through lane (W_e)	19.3	ft	(calculated from Exhibit 17-21)
adjusted midsegment demand flow rate (v_{ma})	465	veh/h	(calculated from Exhibit 17-21)
number of through (vehicle) lanes on the segment in the subject direction of travel (N_{th})	1	lane(s)	
adjusted motorized vehicle running speed (S_{Ra})	31	mi/h	(calculated from Exhibit 17-21)
adjusted percent heavy vehicles in midsegment demand flow rate (P_{HVa})	2	%	(calculated from Exhibit 17-21)
pavement condition rating (P_c)	4.5		(from Exhibit 17-7)

Bicycle Link LOS calc sheet

Defined in Chapter 17 of the 2010 HCM

Roadway:	Beacon Street
Segment:	Oxford Street to Kent Street (Sta 103+00 - Sta 123+50)
Direction:	SB
Alternative:	5ft bike lane

bicycle LOS score for link ($I_{b,link}$)	**2.790**		(calculated with Equation 17-40)
bicycle link LOS	**C**		(from Exhibit 17-4)
cross-section adjustment factor (F_w)	-1.86245		(calculated with Equation 17-41)
motorized vehicle volume adjustment factor (F_v)	2.3473		(calculated with Equation 17-42)
motorized vehicle speed adjustment factor (F_S)	1.1963		(calculated with Equation 17-43)
pavement condition adjustment factor (F_p)	0.3489		(calculated with Equation 17-44)
effective width of outside through lane (W_e)	19.3	ft	(calculated from Exhibit 17-21)
adjusted midsegment demand flow rate (v_{ma})	410	veh/h	(calculated from Exhibit 17-21)
number of through (vehicle) lanes on the segment in the subject direction of travel (N_{th})	1	lane(s)	
adjusted motorized vehicle running speed (S_{Ra})	31	mi/h	(calculated from Exhibit 17-21)
adjusted percent heavy vehicles in midsegment demand flow rate (P_{HVa})	3	%	(calculated from Exhibit 17-21)
pavement condition rating (P_c)	4.5		(from Exhibit 17-7)

Bicycle Link LOS calc sheet

Defined in Chapter 17 of the 2010 HCM

Roadway:	Beacon Street
Segment:	Park Street to Washington Street (Sta 132+75 - Sta 141+50)
Direction:	NB
Alternative:	5ft bike lane

bicycle LOS score for link ($I_{b,link}$)	**3.521**		(calculated with Equation 17-40)
bicycle link LOS	**D**		(from Exhibit 17-4)
cross-section adjustment factor (F_w)	-1.11005		(calculated with Equation 17-41)
motorized vehicle volume adjustment factor (F_v)	2.5072		(calculated with Equation 17-42)
motorized vehicle speed adjustment factor (F_S)	1.0145		(calculated with Equation 17-43)
pavement condition adjustment factor (F_p)	0.3489		(calculated with Equation 17-44)
effective width of outside through lane (W_e)	14.9	ft	(calculated from Exhibit 17-21)
adjusted midsegment demand flow rate (v_{ma})	562	veh/h	(calculated from Exhibit 17-21)
number of through (vehicle) lanes on the segment in the subject direction of travel (N_{th})	1	lane(s)	
adjusted motorized vehicle running speed (S_{Ra})	31	mi/h	(calculated from Exhibit 17-21)
adjusted percent heavy vehicles in midsegment demand flow rate (P_{HVa})	2	%	(calculated from Exhibit 17-21)
pavement condition rating (P_c)	4.5		(from Exhibit 17-7)

Bicycle Link LOS calc sheet

Defined in Chapter 17 of the 2010 HCM

Roadway:	Beacon Street
Segment:	Park Street to Washington Street (Sta 132+75 - Sta 141+50)
Direction:	SB
Alternative:	5ft bike lane

bicycle LOS score for link ($I_{b,link}$)	**3.328**		(calculated with Equation 17-40)
bicycle link LOS	**C**		(from Exhibit 17-4)
cross-section adjustment factor (F_w)	-1.11005		(calculated with Equation 17-41)
motorized vehicle volume adjustment factor (F_v)	2.4813		(calculated with Equation 17-42)
motorized vehicle speed adjustment factor (F_S)	0.8476		(calculated with Equation 17-43)
pavement condition adjustment factor (F_p)	0.3489		(calculated with Equation 17-44)
effective width of outside through lane (W_e)	14.9	ft	(calculated from Exhibit 17-21)
adjusted midsegment demand flow rate (v_{ma})	534	veh/h	(calculated from Exhibit 17-21)
number of through (vehicle) lanes on the segment in the subject direction of travel (N_{th})	1	lane(s)	
adjusted motorized vehicle running speed (S_{Ra})	31	mi/h	(calculated from Exhibit 17-21)
adjusted percent heavy vehicles in midsegment demand flow rate (P_{HVa})	1	%	(calculated from Exhibit 17-21)
pavement condition rating (P_c)	4.5		(from Exhibit 17-7)