Pedalling Forward: The Evolution of Dedicated Cycling Infrastructure in Canadian Cities from 2010 to 2022

R Code for Figures and Tables

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March 11, 2024

Contents

Libraries

Install R libraries if needed.

```
install.packages("rmarkdown")
install.packages("bookdown")
install.packages("knitr")
install.packages("tidyverse")
install.packages("glue")
install.packages("readxl")
install.packages("ggtext")
install.packages("scales")
install.packages("patchwork")
```

Load R libraries.

```
library(tidyverse)
library(ggtext)
library(glue)
library(patchwork)
library(readxl)
```

Settings

```
settings <- list()

# Infrastructure types in order
settings$type_recode_infra <- c(
    PBL = "Cycle Track",
    BUF = "Buffered Lane",
    PL = "Painted Lane",
    LSB = "Local Street\nBikeway"
)

# Infrastructure types to remove
settings$type_filter_infra <- c("N", "None", "SR")

# Road types in order
settings$type_recode_road <- c(
    Arterial = "Arterial",
    Collector = "Collector",
    Local = "Local"
)

# Column references
settings$year_col_road <- "install_year"
settings$type_col_road <- "road_type"
settings$type_col_infra <- "infra_type"

# Set years of interest
settings$year_min <- 2009
settings$year_max <- 2022

# Plot settings
```

```
settings$line_year <- 2019
```

Functions

Calculate Yearly Road Length

The following function calculates yearly road lengths by infrastructure type using cumulative sums and filling in missing years and types.

For a given infrastructure type, the total road length for a given year is expressed below:

$$length_{year,type} = f(year, type) = \sum_{i=year_{min}}^{year} l_{i,type}$$

Where:

- $year$ is the given year
- $type$ is the infrastructure type
- $year_{min}$ is the earliest year available in the data
- $l_{i,type}$ is the road length l for previous years i and infrastructure j
- $l_{i,type}$ is set to 0 if there is no data

```
#' Calculate Yearly Road Lengths By Infrastructure Type
#'
#' Calculates the cumulative yearly road lengths by infrastructure type without considering infrastructu
#'
#' @param df A data.frame with three columns containing the year, type, and road lengths.
#' @param year_col The name (char) or index (int) of the column containing the years.
#' @param type_col The name (char) or index (int) of the column containing the infrastructure type
#' @param len_col The name (char) or index (int) of the column containing the road lengths.
#' @param out_col The name (char) of the column containing the calculated yearly road lengths by type.
#'
#' @return A data.frame with three columns containing the year, type, and calculated yearly road lengths
#' @export
#'
calc_yearly_len <- function(
        df,
        year_col = "install_year",
        type_col = "install_type",
        len_col = "segment_len",
        out_col = "len",
        year_min = settings$year_min,
        year_max = settings$year_max
    ) {

    # Convert data types
    df[[year_col]] <- as.integer(df[[year_col]])
    df[[type_col]] <- as.character(df[[type_col]])
    df[[len_col]] <- as.numeric(df[[len_col]])

    # Remove rows with empty type
    out <- df %>% filter(
        !is.na(.data[[type_col]])
    )
```

```
    # Filter to min and max years
    if (year_min > 0) {
        df <- df %>% filter(
            .data[[year_col]] >= year_min
        )
    } else {
        year_min <- min(out[[year_col]], na.rm = TRUE)
    }
    if (year_max > 0) {
        df <- df %>% filter(
            .data[[year_col]] <= year_max
        )
    } else {
        year_max <- max(out[[year_col]], na.rm = TRUE)
    }

    # Add dummy len for each type and year combo
    # Covers cases where type and year combo does not exist
    # E.g. No new PL installs in 2021, hence a record PL in 2021 does not exist
    type_uniq <- unique(out[[type_col]])
    type_n <- length(type_uniq)
    year_uniq <- year_min:year_max
    year_n <- length(year_uniq)
    out <- out %>% add_row(
        !!year_col := rep(year_uniq, each = type_n),
        !!type_col := rep(type_uniq, year_n),
        !!len_col := rep(0, type_n * year_n)
    )

    # Calc cumsum for each non-empty type ordered by year
    out <- out %>%
        arrange(.data[[year_col]]) %>%
        group_by(.data[[type_col]]) %>%
        mutate(
            !!out_col := cumsum(.data[[len_col]])
        )

    # Get the last cumsum for each year and type
    out <- out %>%
        group_by(.data[[year_col]], .data[[type_col]]) %>%
        arrange(desc(row_number())) %>%
        slice(1)

    # Return only the columns spec
    out <- out %>% select(c(
            year_col,
            type_col,
            out_col
        ))
    return(out)
}
```

Calculate Yearly Adjusted Road Length

The following function calculates yearly adjusted road lengths by infrastructure type using cumulative sums and filling in missing years and types.

For a given infrastructure type, the total adjusted road length for a given year is expressed below:

$$length_{year,type}^{install} + length_{year,type}^{change_i} - length_{year,type}^{replacement_i}$$

Where:

- $length_{year,type}^{install}$ are the yearly cumulative road lengths for an infrastructure *type* installation
- $length_{year,type}^{change_i}$ are the yearly cumulative road lengths for an infrastructure *type* change in order i
- $length_{year,type}^{replacement_i}$ are the yearly cumulative road lengths for an infrastructure *type* replaced by change in order i

```
#' Calculate Yearly Adjusted Road Lengths By Infrastructure Type
#'
#' Calculates the cumulative yearly adjusted road lengths by infrastructure type accounting for installa
#'
#' @param df A data.frame with three columns containing the year, type, and road lengths.
#' @param year_cols A vector of the names (char) or indices (int) of the columns containing the years o
#' @param type_cols A vector of the names (char) or indices (int) of the columns containing the infrast
#' @param type_col The name (char) of the column containing the type.
#' @param len_cols A vector of the names (char) or indices (int) of the columns containing the road leng
#' @param out_cols The name (char) of the column containing the calculated yearly road lengths by type.
#' @param out_col The name (char) of the column containing the calculated yearly adjusted road lengths b
#' @param repl_suffix A suffix (char) to append to the columns representing the road lengths of replaced
#' @param ... Additional arguments passed to calc_yearly_len.
#'
#' @return A data.frame with columns containing the year, type, cumulative road lengths of installations
#' @export
#'
calc_yearly_adj_len <- function(
        df,
        year_cols = c("install_year", "upgrade1_year", "upgrade2_year"),
        type_cols = c("install_type", "upgrade1_type", "upgrade2_type"),
        type_col = "type",
        len_cols = "segment_len",
        out_cols = c("install_len", "upgrade1_len", "upgrade2_len"),
        out_col = "adj_len",
        repl_suffix = "_replaced",
        ...
    ) {

    # Convert len_col if char
    len_cols <- rep(len_cols, length(year_cols))

    # Check cols same size
    year_cols_n <- length(year_cols)
    type_cols_n <- length(type_cols)
    len_cols_n <- length(len_cols)
    out_cols_n <- length(out_cols)
    if (length(unique(c(year_cols_n, type_cols_n, len_cols_n, out_cols_n))) != 1) {
        stop(glue(
            "The arguments 'year_cols' ({year_cols_n}), 'type_cols' ({type_cols_n}), 'len_cols' ({len_co
```

```
    ))
}

# Calc yearly lens by infra type per install or change
out <- list()
for (i in 1:length(year_cols)) {

    # Get year, type, and len cols
    ycol <- year_cols[[i]]
    tcol <- type_cols[[i]]
    lcol <- len_cols[[i]]
    ocol <- out_cols[[i]]

    # Calc yearly len for install or change
    out <- append(
        out,
        calc_yearly_len(
            df,
            year_col = ycol,
            type_col = tcol,
            len_col = lcol,
            out_col = ocol,
            ...
        ) %>%
            rename(
                "year" := !!ycol,
                "type" := !!tcol
            ) %>% list
    )

    # Calc yearly len for replacement
    if (i > 1) {

        # Get repl cols
        tcol_repl <- type_cols[[i - 1]]
        lcol_repl <- len_cols[[i - 1]]

        # Filter for repl records only where type is not eq to change type
        df_repl <- df %>% filter(.data[[tcol]] != .data[[tcol_repl]])

        # Calc repl len if there are any changes
        has_change <- !is.na(df_repl[[tcol]]) %>% all
        if (has_change) {
            out <- append(
                out,
                calc_yearly_len(
                    df_repl,
                    year_col = ycol,
                    type_col = tcol_repl,
                    len_col = lcol_repl,
                    out_col = glue("{ocol}{repl_suffix}"),
                    ...
                ) %>%
```

```
                    rename(
                        "year" := !!ycol,
                        "type" := !!tcol_repl
                    ) %>% list
                )
            }
        }
    }

    # Combine all lens in list to single df
    out <- out %>%
        reduce(
            left_join, by = c("year", "type")
        ) %>%
        ungroup()

    # Create template for change and repl cols
    change_cols <- paste0(out_cols[2:out_cols_n])# change cols
    change_cols <- c(change_cols, paste0(out_cols[2:out_cols_n], repl_suffix)) # repl cols
    change_cols_add <- rep(0, length(change_cols)) # set default vals
    names(change_cols_add) <- change_cols

    # Add change and repl cols set to 0 if not present
    out <- out %>% add_column(
        !!!change_cols_add[setdiff(names(change_cols_add), names(.))]
    )

    # Set NA to 0
    out <- out %>% mutate(
        across(everything(), ~replace_na(., 0))
    )

    # Calc yearly adj lens by infra type
    out <- out %>%
        mutate( # added len by infra types due to install or changes
            !!out_col := reduce(across(all_of(out_cols)), `+`)
        ) %>%
        mutate( # removed len by infra types due to replacements
            !!out_col := .data[[out_col]] - reduce(
                across(all_of(
                    paste0(out_cols[2:out_cols_n], repl_suffix)
                )),
                `_`
            )
        )

    # Rename type col
    out <- out %>% rename(!!type_col := type)
    return(out)
}
```

Plot Lengths by Year for Generic Types

Plots an area chart showing the cumulative road lengths by a user-defined type for each year.

This is a generic function for user-defined types such as infrastructure or road types.

```
#' Plot Yearly Road Lengths By Type
#'
#' Creates an area plot of road lengths by category types.
#'
#' @param df A data.frame with three columns containing the year, type, and road lengths.
#' @param title The title (char) of the plot.
#' @param title_underline Set to TRUE to underline the title.
#' @param x_title The title (char) of the x-axis.
#' @param y_title The title (char) of the y-axis.
#' @param y_suffix The suffix (char) to add to the end of y axis values.
#' @param legend_title The title (char) of the legend.
#' @param legend Set to TRUE to include a legend.
#' @param year_col The name (char) or index (int) of the column containing the years.
#' @param year_min The minimum year (int) to display.
#' @param year_max The maximum year (int) to display.
#' @param year_int The year intervals (int) to display. For example, 1 displays every year, and 2 displa
#' @param len_col The name (char) or index (int) of the column containing the road lengths.
#' @param type_col The name (char) or index (int) of the column containing the type.
#' @param type_filter A vector (char) of types to remove fomr the plot.
#' @param type_recode A named vector (char) of names representing types and values representing the valu
#' @param line_50km Set to TRUE to draw the 50 km red reference line.
#' @param line_year Set to a year (int) to draw a reference line for a year. If FALSE, a line will not l
#' @param color_low The bottom color (char) of the type.
#' @param color_high The top color (char) of the type.
#' @return An area ggplot of the cumulative yearly road lengths by type.
#' @export
#'
plot_yearly_len <- function(
        df,
        title = "",
        title_underline = TRUE,
        x_title = "",
        y_title = "",
        y_suffix = " km",
        legend_title = "Type",
        legend = TRUE,
        year_col = "year",
        year_min = FALSE,
        year_max = FALSE,
        year_int = 1,
        len_col = "adj_len",
        type_col = "type",
        type_filter = c(),
        type_recode = c(),
        line_50km = FALSE,
        line_year = FALSE,
        color_low = "#DFEBF7",
        color_high = "#3683BB"
) {
```

```
    # Filter to start and end years
    if (year_min > 0) {
        df <- df %>% filter(
            .data[[year_col]] >= year_min
        )
    }
    if (year_max > 0) {
        df <- df %>% filter(
            .data[[year_col]] <= year_max
        )
    }

    # Filter out particular infrastructure types
    if (length(type_filter) > 0) {
        df <- df %>% filter(
            !.data[[type_col]] %in% type_filter
        )
    }

    # Recode and reorder category types
    if (length(type_recode) > 0) {

        # Reorder category types
        type_uniq <- unique(df[[type_col]])
        type_reorder <- names(type_recode)
        type_reorder <- c(type_reorder, type_uniq[!type_uniq %in% type_reorder])
        df[[type_col]] <- factor(df[[type_col]], levels = type_reorder)

        # Recode category types
        df[[type_col]] <- recode(df[[type_col]], !!!type_recode)
    }

    # Create fill colors
    type_n <- length(type_uniq)
    type_colors <- scales::seq_gradient_pal(
        color_low,
        color_high
    )(seq(0, 1, length.out = type_n))

    # Create base area plot with legend and labels
    len_max <- max(df[[len_col]], na.rm = TRUE)
    year_max <- max(df[[year_col]], na.rm = TRUE)
    out <- ggplot(
        df,
        aes(
            x = .data[[year_col]],
            y = .data[[len_col]],
            fill = .data[[type_col]],
            order = desc(.data[[type_col]])
        )
    ) +
    geom_area(colour = NA, alpha = 0.7) +
    scale_fill_manual(values = type_colors) +
```

```
    geom_line(
        position = "stack",
        size = 0.2
    ) +
    labs(
        x = x_title,
        y = y_title,
        fill = legend_title
    ) +
    guides(
        fill = FALSE,
        color = FALSE
    ) +
    scale_x_continuous(
        breaks = seq(year_min, year_max, by = year_int),
        labels = seq(year_min, year_max, by = year_int),
        limits = c(year_min, year_max)
    ) +
    scale_y_continuous(
        label = scales::label_number(suffix = y_suffix)
    ) +
    theme_minimal() +
    theme(
        plot.margin = unit(c(5,5,5,5), "points")
    )

    # Add title
    if (title_underline) {
        out <- out + ggtitle(
            bquote(underline(.(title)))
        )
    } else {
        out <- out + ggtitle(title)
    }

    # Add legend
    if (legend) {
        out <- out + guides(fill = guide_legend(
            reverse = FALSE,
            override.aes = list(
                alpha = 0.7,
                color = NA,
                shape = NA
            )
        ))
    }

    # Add dotted year ref line
    if (line_year) {
        out <- out + geom_vline(
            xintercept = line_year,
            color = "black",
            linetype = "dashed"
```

```
    )
}

# Add red 50km ref line
if (line_50km) {
    out <- out + geom_segment( # 50km red line
        aes(
            x = 2009,
            y = 0,
            xend = 2009,
            yend = 50,
            color = "#bb0000",
            hjust = 0.15
        )
    ) +
    geom_segment( # 50km red triangle point down
        aes(
            x = 2009,
            y = 50.01 - (len_max * 0.05),
            xend = 2009,
            yend = 50 - (len_max * 0.05),
            color = "#bb0000",
            hjust = 0.15
        ),
        arrow = arrow(
            length = unit(0.03, "npc"),
            ends = "last",
            type = "closed"
        )
    ) +
    geom_segment( # 50km red triangle point up
        aes(
            x = 2009,
            y = (len_max * 0.05) - 0.01,
            xend = 2009,
            yend = (len_max * 0.05),
            color = "#bb0000",
            hjust = 0.15
        ),
        arrow = arrow(
            length = unit(0.03, "npc"),
            ends = "last",
            type = "closed"
        )
    ) +
    annotate(
        "text",
        x = 2009,
        y = 50,
        label = "50km",
        color = "#bb0000",
        hjust = -0.225
    )
```

```
    }
    return(out)
}
```

Plot Lengths by Year for Infrastructure Types

Plots area charts of yearly road lengths by infrastructure types for a list of data.

This uses the `plot_yearly_len` function.

```
#' Plot Yearly Road Lengths By Infrastructure Type
#'
#' Creates area plots of road lengths by infrastructure type.
#'
#' @param df_list A list of data.frame containing the install and change years, type, and road segment l
#' @return Multiple area ggplots of the cumulative yearly road lengths by infrastructure type combined w
#' @export
#'
plot_yearly_len_infra <- function(df_list) {

    # Create infra plots from data
    p <- list()
    for (i in 1:length(df_list)) {

        # Get data and plot title
        df <- df_list[[i]]
        ptitle <- names(df_list)[[i]]

        # Create and add infra plot to list
        p[[i]] <- calc_yearly_adj_len(df, type_col = settings$type_col_infra) %>%
            plot_yearly_len(
                title = ptitle,
                year_min = settings$year_min,
                year_max = settings$year_max,
                type_col = settings$type_col_infra,
                type_filter = settings$type_filter_infra,
                type_recode = settings$type_recode_infra,
                legend_title = "Infrastructure Type",
                line_50km = TRUE,
                line_year = settings$line_year
            )
    }

    # Y-axis title
    y_title <- ggplot() +
        annotate(
            geom = "text",
            x = 1,
            y = 1,
            label = "Total Length (Centreline km)",
            angle = 90,
            size = 5
        ) +
        coord_cartesian(clip = "off")+
```

```
        theme_void()

    # Combine all infra plots together
    out <- (y_title | wrap_plots(p, nrow = length(p))) +
        plot_annotation(
            title = "Roadways with Dedicated Cycling Infrastructure",
            caption = sprintf("Years (%s-%s)", settings$year_min, settings$year_max),
            theme = theme(
                plot.title = element_text(hjust = 0.5, size = 16),
                plot.caption = element_text(hjust = 0.5, size = 14)
            )
        ) +
        plot_layout(widths = c(0.05, 1))
    return(out)
}
```

Plot Lengths by Year for Road Types

Plots area charts of yearly road lengths by overall road type and by infrastructure separated by each road type.

This uses the `plot_yearly_len` function.

```
#' Plot Yearly Road Lengths By Road Type
#'
#' Creates area plots of road lengths by overall road type, and by infrastructure per road type.
#'
#' @param df The data.frame containing the install and change years, type, and road segment types and le
#' @return Multiple area ggplots of the cumulative yearly road lengths by road type combined with patchw
#' @export
#'
plot_yearly_len_road <- function(df, title = "Roadways with Dedicated Cycling Infrastructure") {

    # Create list to store plots
    p <- list()

    # Plot overall road types
    p[[1]] <- calc_yearly_len(
        df,
        year_col = settings$year_col_road,
        type_col = settings$type_col_road
    ) %>%
        plot_yearly_len(
            title = title,
            title_underline = FALSE,
            year_col = settings$year_col_road,
            year_min = settings$year_min,
            year_max = settings$year_max,
            x_title = sprintf("Years (%s-%s)", settings$year_min, settings$year_max),
            y_title = "Total Length (Centreline km)",
            legend_title = "Roadway Type",
            type_col = settings$type_col_road,
            type_recode = settings$type_recode_road,
            len_col = "len",
```

```
            line_50km = FALSE,
            line_year = settings$line_year,
            color_low = "#C1DDB3",
            color_high = "#297A22"
        ) +
        theme(
            plot.title = element_text(size = 18),
            plot.margin = margin(0, 0, 0, 0, "pt")
        )

    # Plot arterial, collector, and local road by infra
    rtypes <- c("Arterial", "Collector", "Local")
    for (i in 1:length(rtypes)) {

        # Get road type
        r <- rtypes[i]

        # Create infra plot for road type
        p[[i + 1]] <- calc_yearly_adj_len(
            df %>% filter(road_type == r),
            type_col = settings$type_col_infra
        ) %>%
            plot_yearly_len(
                title = sprintf("%s Roadways", r),
                title_underline = FALSE,
                line_50km = FALSE,
                line_year = settings$line_year,
                year_int = 2,
                x_title = sprintf("Years (%s-%s)", settings$year_min, settings$year_max),
                y_title = "Total Length (Centreline km)",
                year_min = settings$year_min,
                year_max = settings$year_max,
                type_col = settings$type_col_infra,
                type_filter = settings$type_filter_infra,
                type_recode = settings$type_recode_infra,
                legend_title = "Infrastructure Type"
            ) +
            theme(
                plot.title = element_text(size = 14),
                plot.margin = margin(0, 12, 0, 0, "pt")
            )
    }

    # Plot horizontal gradient bar
    grad_bar <-  ggplot(data.frame(x = 1:4), aes(x = x, y = 1, color = x)) +
        geom_line(size = 4) +
        scale_color_gradient(low = "#C1DDB3", high = "#297A22") +
        theme_void() +
        guides(color = FALSE) +
        theme(
            axis.title = element_blank(),
            axis.text = element_blank(),
            axis.ticks = element_blank(),
```

```
            axis.line = element_blank(),
            plot.margin = margin(0, 0, 0, 0, "pt")
        )

    # Plot overall and road type plots together
    out <- ( # overall plot
        plot_spacer() +
        p[[1]] +
        plot_spacer() +
        plot_layout(
            widths = c(0.25, 0.35, 0.2)
        )
    ) / ( # gradient bar
        plot_spacer() +
        grad_bar +
        plot_spacer() +
        plot_layout(widths = c(-0.8, 10, -1.1))
    ) / ( # infra plots
        p[[2]] +
        p[[3]] +
        p[[4]]
    ) + plot_layout(
        heights = c(12, 1, 8)
    ) + plot_annotation( # A B tags
        tag_levels = list(c("A", "", "B", "", ""))
    ) & theme(
        plot.tag = element_text(face = "bold", size = 12)
    )
    return(out)
}
```

Plot Yearly Differences

Plots a bar chart of differences between two columns containing years.

This function is used to check the differences in installation years between the city's data and the verified data.

```
#' Plot Yearly Differences
#'
#' Creates a bar plot of the differences between two years.
#'
#' @param df The data.frame containing the two columns with the years.
#' @param year_col1 The name (char) or index (int) of the first year column.
#' @param year_col2 The name (char) or index (int) of the second year column to be subtracted from.
#' @param year_col1_name The name alias (char) of the first year column year_col1.
#' @param year_col2_name The name alias (char) of the second year column year_col2.
#' @param year_min The minimum year (int) to calculate differences for.
#' @param year_max The maximum year (int) to calculate differences for.
#' @param title The title (char) of the plot.
#' @param title_n Set to TRUE to add the number of total segments considered.
#' @param x_title The title (char) of the x-axis.
#' @param y_title The title (char) of the y-axis.
#' @param x_breaks The number (int) of breaks to show on the x-axis. Set to FALSE to let ggplot automati
```

```r
#' @return A ggplot of yearly differences (year_col2 - year_col1), displaying the proportion of rows fo
#' @export
#'
plot_yearly_diff <- function(
        df,
        year_col1 = "install_year_orig",
        year_col2 = "install_year",
        year_col1_name = "City Year",
        year_col2_name = "Verified Year",
        year_min = settings$year_min,
        year_max = settings$year_max,
        title = sprintf(
            "Difference in Years, Comparing %s and %s",
            year_col1_name,
            year_col2_name
        ),
        title_n = TRUE,
        x_title = sprintf(
            "Difference in Years (%s - %s)",
            year_col2_name,
            year_col1_name
        ),
        y_title = "Proportion of Total Segments",
        x_breaks = 15
) {
    ydiff <- df

    # Filter within min year
    if (year_min) {
        ydiff <- ydiff %>% filter(
            .data[[year_col1]] >= year_min | .data[[year_col2]] >= year_min
        )
    }

    # Filter within max year
    if (year_max) {
        ydiff <- ydiff %>% filter(
            .data[[year_col1]] <= year_max | .data[[year_col2]] <= year_max
        )
    }

    # Add n to title
    if (title_n) {
        title <- sprintf("%s (n=%s)", title, nrow(ydiff))
    }

    # Calc yearly diff
    ydiff <- ydiff %>%
        mutate(year_diff = install_year - install_year_orig) %>%
        count(year_diff)

    # Plot yealy diffs
    out <- ydiff %>%
```

```
        ggplot(aes(
            x = year_diff,
            y = (n / sum(n)) * 100
        )) +
        geom_bar(
            stat = "identity",
            color = "#332a94",
            fill = "#c3d5e4",
            width = 1
        ) +
        labs(
            title = title,
            x = x_title,
            y = y_title
        ) +
        scale_y_continuous(
            label = scales::label_number(suffix = "%")
        ) +
        theme(
            plot.title = element_text(size = 12)
        )

    # Set x interval breaks
    if (x_breaks) {
        out <- out + scale_x_continuous(
            breaks = scales::breaks_pretty(x_breaks)
        )
    }
    return(out)
}
```

Data

Vancouver Data

```
# Load raw data
vanc_bikeways <- read_csv("../data/vancouver_bikeways_2009_2022_v1.csv")
```

```
## Rows: 745 Columns: 89
## -- Column specification --------------------------------------------------------
## Delimiter: ","
## chr (73): bike_rout0, street_na0, bikeway_t0, subtype, status, street_se0, o...
## dbl (16): OID_, object_id, speed_lim0, year_of_c0, upgrade_y0, ID_DATAENTRY,...
##
## i Use `spec()` to retrieve the full column specification for this data.
## i Specify the column types or set `show_col_types = FALSE` to quiet this message.
```

```
vanc_roads <- read_csv("../data/vancouver_roads_2009_2022_v1.csv")
```

```
## Rows: 780 Columns: 72
## -- Column specification --------------------------------------------------------
## Delimiter: ","
## chr (61): ID_ROUTE, DPR_CHECK_FLAG, DPR_ENTRY, DPR_EXCL_FLAG, DPR_EXCL1318_R...
## dbl (11): ID_CITY, ID_DATAENTRY, DPR_ORDER, ATR_SEGMENT_LENGTH, ATR_SPEEDLIM...
```

```
##
## i Use `spec()` to retrieve the full column specification for this data.
## i Specify the column types or set `show_col_types = FALSE` to quiet this message.
```

```r
# Combine raw data
vanc <- vanc_bikeways %>%
    select(
        ID_DATAENTRY,
        INST_YR_ORIG,
        INST_YR,
        INST_MIN_HTYPE,
        UPGR1_YR,
        UPGR1_MIN_HTYPE,
        UPGR2_YR,
        UPGR2_MIN_TYPE,
        ATR_SEGMENT_LENGTH
    ) %>%
    left_join(
        vanc_roads %>% select(
            ID_DATAENTRY,
            ATR_SEGMENT_TYPE
        ),
        by = "ID_DATAENTRY"
    ) %>%
    rename(
        id = ID_DATAENTRY,
        install_year_orig = INST_YR_ORIG,
        install_year = INST_YR,
        install_type = INST_MIN_HTYPE,
        upgrade1_year = UPGR1_YR,
        upgrade1_type = UPGR1_MIN_HTYPE,
        upgrade2_year = UPGR2_YR,
        upgrade2_type = UPGR2_MIN_TYPE,
        segment_len = ATR_SEGMENT_LENGTH,
        segment_type = ATR_SEGMENT_TYPE
    ) %>%
    mutate(
        segment_len = segment_len / 1000,
        road_type = case_when( # create road types
            segment_type %in% c( # arterial equiv
                "Arterial"
            ) ~ "Arterial",
            segment_type %in% c( # collector equiv
                "Collector",
                "Secondary Arterial",
                "Sec Arterial"
            ) ~ "Collector",
            segment_type %in% c( # local equiv
                "Lane",
                "Residential",
                "Leased",
                "Recreational"
            ) ~ "Local",
            .default = segment_type
```

```
        )
    )
vanc
```

```
## # A tibble: 745 x 11
##       id install_year_orig install_year install_type upgrade1_year upgrade1_type
##    <dbl>             <dbl>        <dbl> <chr>                <dbl> <chr>
##  1   775              2014         2014 PBL                     NA <NA>
##  2   774              2014         2014 PBL                     NA <NA>
##  3   773              1999         1999 None                  2021 PBL
##  4   770              2015         2015 PL                      NA <NA>
##  5   769              2015         2015 PL                      NA <NA>
##  6   768              2015         2015 PL                      NA <NA>
##  7   767              2015         2015 PL                      NA <NA>
##  8   766              2015         2015 PL                      NA <NA>
##  9   765              2015         2015 PL                      NA <NA>
## 10   764              2015         2015 PL                      NA <NA>
## # i 735 more rows
## # i 5 more variables: upgrade2_year <dbl>, upgrade2_type <chr>,
## #   segment_len <dbl>, segment_type <chr>, road_type <chr>
```

Calgary Data

```
# Load raw data
calg_bikeways <- read_csv("../data/calgary_bikeways_2009_2022_v1.csv")
```

```
## Rows: 750 Columns: 54
## -- Column specification --------------------------------------------------------
## Delimiter: ","
## chr  (41): STATUS, TYPE, BICYCLE_CLASS, COMFORT_LEVEL, CURRENT_TYPE_VERIFIED...
## dbl  (11): ORIG_ID, ATR_SEGMENT_LENGTH, INST_YR, UPGR2_YR, SHAPE_ID, STARTIN...
## date  (2): CREATED_DT, MODIFIED_DT
##
## i Use `spec()` to retrieve the full column specification for this data.
## i Specify the column types or set `show_col_types = FALSE` to quiet this message.
```

```
calg_roads <- read_csv("../data/calgary_roads_2009_2022_v1.csv")
```

```
## Rows: 4170 Columns: 39
## -- Column specification --------------------------------------------------------
## Delimiter: ","
## chr  (18): status, type, bicycle_cl, comfort_le, date_creat, date_modif, ful...
## dbl  (15): OID_, len_m, lenm, startx, starty, endx, endy, shape_id, OBJECTID...
## lgl   (1): length
## time  (5): time_creat, time_modif, time_creat_1, time_modif_1, time_mod_2
##
## i Use `spec()` to retrieve the full column specification for this data.
## i Specify the column types or set `show_col_types = FALSE` to quiet this message.
```

```
# Combine raw data
calg <- calg_bikeways %>%
    select(
        SHAPE_ID,
        YEAR_ORIG,
        INST_YR,
```

```
        INST_MIN_HTYPE,
        UPGR1_YR,
        UPGR1_MIN_HTYPE,
        UPGR2_YR,
        UPGR2_MIN_HTYPE,
        ATR_SEGMENT_LENGTH
    ) %>%
    left_join(
        calg_roads %>% select(
            shape_id,
            ctp_class
        ),
        by = join_by(SHAPE_ID == shape_id)
    ) %>%
    rename(
        id = SHAPE_ID,
        install_year_orig = YEAR_ORIG,
        install_year = INST_YR,
        install_type = INST_MIN_HTYPE,
        upgrade1_year = UPGR1_YR,
        upgrade1_type = UPGR1_MIN_HTYPE,
        upgrade2_year = UPGR2_YR,
        upgrade2_type = UPGR2_MIN_HTYPE,
        segment_len = ATR_SEGMENT_LENGTH,
        segment_type = ctp_class
    ) %>%
    mutate(
        segment_len = segment_len / 1000,
        road_type = case_when( # create road types
            segment_type %in% c( # arterial equiv
                "Arterial Street",
                "Industrial Arterial",
                "Local Arterial",
                "Parkway",
                "Urban Boulevard"
            ) ~ "Arterial",
            segment_type %in% c( # collector equiv
                "Neighbourhood Boulevard",
                "Collector",
                "Primary Collector",
                "Skeletal Road"
            ) ~ "Collector",
            segment_type %in% c( # local equiv
                "Access Route",
                "Residential Street",
                "Activity Center Street",
                "Historic Road Allowance",
                "Lanes (Alleys)",
                "Industrial Street"
            ) ~ "Local",
            .default = segment_type
        )
    )
```

```
calg
```

```
## # A tibble: 750 x 11
##       id install_year_orig install_year install_type upgrade1_year upgrade1_type
##    <dbl>              <dbl>        <dbl> <chr>        <chr>         <chr>
##  1   498                 NA         2011 PL           <NA>          <NA>
##  2   497                 NA         2011 PL           <NA>          <NA>
##  3   499                 NA         2011 PL           <NA>          <NA>
##  4   493               2013         2012 None         2015          PL
##  5  1574               2014         2014 PL           <NA>          <NA>
##  6  1572               2014         2014 PL           <NA>          <NA>
##  7   671                 NA         2009 PL           <NA>          <NA>
##  8  2549               2021         2021 PBL          <NA>          <NA>
##  9  2558               2021         2021 PBL          <NA>          <NA>
## 10  2560               2021         2021 PBL          <NA>          <NA>
## # i 740 more rows
## # i 5 more variables: upgrade2_year <dbl>, upgrade2_type <chr>,
## #   segment_len <dbl>, segment_type <chr>, road_type <chr>
```

Toronto Data

```
# Load raw data
toron_bikeways <- read_csv("../data/toronto_bikeways_2009_2022_v1.csv")
```

```
## Rows: 326 Columns: 53
## -- Column specification --------------------------------------------------------
## Delimiter: ","
## chr  (35): CITY_INFRA_HIGHORDER, CITY_INFRA_LOWORDER, STREET_NAME, FROM_STRE...
## dbl  (16): ID_OID, ID_DATAENTRY, ID_1_OBJ2, OBJECTID, CITY_INST_YR, CITY_UPG...
## lgl   (1): DPR_EXCL_FLAG
## dttm  (1): CITY_LAST_REVIEWED
##
## i Use `spec()` to retrieve the full column specification for this data.
## i Specify the column types or set `show_col_types = FALSE` to quiet this message.
```

```
toron_roads <- read_csv("../data/toronto_roads_2009_2022_v1.csv")
```

```
## Rows: 331 Columns: 59
## -- Column specification --------------------------------------------------------
## Delimiter: ","
## chr  (14): STREET_7, FROM_ST8, TO_STRE9, INFRA_L15, INFRA_H20, LINEAR_26, LI...
## dbl  (28): OID_, _id1, OBJECTI2, SEGMENT3, INSTALL4, UPGRADE5, CONVERT28, st...
## lgl  (16): PRE_AMA6, ROADCLA10, CNPCLAS11, SURFACE12, OWNER13, DIR_LOW14, SE...
## dttm  (1): LAST_ED26
##
## i Use `spec()` to retrieve the full column specification for this data.
## i Specify the column types or set `show_col_types = FALSE` to quiet this message.
```

```
# Combine raw data
toron <- toron_bikeways %>%
    select(
        ID_OID,
        INSTALLED_ORIG,
        INST_YR,
        INST_MIN_HTYPE,
```

```
        UPGR1_YR,
        UPGR1_MIN_HTYPE,
        UPGR2_YR,
        UPGR2_MIN_HTYPE,
        ATR_SEGMENT_LENGTH
    ) %>%
    left_join(
        toron_roads %>% select(
            OID_,
            FEATURE36
        ),
        by = join_by(ID_OID == OID_)
    ) %>%
    rename(
        id = ID_OID,
        install_year_orig = INSTALLED_ORIG,
        install_year = INST_YR,
        install_type = INST_MIN_HTYPE,
        upgrade1_year = UPGR1_YR,
        upgrade1_type = UPGR1_MIN_HTYPE,
        upgrade2_year = UPGR2_YR,
        upgrade2_type = UPGR2_MIN_HTYPE,
        segment_len = ATR_SEGMENT_LENGTH,
        segment_type = FEATURE36
    ) %>%
    mutate(
        segment_len = segment_len / 1000,
        road_type = case_when( # create road types
            segment_type %in% c( # arterial equiv
                "Major Arterial",
                "Major Arterial Ramp",
                "Minor Arterial"
            ) ~ "Arterial",
            segment_type %in% c( # collector equiv
                "Collector"
            ) ~ "Collector",
            segment_type %in% c(  # local equiv
                "Local",
                "Other"
            ) ~ "Local",
            .default = segment_type
        )
    )
toron
```

```
## # A tibble: 326 x 11
##       id install_year_orig install_year install_type upgrade1_year upgrade1_type
##    <dbl>             <dbl>        <dbl> <chr>                <dbl> <chr>
##  1  1133              2015         2015 PBL                   2020 PBL
##  2  1136              2015         2015 PL                    2020 PL
##  3  1135              2015         2015 BUF                   2020 BUF
##  4  1134              2014         2014 PBL                   2020 PBL
##  5  1004                NA         2009 PL                      NA <NA>
##  6  1009              2009         2009 PL                      NA <NA>
```

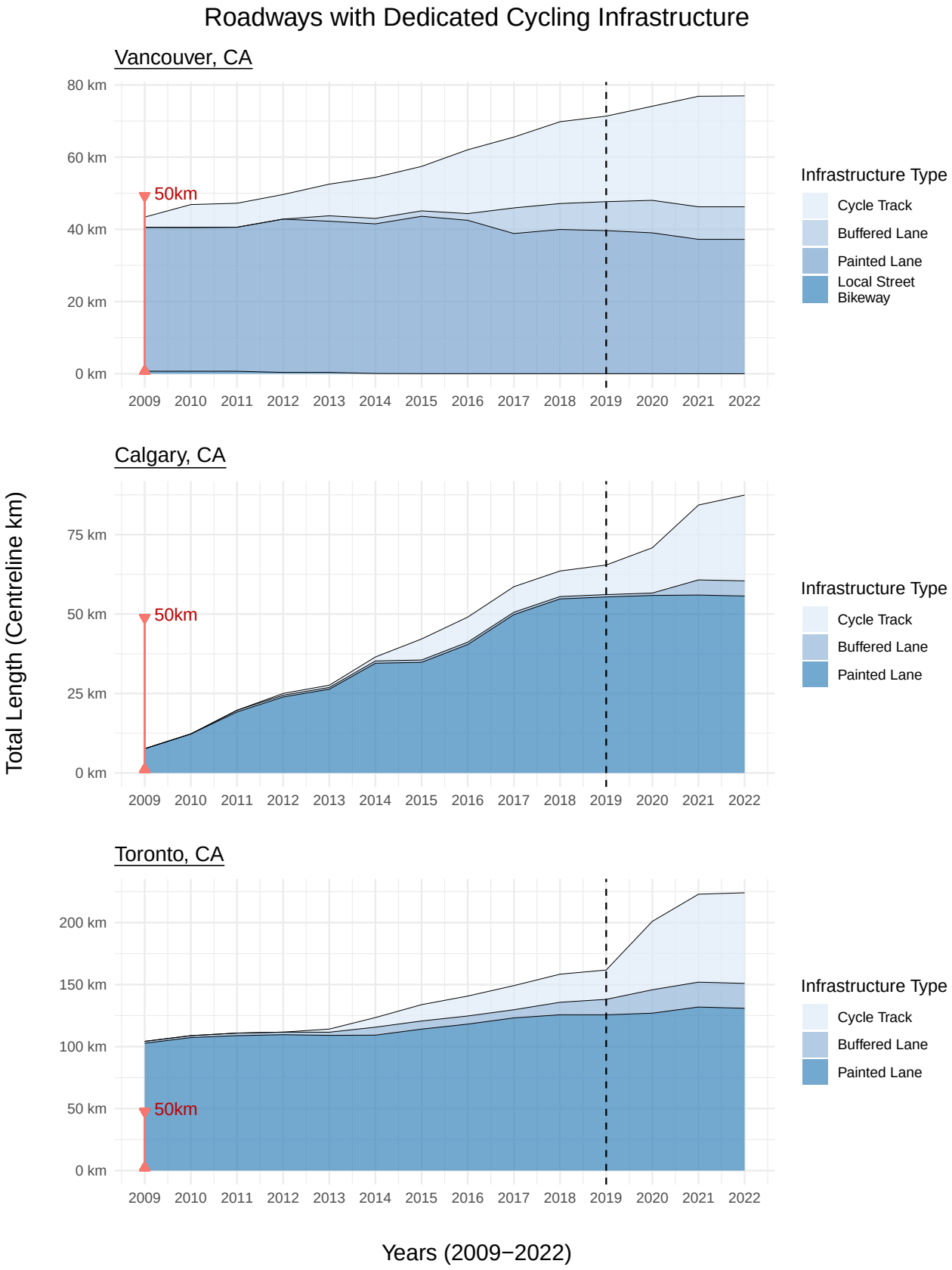
```
##  7  1220              2015         2015 None                  2020 PL
##  8  1229              2015         2015 None                  2020 PL
##  9  1230              2015         2015 PL                      NA <NA>
## 10  1145              2015         2015 PL                      NA <NA>
## # i 316 more rows
## # i 5 more variables: upgrade2_year <dbl>, upgrade2_type <chr>,
## #   segment_len <dbl>, segment_type <chr>, road_type <chr>
```

Figures

Figure 2: Changes in dedicated cycling infrastructure between 2009 and 2022 for Vancouver, Calgary, and Toronto by infrastructure category.

Assessed using roadway centreline-km, with infrastructure classifications determined by the most protective element present along each road segment.

```
plot_yearly_len_infra(list(
    "Vancouver, CA" = vanc,
    "Calgary, CA" = calg,
    "Toronto, CA" = toron
))
```

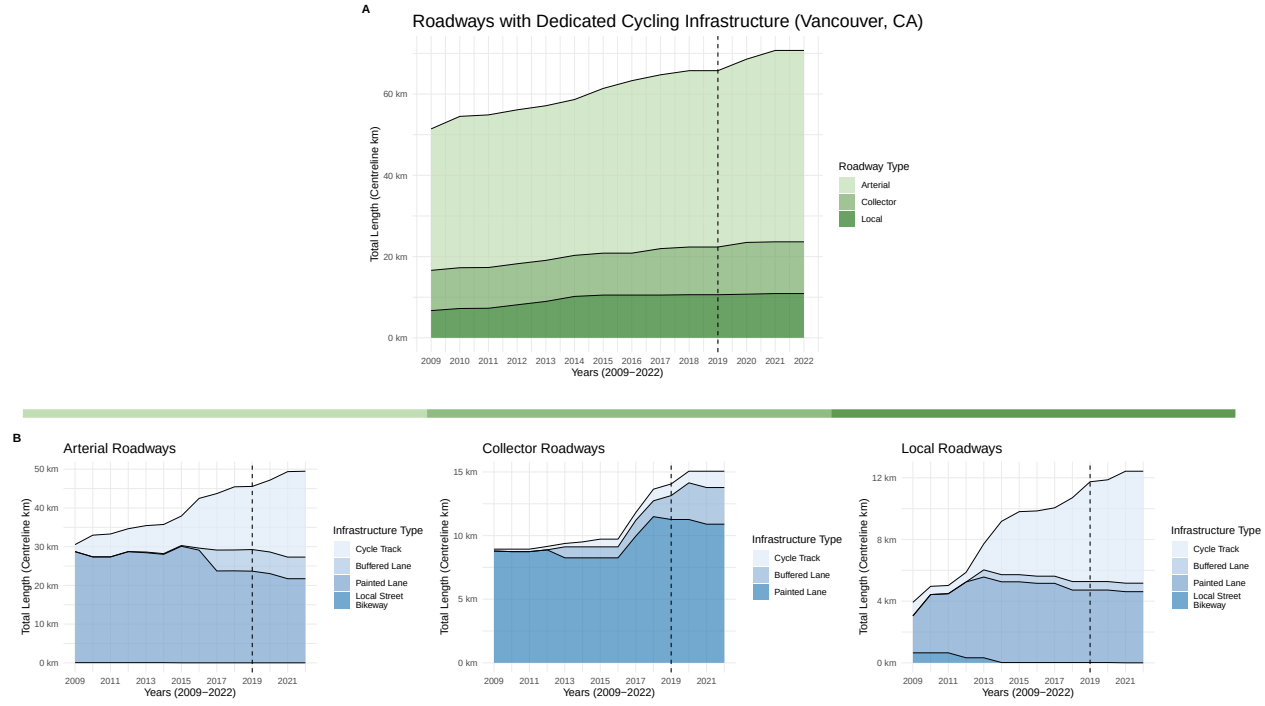

Roadways with Dedicated Cycling Infrastructure
Vancouver, CA
80 km
60 km
40 km
20 km
0 km
50km
2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022
Infrastructure Type
Cycle Track
Buffered Lane
Painted Lane
Local Street Bikeway
Calgary, CA
75 km
50 km
25 km
0 km
50km
2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022
Infrastructure Type
Cycle Track
Buffered Lane
Painted Lane
Toronto, CA
200 km
150 km
100 km
50 km
0 km
50km
2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022
Infrastructure Type
Cycle Track
Buffered Lane
Painted Lane
Total Length (Centreline km)
Years (2009−2022)

Appendix 1 - Supplementary Results

Supplementary Figure 4: Changes in dedicated cycling infrastructure between 2009 and 2021 for the Municipality of Vancouver, CA.

By (A) roadway classification, and (B) infrastructure distribution within each road class. Assessed using roadway centreline-km, with infrastructure classification determined by the most protective element present along each road segment.

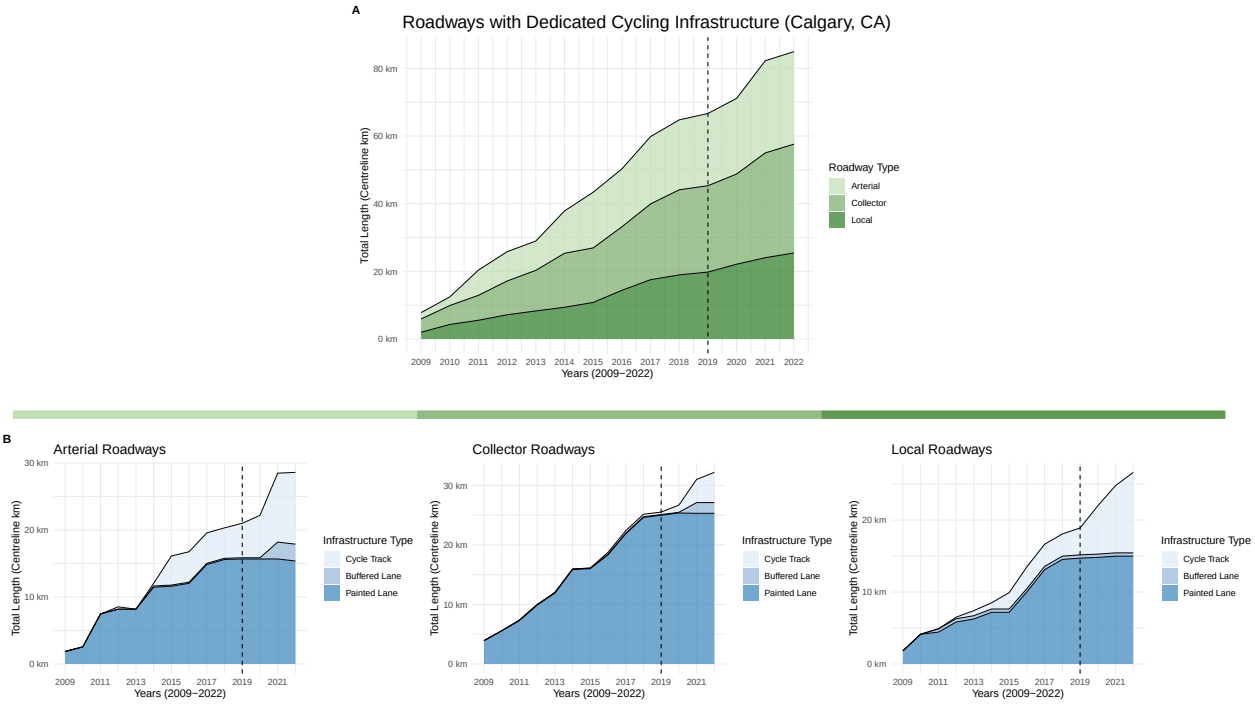
```
plot_yearly_len_road(
    vanc,
    title = "Roadways with Dedicated Cycling Infrastructure (Vancouver, CA)"
)
```



Supplementary Figure 5: Changes in dedicated cycling infrastructure between 2009 and 2022 for the Municipality of Calgary, CA.

By (A) roadway classification, and (B) infrastructure distribution within each road class. Assessed using roadway centreline-km, with infrastructure classification determined by the most protective element present along each road segment.

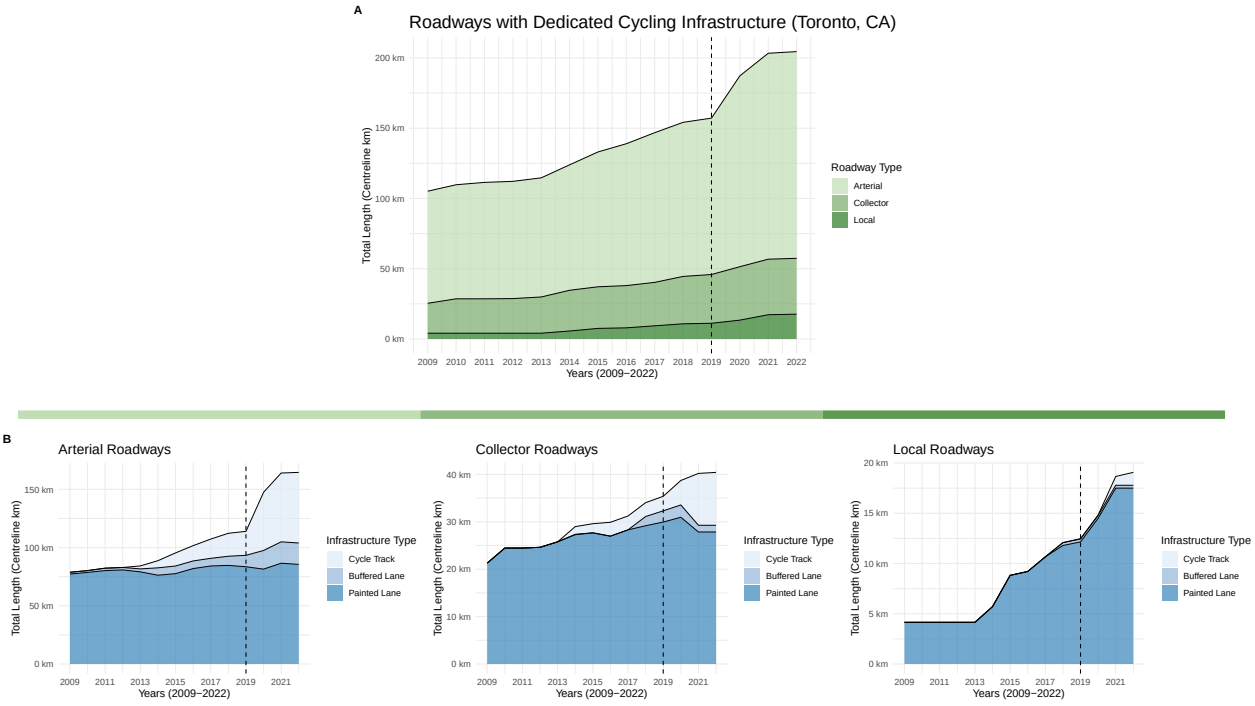
```
plot_yearly_len_road(
    calg,
    title = "Roadways with Dedicated Cycling Infrastructure (Calgary, CA)"
)
```



Supplementary Figure 6: Changes in dedicated cycling infrastructure between 2009 and 2022 for the Municipality of Toronto, CA.

By (A) roadway classification, and (B) infrastructure distribution within each road class. Assessed using roadway centreline-km, with infrastructure classification determined by the most protective element present along each road segment.

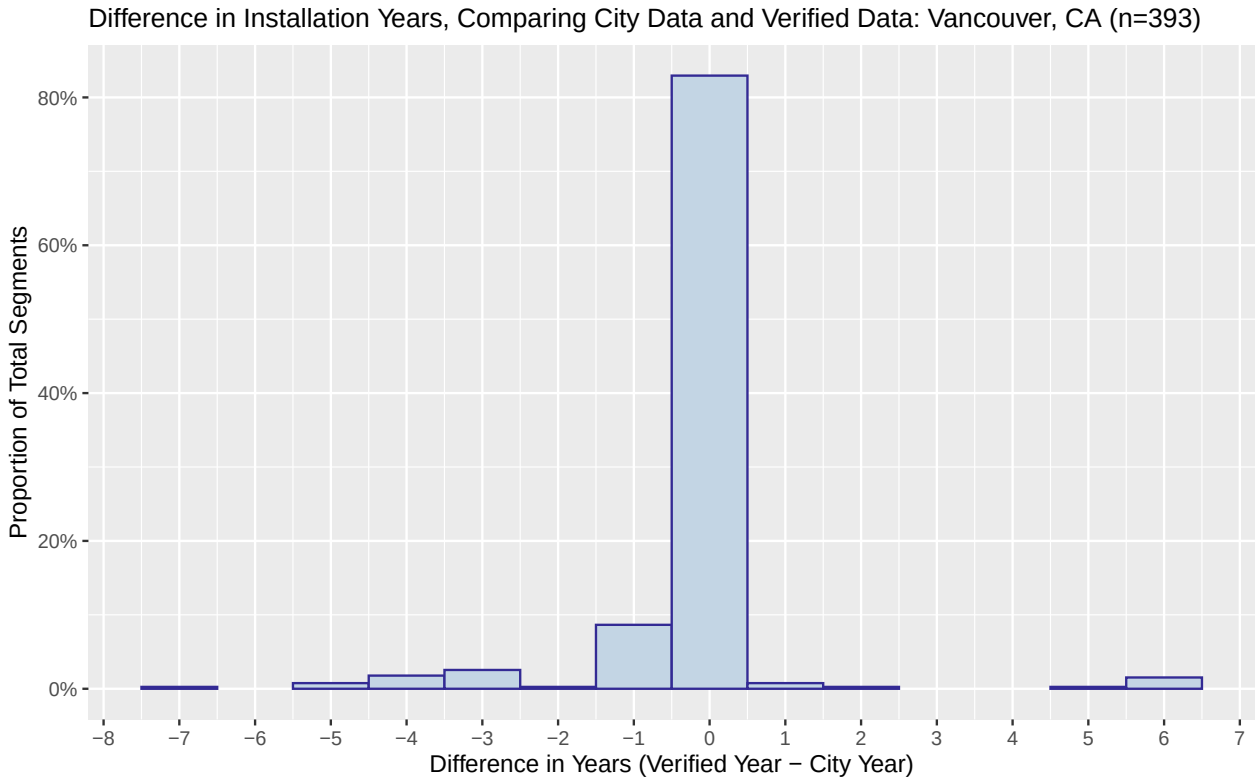
```
plot_yearly_len_road(
    toron,
    title = "Roadways with Dedicated Cycling Infrastructure (Toronto, CA)"
)
```



Supplementary Figure 7: A comparative analysis between municipal data and verified data on the installation years for cycling infrastructure in Vancouver, CA.

Any data where a city provided installation year was missing or the verified year occurred earlier than the start of the study period (2009) has been excluded from analysis, yielding n = 252 segments. The graph shows that 83.3% of the included segments had the correct installation year as per the city's data, and 97.6% were accurate within a range of ±1 year.

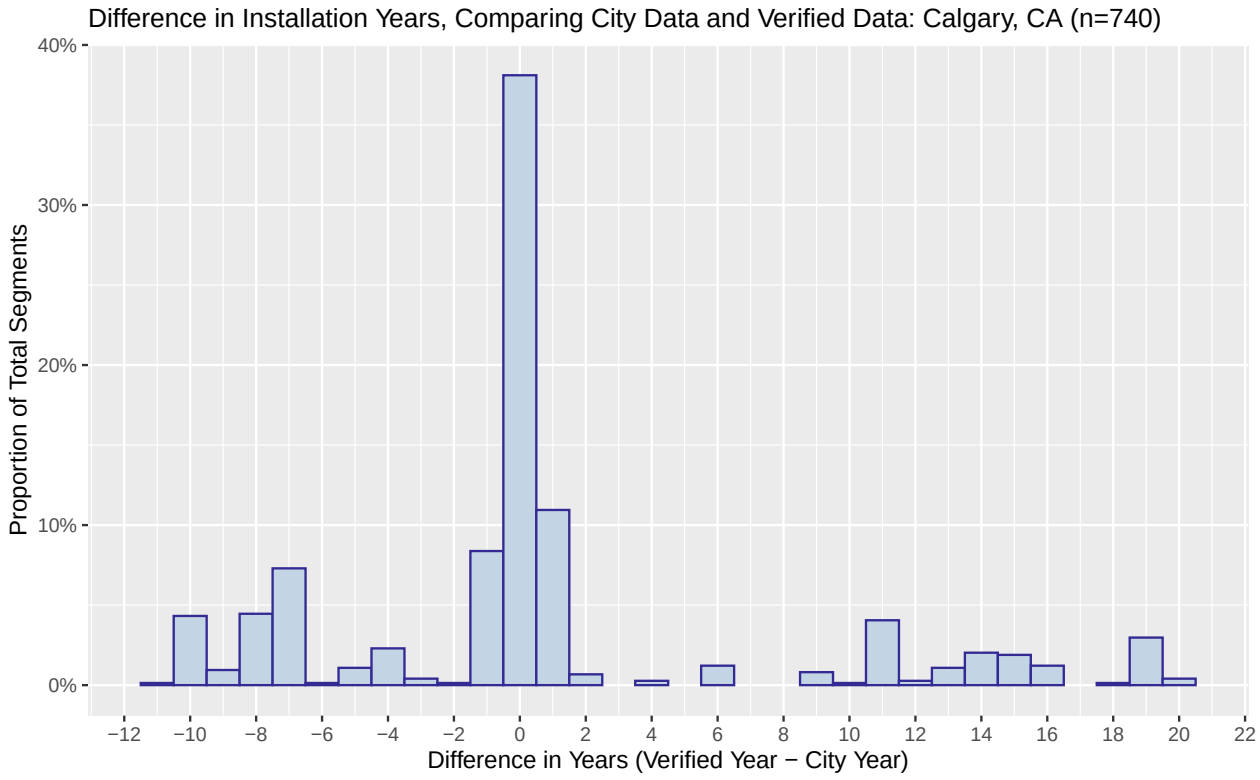
```
plot_yearly_diff(
    vanc,
    title = "Difference in Installation Years, Comparing City Data and Verified Data: Vancouver, CA"
)
```



Supplementary Figure 8: A comparative analysis between municipal data and verified data on the installation years for cycling infrastructure in Calgary, CA.

Any data where a city provided installation year was missing or the verified year occurred earlier than the start of the study period (2009) has been excluded from analysis, yielding n=670 segments. The graph shows that 42.1% of the included segments had the correct installation year as per the city's data, and 62.8% were accurate within a range of ±1 year.

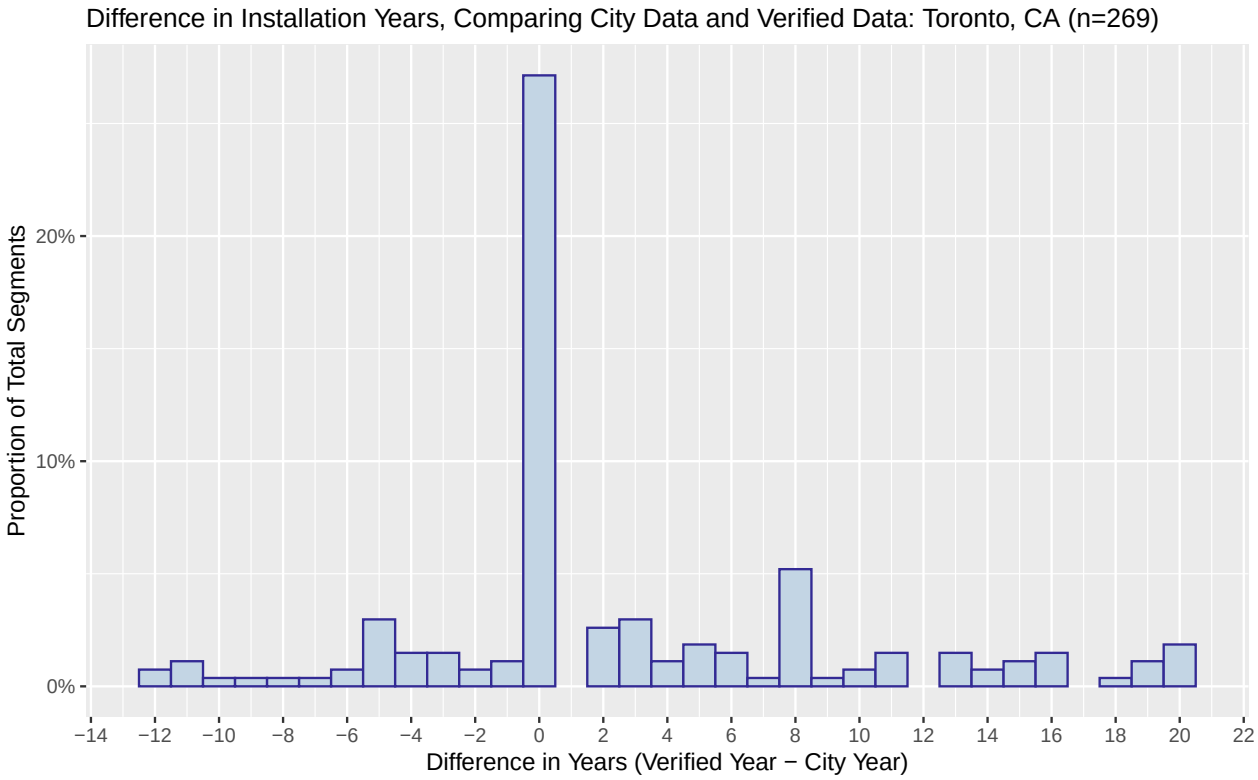
```
plot_yearly_diff(
    calg,
    title = "Difference in Installation Years, Comparing City Data and Verified Data: Calgary, CA"
)
```



Supplementary Figure 9: A comparative analysis between municipal data and verified data on the installation years for cycling infrastructure in Toronto, CA.

Any data where a city provided installation year was missing or the verified year occurred than the start of the study period (2009) has been excluded from analysis, yielding n=192 segments. The graph shows that 75.5% of the included segments had the correct installation year as per the city's data, and 78.1% were accurate within a range of ±1 year.

```
plot_yearly_diff(
    toron,
    title = "Difference in Installation Years, Comparing City Data and Verified Data: Toronto, CA"
)
```



Miscellaneous Details

R Version

R and RMarkdown in RStudio was used to generate this document.

```
##                _
## platform       x86_64-apple-darwin20
## arch           x86_64
## os             darwin20
## system         x86_64, darwin20
## status
## major          4
## minor          3.1
## year           2023
## month          06
## day            16
## svn rev        84548
## language       R
## version.string R version 4.3.1 (2023-06-16)
## nickname       Beagle Scouts
```

R Code

The R script below runs all the code in this document.

```
knitr::opts_chunk$set(warning = FALSE)
install.packages("rmarkdown")
install.packages("bookdown")
```

```r
install.packages("knitr")
install.packages("tidyverse")
install.packages("glue")
install.packages("readxl")
install.packages("ggtext")
install.packages("scales")
install.packages("patchwork")
library(tidyverse)
library(ggtext)
library(glue)
library(patchwork)
library(readxl)
settings <- list()

# Infrastructure types in order
settings$type_recode_infra <- c(
    PBL = "Cycle Track",
    BUF = "Buffered Lane",
    PL = "Painted Lane",
    LSB = "Local Street\nBikeway"
)

# Infrastructure types to remove
settings$type_filter_infra <- c("N", "None", "SR")

# Road types in order
settings$type_recode_road <- c(
    Arterial = "Arterial",
    Collector = "Collector",
    Local = "Local"
)

# Column references
settings$year_col_road <- "install_year"
settings$type_col_road <- "road_type"
settings$type_col_infra <- "infra_type"

# Set years of interest
settings$year_min <- 2009
settings$year_max <- 2022

# Plot settings
settings$line_year <- 2019

#' Calculate Yearly Road Lengths By Infrastructure Type
#'
#' Calculates the cumulative yearly road lengths by infrastructure type without considering infrastructu
#'
#' @param df A data.frame with three columns containing the year, type, and road lengths.
#' @param year_col The name (char) or index (int) of the column containing the years.
#' @param type_col The name (char) or index (int) of the column containing the infrastructure type
#' @param len_col The name (char) or index (int) of the column containing the road lengths.
#' @param out_col The name (char) of the column containing the calculated yearly road lengths by type.
```

```r
#'
#' @return A data.frame with three columns containing the year, type, and calculated yearly road lengths
#' @export
#'
calc_yearly_len <- function(
        df,
        year_col = "install_year",
        type_col = "install_type",
        len_col = "segment_len",
        out_col = "len",
        year_min = settings$year_min,
        year_max = settings$year_max
    ) {

    # Convert data types
    df[[year_col]] <- as.integer(df[[year_col]])
    df[[type_col]] <- as.character(df[[type_col]])
    df[[len_col]] <- as.numeric(df[[len_col]])

    # Remove rows with empty type
    out <- df %>% filter(
        !is.na(.data[[type_col]])
    )

    # Filter to min and max years
    if (year_min > 0) {
        df <- df %>% filter(
            .data[[year_col]] >= year_min
        )
    } else {
        year_min <- min(out[[year_col]], na.rm = TRUE)
    }
    if (year_max > 0) {
        df <- df %>% filter(
            .data[[year_col]] <= year_max
        )
    } else {
        year_max <- max(out[[year_col]], na.rm = TRUE)
    }

    # Add dummy len for each type and year combo
    # Covers cases where type and year combo does not exist
    # E.g. No new PL installs in 2021, hence a record PL in 2021 does not exist
    type_uniq <- unique(out[[type_col]])
    type_n <- length(type_uniq)
    year_uniq <- year_min:year_max
    year_n <- length(year_uniq)
    out <- out %>% add_row(
        !!year_col := rep(year_uniq, each = type_n),
        !!type_col := rep(type_uniq, year_n),
        !!len_col := rep(0, type_n * year_n)
    )
```

```
    # Calc cumsum for each non-empty type ordered by year
    out <- out %>%
        arrange(.data[[year_col]]) %>%
        group_by(.data[[type_col]]) %>%
        mutate(
            !!out_col := cumsum(.data[[len_col]])
        )

    # Get the last cumsum for each year and type
    out <- out %>%
        group_by(.data[[year_col]], .data[[type_col]]) %>%
        arrange(desc(row_number())) %>%
        slice(1)

    # Return only the columns spec
    out <- out %>% select(c(
            year_col,
            type_col,
            out_col
        ))
    return(out)
}

#' Calculate Yearly Adjusted Road Lengths By Infrastructure Type
#'
#' Calculates the cumulative yearly adjusted road lengths by infrastructure type accounting for installa
#'
#' @param df A data.frame with three columns containing the year, type, and road lengths.
#' @param year_cols A vector of the names (char) or indices (int) of the columns containing the years o
#' @param type_cols A vector of the names (char) or indices (int) of the columns containing the infrast
#' @param type_col The name (char) of the column containing the type.
#' @param len_cols A vector of the names (char) or indices (int) of the columns containing the road leng
#' @param out_cols The name (char) of the column containing the calculated yearly road lengths by type.
#' @param out_col The name (char) of the column containing the calculated yearly adjusted road lengths b
#' @param repl_suffix A suffix (char) to append to the columns representing the road lengths of replaced
#' @param ... Additional arguments passed to calc_yearly_len.
#'
#' @return A data.frame with columns containing the year, type, cumulative road lengths of installations
#' @export
#'
calc_yearly_adj_len <- function(
        df,
        year_cols = c("install_year", "upgrade1_year", "upgrade2_year"),
        type_cols = c("install_type", "upgrade1_type", "upgrade2_type"),
        type_col = "type",
        len_cols = "segment_len",
        out_cols = c("install_len", "upgrade1_len", "upgrade2_len"),
        out_col = "adj_len",
        repl_suffix = "_replaced",
        ...
    ) {

    # Convert len_col if char
```

```
    len_cols <- rep(len_cols, length(year_cols))

    # Check cols same size
    year_cols_n <- length(year_cols)
    type_cols_n <- length(type_cols)
    len_cols_n <- length(len_cols)
    out_cols_n <- length(out_cols)
    if (length(unique(c(year_cols_n, type_cols_n, len_cols_n, out_cols_n))) != 1) {
        stop(glue(
            "The arguments 'year_cols' ({year_cols_n}), 'type_cols' ({type_cols_n}), 'len_cols' ({len_c
        ))
    }

    # Calc yearly lens by infra type per install or change
    out <- list()
    for (i in 1:length(year_cols)) {

        # Get year, type, and len cols
        ycol <- year_cols[[i]]
        tcol <- type_cols[[i]]
        lcol <- len_cols[[i]]
        ocol <- out_cols[[i]]

        # Calc yearly len for install or change
        out <- append(
            out,
            calc_yearly_len(
                df,
                year_col = ycol,
                type_col = tcol,
                len_col = lcol,
                out_col = ocol,
                ...
            ) %>%
                rename(
                    "year" := !!ycol,
                    "type" := !!tcol
                ) %>% list
        )

        # Calc yearly len for replacement
        if (i > 1) {

            # Get repl cols
            tcol_repl <- type_cols[[i - 1]]
            lcol_repl <- len_cols[[i - 1]]

            # Filter for repl records only where type is not eq to change type
            df_repl <- df %>% filter(.data[[tcol]] != .data[[tcol_repl]])

            # Calc repl len if there are any changes
            has_change <- !is.na(df_repl[[tcol]]) %>% all
            if (has_change) {
```

```
                out <- append(
                    out,
                    calc_yearly_len(
                        df_repl,
                        year_col = ycol,
                        type_col = tcol_repl,
                        len_col = lcol_repl,
                        out_col = glue("{ocol}{repl_suffix}"),
                        ...
                    ) %>%
                    rename(
                        "year" := !!ycol,
                        "type" := !!tcol_repl
                    ) %>% list
                )
            }
        }
    }

    # Combine all lens in list to single df
    out <- out %>%
        reduce(
            left_join, by = c("year", "type")
        ) %>%
        ungroup()

    # Create template for change and repl cols
    change_cols <- paste0(out_cols[2:out_cols_n])# change cols
    change_cols <- c(change_cols, paste0(out_cols[2:out_cols_n], repl_suffix)) # repl cols
    change_cols_add <- rep(0, length(change_cols)) # set default vals
    names(change_cols_add) <- change_cols

    # Add change and repl cols set to 0 if not present
    out <- out %>% add_column(
        !!!change_cols_add[setdiff(names(change_cols_add), names(.))]
    )

    # Set NA to 0
    out <- out %>% mutate(
        across(everything(), ~replace_na(., 0))
    )

    # Calc yearly adj lens by infra type
    out <- out %>%
        mutate( # added len by infra types due to install or changes
            !!out_col := reduce(across(all_of(out_cols)), `+`)
        ) %>%
        mutate( # removed len by infra types due to replacements
            !!out_col := .data[[out_col]] - reduce(
                across(all_of(
                    paste0(out_cols[2:out_cols_n], repl_suffix)
                )),
                `_`
```

```
            )
        )

    # Rename type col
    out <- out %>% rename(!!type_col := type)
    return(out)
}

#' Plot Yearly Road Lengths By Type
#'
#' Creates an area plot of road lengths by category types.
#'
#' @param df A data.frame with three columns containing the year, type, and road lengths.
#' @param title The title (char) of the plot.
#' @param title_underline Set to TRUE to underline the title.
#' @param x_title The title (char) of the x-axis.
#' @param y_title The title (char) of the y-axis.
#' @param y_suffix The suffix (char) to add to the end of y axis values.
#' @param legend_title The title (char) of the legend.
#' @param legend Set to TRUE to include a legend.
#' @param year_col The name (char) or index (int) of the column containing the years.
#' @param year_min The minimum year (int) to display.
#' @param year_max The maximum year (int) to display.
#' @param year_int The year intervals (int) to display. For example, 1 displays every year, and 2 displa
#' @param len_col The name (char) or index (int) of the column containing the road lengths.
#' @param type_col The name (char) or index (int) of the column containing the type.
#' @param type_filter A vector (char) of types to remove fomr the plot.
#' @param type_recode A named vector (char) of names representing types and values representing the valu
#' @param line_50km Set to TRUE to draw the 50 km red reference line.
#' @param line_year Set to a year (int) to draw a reference line for a year. If FALSE, a line will not b
#' @param color_low The bottom color (char) of the type.
#' @param color_high The top color (char) of the type.
#' @return An area ggplot of the cumulative yearly road lengths by type.
#' @export
#'
plot_yearly_len <- function(
        df,
        title = "",
        title_underline = TRUE,
        x_title = "",
        y_title = "",
        y_suffix = " km",
        legend_title = "Type",
        legend = TRUE,
        year_col = "year",
        year_min = FALSE,
        year_max = FALSE,
        year_int = 1,
        len_col = "adj_len",
        type_col = "type",
        type_filter = c(),
        type_recode = c(),
        line_50km = FALSE,
```

```
        line_year = FALSE,
        color_low = "#DFEBF7",
        color_high = "#3683BB"
) {

    # Filter to start and end years
    if (year_min > 0) {
        df <- df %>% filter(
            .data[[year_col]] >= year_min
        )
    }
    if (year_max > 0) {
        df <- df %>% filter(
            .data[[year_col]] <= year_max
        )
    }

    # Filter out particular infrastructure types
    if (length(type_filter) > 0) {
        df <- df %>% filter(
            !.data[[type_col]] %in% type_filter
        )
    }

    # Recode and reorder category types
    if (length(type_recode) > 0) {

        # Reorder category types
        type_uniq <- unique(df[[type_col]])
        type_reorder <- names(type_recode)
        type_reorder <- c(type_reorder, type_uniq[!type_uniq %in% type_reorder])
        df[[type_col]] <- factor(df[[type_col]], levels = type_reorder)

        # Recode category types
        df[[type_col]] <- recode(df[[type_col]], !!!type_recode)
    }

    # Create fill colors
    type_n <- length(type_uniq)
    type_colors <- scales::seq_gradient_pal(
        color_low,
        color_high
    )(seq(0, 1, length.out = type_n))

    # Create base area plot with legend and labels
    len_max <- max(df[[len_col]], na.rm = TRUE)
    year_max <- max(df[[year_col]], na.rm = TRUE)
    out <- ggplot(
        df,
        aes(
            x = .data[[year_col]],
            y = .data[[len_col]],
            fill = .data[[type_col]],
```

```
            order = desc(.data[[type_col]])
        )
    ) +
    geom_area(colour = NA, alpha = 0.7) +
    scale_fill_manual(values = type_colors) +
    geom_line(
        position = "stack",
        size = 0.2
    ) +
    labs(
        x = x_title,
        y = y_title,
        fill = legend_title
    ) +
    guides(
        fill = FALSE,
        color = FALSE
    ) +
    scale_x_continuous(
        breaks = seq(year_min, year_max, by = year_int),
        labels = seq(year_min, year_max, by = year_int),
        limits = c(year_min, year_max)
    ) +
    scale_y_continuous(
        label = scales::label_number(suffix = y_suffix)
    ) +
    theme_minimal() +
    theme(
        plot.margin = unit(c(5,5,5,5), "points")
    )

    # Add title
    if (title_underline) {
        out <- out + ggtitle(
            bquote(underline(.(title)))
        )
    } else {
        out <- out + ggtitle(title)
    }

    # Add legend
    if (legend) {
        out <- out + guides(fill = guide_legend(
            reverse = FALSE,
            override.aes = list(
                alpha = 0.7,
                color = NA,
                shape = NA
            )
        ))
    }

    # Add dotted year ref line
```

```
    if (line_year) {
        out <- out + geom_vline(
            xintercept = line_year,
            color = "black",
            linetype = "dashed"
        )
    }

    # Add red 50km ref line
    if (line_50km) {
        out <- out + geom_segment( # 50km red line
            aes(
                x = 2009,
                y = 0,
                xend = 2009,
                yend = 50,
                color = "#bb0000",
                hjust = 0.15
            )
        ) +
        geom_segment( # 50km red triangle point down
            aes(
                x = 2009,
                y = 50.01 - (len_max * 0.05),
                xend = 2009,
                yend = 50 - (len_max * 0.05),
                color = "#bb0000",
                hjust = 0.15
            ),
            arrow = arrow(
                length = unit(0.03, "npc"),
                ends = "last",
                type = "closed"
            )
        ) +
        geom_segment( # 50km red triangle point up
            aes(
                x = 2009,
                y = (len_max * 0.05) - 0.01,
                xend = 2009,
                yend = (len_max * 0.05),
                color = "#bb0000",
                hjust = 0.15
            ),
            arrow = arrow(
                length = unit(0.03, "npc"),
                ends = "last",
                type = "closed"
            )
        ) +
        annotate(
            "text",
            x = 2009,
```

```
            y = 50,
            label = "50km",
            color = "#bb0000",
            hjust = -0.225
        )
    }
    return(out)
}

#' Plot Yearly Road Lengths By Infrastructure Type
#'
#' Creates area plots of road lengths by infrastructure type.
#'
#' @param df_list A list of data.frame containing the install and change years, type, and road segment l
#' @return Multiple area ggplots of the cumulative yearly road lengths by infrastructure type combined w
#' @export
#'
plot_yearly_len_infra <- function(df_list) {

    # Create infra plots from data
    p <- list()
    for (i in 1:length(df_list)) {

        # Get data and plot title
        df <- df_list[[i]]
        ptitle <- names(df_list)[[i]]

        # Create and add infra plot to list
        p[[i]] <- calc_yearly_adj_len(df, type_col = settings$type_col_infra) %>%
            plot_yearly_len(
                title = ptitle,
                year_min = settings$year_min,
                year_max = settings$year_max,
                type_col = settings$type_col_infra,
                type_filter = settings$type_filter_infra,
                type_recode = settings$type_recode_infra,
                legend_title = "Infrastructure Type",
                line_50km = TRUE,
                line_year = settings$line_year
            )
    }

    # Y-axis title
    y_title <- ggplot() +
        annotate(
            geom = "text",
            x = 1,
            y = 1,
            label = "Total Length (Centreline km)",
            angle = 90,
            size = 5
        ) +
        coord_cartesian(clip = "off")+
```

```
        theme_void()

    # Combine all infra plots together
    out <- (y_title | wrap_plots(p, nrow = length(p))) +
        plot_annotation(
            title = "Roadways with Dedicated Cycling Infrastructure",
            caption = sprintf("Years (%s-%s)", settings$year_min, settings$year_max),
            theme = theme(
                plot.title = element_text(hjust = 0.5, size = 16),
                plot.caption = element_text(hjust = 0.5, size = 14)
            )
        ) +
        plot_layout(widths = c(0.05, 1))
    return(out)
}

#' Plot Yearly Road Lengths By Road Type
#'
#' Creates area plots of road lengths by overall road type, and by infrastructure per road type.
#'
#' @param df The data.frame containing the install and change years, type, and road segment types and le
#' @return Multiple area ggplots of the cumulative yearly road lengths by road type combined with patchw
#' @export
#'
plot_yearly_len_road <- function(df, title = "Roadways with Dedicated Cycling Infrastructure") {

    # Create list to store plots
    p <- list()

    # Plot overall road types
    p[[1]] <- calc_yearly_len(
        df,
        year_col = settings$year_col_road,
        type_col = settings$type_col_road
    ) %>%
        plot_yearly_len(
            title = title,
            title_underline = FALSE,
            year_col = settings$year_col_road,
            year_min = settings$year_min,
            year_max = settings$year_max,
            x_title = sprintf("Years (%s-%s)", settings$year_min, settings$year_max),
            y_title = "Total Length (Centreline km)",
            legend_title = "Roadway Type",
            type_col = settings$type_col_road,
            type_recode = settings$type_recode_road,
            len_col = "len",
            line_50km = FALSE,
            line_year = settings$line_year,
            color_low = "#C1DDB3",
            color_high = "#297A22"
        ) +
        theme(
```

```
            plot.title = element_text(size = 18),
            plot.margin = margin(0, 0, 0, 0, "pt")
        )

    # Plot arterial, collector, and local road by infra
    rtypes <- c("Arterial", "Collector", "Local")
    for (i in 1:length(rtypes)) {

        # Get road type
        r <- rtypes[i]

        # Create infra plot for road type
        p[[i + 1]] <- calc_yearly_adj_len(
            df %>% filter(road_type == r),
            type_col = settings$type_col_infra
        ) %>%
            plot_yearly_len(
                title = sprintf("%s Roadways", r),
                title_underline = FALSE,
                line_50km = FALSE,
                line_year = settings$line_year,
                year_int = 2,
                x_title = sprintf("Years (%s-%s)", settings$year_min, settings$year_max),
                y_title = "Total Length (Centreline km)",
                year_min = settings$year_min,
                year_max = settings$year_max,
                type_col = settings$type_col_infra,
                type_filter = settings$type_filter_infra,
                type_recode = settings$type_recode_infra,
                legend_title = "Infrastructure Type"
            ) +
            theme(
                plot.title = element_text(size = 14),
                plot.margin = margin(0, 12, 0, 0, "pt")
            )
    }

    # Plot horizontal gradient bar
    grad_bar <-  ggplot(data.frame(x = 1:4), aes(x = x, y = 1, color = x)) +
        geom_line(size = 4) +
        scale_color_gradient(low = "#C1DDB3", high = "#297A22") +
        theme_void() +
        guides(color = FALSE) +
        theme(
            axis.title = element_blank(),
            axis.text = element_blank(),
            axis.ticks = element_blank(),
            axis.line = element_blank(),
            plot.margin = margin(0, 0, 0, 0, "pt")
        )

    # Plot overall and road type plots together
    out <- ( # overall plot
```

```
        plot_spacer() +
        p[[1]] +
        plot_spacer() +
        plot_layout(
            widths = c(0.25, 0.35, 0.2)
        )
    ) / ( # gradient bar
        plot_spacer() +
        grad_bar +
        plot_spacer() +
        plot_layout(widths = c(-0.8, 10, -1.1))
    ) / ( # infra plots
        p[[2]] +
        p[[3]] +
        p[[4]]
    ) + plot_layout(
        heights = c(12, 1, 8)
    ) + plot_annotation( # A B tags
        tag_levels = list(c("A", "", "B", "", ""))
    ) & theme(
        plot.tag = element_text(face = "bold", size = 12)
    )
    return(out)
}
#' Plot Yearly Differences
#'
#' Creates a bar plot of the differences between two years.
#'
#' @param df The data.frame containing the two columns with the years.
#' @param year_col1 The name (char) or index (int) of the first year column.
#' @param year_col2 The name (char) or index (int) of the second year column to be subtracted from.
#' @param year_col1_name The name alias (char) of the first year column year_col1.
#' @param year_col2_name The name alias (char) of the second year column year_col2.
#' @param year_min The minimum year (int) to calculate differences for.
#' @param year_max The maximum year (int) to calculate differences for.
#' @param title The title (char) of the plot.
#' @param title_n Set to TRUE to add the number of total segments considered.
#' @param x_title The title (char) of the x-axis.
#' @param y_title The title (char) of the y-axis.
#' @param x_breaks The number (int) of breaks to show on the x-axis. Set to FALSE to let ggplot automati
#' @return A ggplot of yearly differences (year_col2 - year_col1), displaying the proportion of rows fo
#' @export
#'
plot_yearly_diff <- function(
        df,
        year_col1 = "install_year_orig",
        year_col2 = "install_year",
        year_col1_name = "City Year",
        year_col2_name = "Verified Year",
        year_min = settings$year_min,
        year_max = settings$year_max,
        title = sprintf(
            "Difference in Years, Comparing %s and %s",
```

```
            year_col1_name,
            year_col2_name
        ),
        title_n = TRUE,
        x_title = sprintf(
            "Difference in Years (%s - %s)",
            year_col2_name,
            year_col1_name
        ),
        y_title = "Proportion of Total Segments",
        x_breaks = 15
) {
    ydiff <- df

    # Filter within min year
    if (year_min) {
        ydiff <- ydiff %>% filter(
            .data[[year_col1]] >= year_min | .data[[year_col2]] >= year_min
        )
    }

    # Filter within max year
    if (year_max) {
        ydiff <- ydiff %>% filter(
            .data[[year_col1]] <= year_max | .data[[year_col2]] <= year_max
        )
    }

    # Add n to title
    if (title_n) {
        title <- sprintf("%s (n=%s)", title, nrow(ydiff))
    }

    # Calc yearly diff
    ydiff <- ydiff %>%
        mutate(year_diff = install_year - install_year_orig) %>%
        count(year_diff)

    # Plot yealy diffs
    out <- ydiff %>%
        ggplot(aes(
            x = year_diff,
            y = (n / sum(n)) * 100
        )) +
        geom_bar(
            stat = "identity",
            color = "#332a94",
            fill = "#c3d5e4",
            width = 1
        ) +
        labs(
            title = title,
            x = x_title,
```

```
            y = y_title
        ) +
        scale_y_continuous(
            label = scales::label_number(suffix = "%")
        ) +
        theme(
            plot.title = element_text(size = 12)
        )

    # Set x interval breaks
    if (x_breaks) {
        out <- out + scale_x_continuous(
            breaks = scales::breaks_pretty(x_breaks)
        )
    }
    return(out)
}


# Load raw data
vanc_bikeways <- read_csv("../data/vancouver_bikeways_2009_2022_v1.csv")
vanc_roads <- read_csv("../data/vancouver_roads_2009_2022_v1.csv")

# Combine raw data
vanc <- vanc_bikeways %>%
    select(
        ID_DATAENTRY,
        INST_YR_ORIG,
        INST_YR,
        INST_MIN_HTYPE,
        UPGR1_YR,
        UPGR1_MIN_HTYPE,
        UPGR2_YR,
        UPGR2_MIN_TYPE,
        ATR_SEGMENT_LENGTH
    ) %>%
    left_join(
        vanc_roads %>% select(
            ID_DATAENTRY,
            ATR_SEGMENT_TYPE
        ),
        by = "ID_DATAENTRY"
    ) %>%
    rename(
        id = ID_DATAENTRY,
        install_year_orig = INST_YR_ORIG,
        install_year = INST_YR,
        install_type = INST_MIN_HTYPE,
        upgrade1_year = UPGR1_YR,
        upgrade1_type = UPGR1_MIN_HTYPE,
        upgrade2_year = UPGR2_YR,
        upgrade2_type = UPGR2_MIN_TYPE,
        segment_len = ATR_SEGMENT_LENGTH,
```

```
        segment_type = ATR_SEGMENT_TYPE
    ) %>%
    mutate(
        segment_len = segment_len / 1000,
        road_type = case_when( # create road types
            segment_type %in% c( # arterial equiv
                "Arterial"
            ) ~ "Arterial",
            segment_type %in% c( # collector equiv
                "Collector",
                "Secondary Arterial",
                "Sec Arterial"
            ) ~ "Collector",
            segment_type %in% c( # local equiv
                "Lane",
                "Residential",
                "Leased",
                "Recreational"
            ) ~ "Local",
            .default = segment_type
        )
    )
vanc

# Load raw data
calg_bikeways <- read_csv("../data/calgary_bikeways_2009_2022_v1.csv")
calg_roads <- read_csv("../data/calgary_roads_2009_2022_v1.csv")

# Combine raw data
calg <- calg_bikeways %>%
    select(
        SHAPE_ID,
        YEAR_ORIG,
        INST_YR,
        INST_MIN_HTYPE,
        UPGR1_YR,
        UPGR1_MIN_HTYPE,
        UPGR2_YR,
        UPGR2_MIN_HTYPE,
        ATR_SEGMENT_LENGTH
    ) %>%
    left_join(
        calg_roads %>% select(
            shape_id,
            ctp_class
        ),
        by = join_by(SHAPE_ID == shape_id)
    ) %>%
    rename(
        id = SHAPE_ID,
        install_year_orig = YEAR_ORIG,
        install_year = INST_YR,
        install_type = INST_MIN_HTYPE,
```

```
        upgrade1_year = UPGR1_YR,
        upgrade1_type = UPGR1_MIN_HTYPE,
        upgrade2_year = UPGR2_YR,
        upgrade2_type = UPGR2_MIN_HTYPE,
        segment_len = ATR_SEGMENT_LENGTH,
        segment_type = ctp_class
    ) %>%
    mutate(
        segment_len = segment_len / 1000,
        road_type = case_when( # create road types
            segment_type %in% c( # arterial equiv
                "Arterial Street",
                "Industrial Arterial",
                "Local Arterial",
                "Parkway",
                "Urban Boulevard"
            ) ~ "Arterial",
            segment_type %in% c( # collector equiv
                "Neighbourhood Boulevard",
                "Collector",
                "Primary Collector",
                "Skeletal Road"
            ) ~ "Collector",
            segment_type %in% c( # local equiv
                "Access Route",
                "Residential Street",
                "Activity Center Street",
                "Historic Road Allowance",
                "Lanes (Alleys)",
                "Industrial Street"
            ) ~ "Local",
            .default = segment_type
        )
    )
calg

# Load raw data
toron_bikeways <- read_csv("../data/toronto_bikeways_2009_2022_v1.csv")
toron_roads <- read_csv("../data/toronto_roads_2009_2022_v1.csv")

# Combine raw data
toron <- toron_bikeways %>%
    select(
        ID_OID,
        INSTALLED_ORIG,
        INST_YR,
        INST_MIN_HTYPE,
        UPGR1_YR,
        UPGR1_MIN_HTYPE,
        UPGR2_YR,
        UPGR2_MIN_HTYPE,
        ATR_SEGMENT_LENGTH
    ) %>%
```

```
    left_join(
        toron_roads %>% select(
            OID_,
            FEATURE36
        ),
        by = join_by(ID_OID == OID_)
    ) %>%
    rename(
        id = ID_OID,
        install_year_orig = INSTALLED_ORIG,
        install_year = INST_YR,
        install_type = INST_MIN_HTYPE,
        upgrade1_year = UPGR1_YR,
        upgrade1_type = UPGR1_MIN_HTYPE,
        upgrade2_year = UPGR2_YR,
        upgrade2_type = UPGR2_MIN_HTYPE,
        segment_len = ATR_SEGMENT_LENGTH,
        segment_type = FEATURE36
    ) %>%
    mutate(
        segment_len = segment_len / 1000,
        road_type = case_when( # create road types
            segment_type %in% c( # arterial equiv
                "Major Arterial",
                "Major Arterial Ramp",
                "Minor Arterial"
            ) ~ "Arterial",
            segment_type %in% c( # collector equiv
                "Collector"
            ) ~ "Collector",
            segment_type %in% c(  # local equiv
                "Local",
                "Other"
            ) ~ "Local",
            .default = segment_type
        )
    )
toron
plot_yearly_len_infra(list(
    "Vancouver, CA" = vanc,
    "Calgary, CA" = calg,
    "Toronto, CA" = toron
))
plot_yearly_len_road(
    vanc,
    title = "Roadways with Dedicated Cycling Infrastructure (Vancouver, CA)"
)
plot_yearly_len_road(
    calg,
    title = "Roadways with Dedicated Cycling Infrastructure (Calgary, CA)"
)
plot_yearly_len_road(
    toron,
```

```
    title = "Roadways with Dedicated Cycling Infrastructure (Toronto, CA)"
)
plot_yearly_diff(
    vanc,
    title = "Difference in Installation Years, Comparing City Data and Verified Data: Vancouver, CA"
)
plot_yearly_diff(
    calg,
    title = "Difference in Installation Years, Comparing City Data and Verified Data: Calgary, CA"
)
plot_yearly_diff(
    toron,
    title = "Difference in Installation Years, Comparing City Data and Verified Data: Toronto, CA"
)
version
```