Put your PhD title here

Your name

Submitted in accordance with the requirements
for the degree of Doctor of Philosophy
May 2023

University of Leeds

School of Geography

Intellectual Property and Publications

The candidate confirms that the work submitted is their own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicity indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

The following chapters contain jointly authored manuscripts where Caroline Jane Tait is the lead author:

- The work in Chapter 3 of the thesis has appeared in publicaton as:

  Tait, C., Beecham, R., Lovelace, R. and Barber, S. (2023). Contraflow and cycling safety: Evidence from 22 years of data involving 508 one-way streets. *Accident Analysis & Prevention*, 179, 106895, https://doi.org/10.1016/j.aap.2022.106895.

  Caroline Jane Tait was the lead author and responsible for conceptualisation, primary data creation, writing, data analysis, visualisation, review and editing. Drs Roger Beecham, Robin Lovelace and Stuart Barber supervised the research and provided editorial and advisory comments.

- The work in Chapter 4 of the thesis is formatted and ready for submission pending feedback from all contributing authors as:

  Tait, C., Beecham, R., Lovelace, R. and Barber, S. (2023). Build it but will they come? Exploring the impact of introducing contraflow cycling on cycling volumes with crowdsourced data. *Intended submission to: Journal of Transport & Health.*

  Caroline Jane Tait was the lead author and responsible for conceptualisation, writing, data analysis, visualisation, review and editing. Drs Roger Beecham, Robin Lovelace and Stuart Barber supervised the research and provided editorial and advisory comments.

Abstract

This is where you type your abstract….

this is where you type the second paragraph of your abstract…

here is where your third one goes….etc etc

Acknowledgements

Completion of this thesis would not have been possible without the support of many people.

Firstly, I would like to thank....

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List of Abbreviations

ASL	**A**dvanced **S**top **L**ine
ATE	**A**ctive **T**ravel **E**ngland
CI	**C**onfidence **I**nterval
CID	**C**ycling **I**nfrastructure **D**atabase
DfT	**D**epartment for **T**ransport
GB	**G**reat **B**ritain
OSM	**O**pen **S**treet **M**ap
TRO	**T**raffic **R**egulation **O**rder
TfL	**T**ransport for **L**ondon
UK	**U**nited **K**ingdom
WHO	**W**orld **H**ealth **O**rganisation

Chapter 1

How to use this Template

This ‘how to chapter’ has come from the original excellent quarto-thesis template created by Dr Eli Holmes. Her original repo is here:

https://github.com/nmfs-opensci/quarto-thesis

There are some bits in this that she refers to that I have removed or adapted in my template so that this template meets the UoL thesis requirements. However, if you go to her original repo then you can see them.

To build the thesis click on the ‘Build’ tab in the Environment, History etc pane. Then click on ‘Render Book and select ’quarto-thesis-pdf Format’(see Figure 1.1). Your document will then be built and appear as a pdf that is titled with whatever you have put as the title of your thesis.

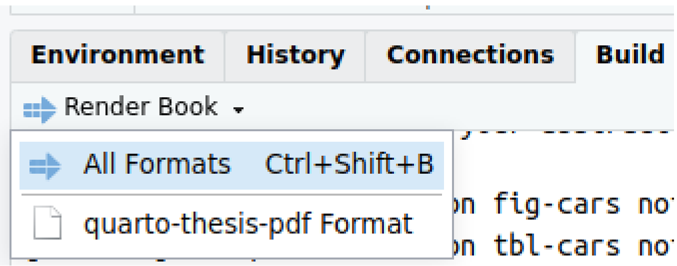

FIGURE 1.1: How to build thesis

If you want to reduce the size of the document you render (for example, just want to see what a particular chapter looks like or how the front matter looks) you can comment out the Chapters or Appendices in the *_quarto.yml* file.

NB for some reason, in Chapter 1, to add a png or image file you have to code it like this (which will give you Figure 1.1):

```
![How to build thesis](Figures/quarto_render.png){#fig-quarto-render}
```

but you use this style of code to add image files in the subsequent chapters and appendices:

```
knitr::include_graphics(path = "../Figures/fig_speed_limits.png")
```

This quarto document is set up so the references will display at the end of each chapter (I cant remember if this is a requirement for all UoL thesis or just those by publication). This is controlled via the *_quarto.yml* file and the *_extensions/pandoc-ext* folder. However, you may need to install the pandoc extension so that this works. This is available here: https://github.com/pandoc-ext/section-bibliographies

I used zotero as my reference manager when I added a reference in quarto then it populated the *example.bib* file. However if you go to the original repo created by Dr Holmes and use that version then the references will all appear at the end of your thesis.

If you want to add multiple paragraphs in your abstract then look at this: https://github.com/nmfs-opensci/quarto-thesis/discussions/16

Dr Holmes is super helpful and has a discussion board on her repo so you can ask questions. There are also questions in the 'issues' part of the repo.

1.1 Below is the original text included by Dr Holmes on how to use this template

Welcome to this LaTeX Thesis Template, using the LaTeX typesetting system and Quarto and based on the LaTeX thesis template MastersDoctoralThesis version 2.0 downloaded from LaTeXTemplates. This LaTeX document class was authored by Vel (vel@latextemplates.com) and Johannes Böttcher based on a style file by Steve R. Gunn from the University of Southampton (UK), department of Electronics and Computer Science.

1.2 A Short Math Guide for LaTeX

If you are writing a technical or mathematical thesis, then you may want to read the document by the AMS (American Mathematical Society) called, ?A Short Math Guide for LaTeX?. It can be found online at AMS under the ?Additional Documentation? section towards the bottom of the page.

1.2.1 Common LaTeX Math Symbols

There are a multitude of mathematical symbols available for LaTeX and it would take a great effort to learn the commands for them all. The most common ones you are likely to use are shown on this page.

You can use this page as a reference or crib sheet, the symbols are rendered as large, high quality images so you can quickly find the LaTeX command for the symbol you need.

1.3 About this Template

This LaTeX Thesis Template is originally based and created around a LaTeX style file created by Steve R. Gunn from the University of Southampton (UK), department of Electronics and Computer Science. You can find his original thesis style file at his site, here: http://www.ecs.soton.ac.uk/~srg/softwaretools/document/templates/.

Steve's `ecsthesis.cls` was then taken by Sunil Patel who modified it by creating a skeleton framework and folder structure to place the thesis files in. The resulting template can be found on Sunil's site here: http://www.sunilpatel.co.uk/thesis-template.

Sunil's template was made available through LaTeXTemplates where it was modified many times based on user requests and questions. Version 2.0 and onwards of this template represents a major modification to Sunil's template and is, in fact, hardly recognisable. The work to make version 2.0 possible was carried out by Vel (vel@latextemplates.com) and Johannes Böttcher.

1.4 What this Template Includes

1.4.1 Folders

- Appendices – this is the folder where you put the appendices. Each appendix should go into its own separate qmd file. An example and template are included in the directory.
- Chapters – this is the folder where you put the thesis chapters. Each chapter should go in its own separate qmd file.
- Figures – this folder contains static figures for the thesis, i.e. figures that are not generated by code in the chapters.

1.4.2 Files

- example.bib – this is file that contains all the bibliographic information and references that you will be citing in the thesis for use with BibTeX. You can write it manually, but there are reference manager programs available that will create and manage it for you. Zotero is popular and integrates with RStudio IDE if you use that.
- MastersDoctoralThesis.cls – this is the class file that tells LaTeX how to format the thesis.
- pdf in docs folder – this is your typeset thesis.
- Frontmater folder – this has the files for the various front matter elements.

1.5 Filling in Your Information

Most of the personal information is found on in the `_quarto.yml` file.

- author – you; optionally add url
- supervisor – your supervisor; optionally add url.
- university – your university
- department – your department
- faculty – faculty name
- group – research group name (optional)
- abstract

1.6 The `tex\before-body.tex` File Explained

The `tex\before-body.tex` file contains the structure of the thesis and is a mix of Pandoc template and LaTeX code. The bits that look like `$book.university$` say are Pandoc and are referencing variables in the `_quarto.yml` file. Knowing that, you should be able to figure out what is happening.

There are plenty of written comments that explain what pages, sections and formatting the LaTeX code is creating. Each major document element is divided into commented blocks with titles in all capitals to make it obvious what the following bit of code is doing. Initially there seems to be a lot of LaTeX code, but this is all formatting, and it has all been taken care of so you don't have to do it.

Many of the sections have `$if(...)$` so that the section is only included if you included information for that in `_quarto.yml`.

In the `_quarto.yml`, `pdf: toc: false` is used so that Quarto/Pandoc doesn't add a table of contents. This template puts the table of contents before the abbreviations and symbols pages and Quarto/Pandoc doesn't let us control where it puts the table of contents. So we have to add the TOC manually for pdf and pass in `toc: false`.

The list of figures and tables are all taken care of for you and do not need to be manually created or edited. The next set of pages are more likely to be optional and can be deleted since they are for a more technical thesis: insert a list of abbreviations you have used in the thesis, then a list of the physical constants and numbers you refer to and finally, a list of mathematical symbols used in any formulae. Making the effort to fill these tables means the reader has a one-stop place to refer to instead of searching the internet and references to try and find out what you meant by certain abbreviations or symbols.

The list of symbols is split into the Roman and Greek alphabets. Whereas the abbreviations and symbols ought to be listed in alphabetical order (and this is **not** done automatically for you) the list of physical constants should be grouped into similar themes.

The next page contains a one line dedication. Who will you dedicate your thesis to?

1.7 Adding Your Chapters and Appendices

Add your chapters and appendices to `_quarto.yml`. Note that the spacing is important as is the leading `-`.

1.8 Bibliography and Citations

Citations will be added and formatted automatically for you.

If you use the RStudio IDE, then you can link Zotero to RStudio and Quarto will find your citations for you when you enter `@`. This is in the visual editor mode. Make sure to search for videos on how to do this as using Zotero libraries will make your citation and bibliography management much much easier.

In the text use `@smith2000` to produce Smith (2000) add use `[@smith2000, @jones1999]` to produce (Smith 2000; Jones 1999). See the natbib cheatsheet for how to do other types of formatting for your in text citations. The bibliography style (`classoption: "authoryear"`) is used for the bibliography and is a fully featured style that will even include links to where the referenced paper can be found online.

1.8.0.1 A Note on bibtex

The bibtex backend used in the template by default does not correctly handle unicode character encoding (i.e. "international" characters). You may see a warning about this in the compilation log and, if your references contain unicode characters, they may not show up correctly or at all. One solution to this is to use the biber backend instead of the outdated bibtex backend. This is done by finding this in `tex/in-header.tex`: `backend=bibtex` and changing it to `backend=biber`. Google a bit to find information on this.

1.9 Thesis Features and Conventions {sec-ThesisConventions}

To get the best out of this template, there are a few conventions that you may want to follow.

1.9.1 Printing Format

This thesis template is designed for double sided printing (i.e. content on the front and back of pages) as most theses are printed and bound this way. Switching to one sided printing is as simple as adding `"oneside"` to `classoptions:` in the `_quarto.yml` file. The headers for the pages contain the page number on the outer side (so it is easy to flick through to the page you want) and the chapter name on the inner side.

The text is set to 11 point by default with single line spacing, again, you can tune the text size and spacing should you want or need to using the class options. The spacing can be changed similarly by replacing the `"singlespacing"` with `"onehalfspacing"` or `"doublespacing"` in the class options.

1.9.2 Using US Letter Paper

The paper size used in the template is A4, which is the standard size in Europe. If you are using this thesis template elsewhere and particularly in the United States, then you may have to change the A4 paper size to the US Letter size. This can be by editting `geometry:` in `_quarto.yml` in the pdf format section.

1.10 Tables

When you render your Quarto thesis to PDF, it will process LaTeX table code just fine. However, if you are doing that, I am guessing you would be writing your thesis in LaTeX not Quarto. So I will not discuss LaTeX tables. Instead here is how you create tables using R. Python and Julia users, you'll have your own table packages but the idea will be similar.

````
```{{r}}
#| label: tbl-cars
#| tbl-cap: This is my caption.
knitr::kable(head(mtcars))
```
````

The `#|` is what sets up our cross-references and you can then reference the table as `@tbl-cars`. Note in order for table numbering to work in Quarto, you **must** label your tables with the `tbl-` prefix.

Table 1.1: This is my caption.

	mpg	cyl	disp	hp	drat	wt	qsec	vs	am	gear	carb
Mazda RX4	21.0	6	160	110	3.90	2.620	16.46	0	1	4	4
Mazda RX4 Wag	21.0	6	160	110	3.90	2.875	17.02	0	1	4	4
Datsun 710	22.8	4	108	93	3.85	2.320	18.61	1	1	4	1
Hornet 4 Drive	21.4	6	258	110	3.08	3.215	19.44	1	0	3	1

	mpg	cyl	disp	hp	drat	wt	qsec	vs	am	gear	carb
Hornet Sportabout	18.7	8	360	175	3.15	3.440	17.02	0	0	3	2
Valiant	18.1	6	225	105	2.76	3.460	20.22	1	0	3	1

This is Table 1.1.

See the Quarto manual for full examples and instructions.

1.11 Figures

Again we write in Quarto (markdown) not LaTeX for our figures. You can write in LaTeX if you really want but it would only be interpreted for the PDF output.

```
```{{r}}
#| label: fig-cars
#| fig-cap: This is my caption.
plot(mtcars[,1:4])
```
```

The `#|` is what sets up our cross-references and you can then reference the table as `@fig-cars`.

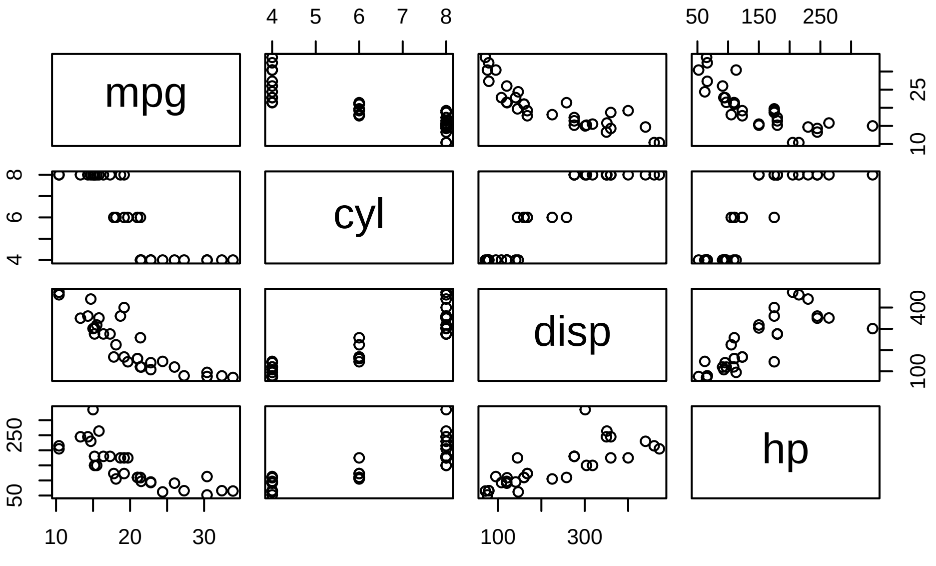

FIGURE 1.2: This is my caption.

This is Figure 1.2.

See the Quarto manual for full examples and instructions.

1.11.1 Typesetting mathematics

If your thesis is going to contain heavy mathematical content, LaTeX will make it look beautiful, for HTML or PDF output.

The Not So Short Introduction to LaTeX should tell you everything you need to know for most cases of typesetting mathematics. If you need more information, a much more thorough mathematical guide is available from the AMS called, A Short Math Guide to LaTeX.

1.12 In Closing

Good luck and have lots of fun!

This guide was written originally by

Sunil Patel: http://www.sunilpatel.co.uk}{www.sunilpatel.co.uk

and Vel: http://www.LaTeXTemplates.com

and heavily shortened and adapted for Quarto by Eli Holmes.

Chapter 2

Introduction - I have included an extract of my thesis so you can see how it is coded and looks....

This thesis examines the evaluation of cycling infrastructure with large observational data. Part 1 of this introductory chapter explores the background, starting broadly with the history of cycling before narrowing its geographical focus to England and subject focus to cycling infrastructure and the evidence base for its effectiveness in terms of cyclist safety and participation. Part 2 of the Introduction builds on these foundations, developing the research rationale through highlighting the gaps in this evidence base. It describes the importance of data in evaluating such infrastructure and potential for London as a setting for such an evaluation. It then defines the thesis aim and research questions, linking the questions to the research gaps and outlining the principles that have underpinned the research. Finally it describes the research strategy, thesis structure and outputs.

The Introduction is followed by three chapters each containing a discrete piece of research that evaluates cycling infrastructure with large observational data. Chapter 2 (Paper 1) examines what cycling infrastructure exists in London using a new database and evaluates it against design standards. This paper has been published in the Journal of Transport & Health. Chapter 3 (Paper 2) examines the effect of a specific type of cycling infrastructure, contraflow cycling where cyclists can travel against the flow of motor vehicles on one-way streets, on cyclist safety using crash and casualty datasets. This paper has been published in Accident Analysis & Prevention. Chapter 4 (Paper 3) also examines the effect of introducing contraflow cycling but instead looks at cycling volume using crowd-sourced data. This paper is ready to submit to the Journal of Transport & Health.

Chapter 5 is the Discussion that brings the preceding chapters and research together into a coherent evaluation of cycling infrastructure with large observational datasets. It discusses the key findings, strengths, limitations, policy implications and research recommendations. Chapter 6 is the Conclusion.

Part 1: Background

Part 1 of the Introduction provides the background to this thesis. It focuses on cycling as a physical activity and mode of transport and the popularity of cycling in different countries before examining cycling in England, the country studied in this thesis. It considers the importance of cycling and why the English government appears to be keen to encourage participation before discussing approaches to getting more people cycling and their implementation in England. Having identified safety and infrastructure as key barriers for individuals taking up cycling, it discusses infrastructure and the evidence base around its effectiveness on cycling participation and safety, both actual and perceived.

2.1 The bicycle and cycling

2.1.1 History of the bicycle

The exact origins of the bicycle are unknown but it has been suggested that it was invented out of necessity for a horse-less form of transport in the 1800s in Europe (Malizia and Blocken, 2020). During that century, design advancements such as pedals, the indirect drive system, wire wheels and pneumatic tyres meant that the modern bicycle came into existence (Van Nierop et al., 1997; Malizia and Blocken, 2020). This evolution cemented the bicycle for utility and facilitated the popularity of cycling for recreation, touring and racing by individuals and groups (Ritchie, 1999; Oosterhuis, 2016). Cyclists were central to the development of roads suitable for bicycles (and subsequently cars) and improvements in road quality (Reid, 2015). Bicycles have evolved further with specialisations for different types of cycling such a racing or bmxing (Lindsey, 2022); transportation such as cargo bikes (Cox and Rzenwnicki, 2015); and adaptive bicycles that support those who cannot use conventional bicycles (Rodger et al., 2014). More recent innovations include bike sharing schemes (Fishman et al., 2013) and electric bikes (Fishman and Cherry, 2016).

……………………………………………………………………..

References

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Fishman, E. and Cherry, C. 2016. E-bikes in the mainstream: Reviewing a decade of research. *Transport Reviews*. **36**(1), pp.72–91.

Fishman, E., Washington, S. and Haworth, N. 2013. Bike share: A synthesis of the literature. *Transport Reviews*. **33**(2), pp.148–165.

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Ritchie, A. 1999. The origins of bicycle racing in england: Technology, entertainment, sponsorship and advertising in the early history of the sport. *Journal of Sport History.* **26**(3), pp.489–520.

Rodger, K.J., DeCristoforo, J.T., Waller, A.N. and Axelsson, B.E. 2014. Worcester earn-a-bike: Creating an adaptive bicycle. Available from: https://digital.wpi.edu/concern/parent/rx913q198/file_sets/12579s73g.

Van Nierop, O.A., Blankendaal, A.C.M. and Overbeeke, C.J. 1997. The evolution of the bicycle: A dynamic systems approach. *Journal of Design History.* **10**(3), pp.253–267.

Chapter 3

Paper 2: Contraflows and cycling safety: Evidence from 22 years of data involving 508 one-way streets

Here I am showing that you can insert pdfs of published papers or other pdfs. This is managed via the _quarto.yml file.

More info on how to do this (it is already done for you in the _quarto.yml*) and how to make changes to how the pdfs look can be found here:* https://github.com/nmfs-opensci/quarto-thesis/issues/3

Accident Analysis and Prevention 179 (2023) 106895

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Contraflows and cycling safety: Evidence from 22 years of data involving 508 one-way streets

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ARTICLE INFO

Keywords:
Infrastructure
Contraflow
One-way streets
Crash
Cycling

ABSTRACT

Contraflow cycling on one-way streets is a low cost intervention that research shows can improve the cycling experience and increase participation. Evidence from several studies suggest that cyclists on contraflows have a lower crash risk. However, implementing contraflow cycling is often controversial, including in the United Kingdom (UK). In this paper we examine whether contraflow cycling on one-way streets alters crash or casualty rates for pedal cyclists.

Focusing on inner London boroughs between 1998 and 2019, we identified 508 road segments where contraflow cycling was introduced on one-way streets. We identified road traffic crashes occurring within 10 m of these segments and labelled them as pre-contraflow, contraflow or contraflow removed crashes. We calculated rates using the number of crashes or casualties divided by the time exposed and generated 95 % confidence intervals using bootstrap resampling. We adjusted the rates for changes in cordon cycling volume and injury severity reporting.

There were 1498 crashes involving pedal cyclists: 788 pre-contraflow, 703 contraflow and 7 following contraflow removal. There was no change in adjusted overall pedal cyclist crash or casualty rates when contraflow cycling was introduced. Proximity to a junction doubled the crash rate. The crash rate when pedal cyclists were travelling contraflow was the same as those travelling with flow.

We have found no evidence that introducing contraflow cycling increases the crash or casualty rate for pedal cyclists. It is possible that such rates may indeed fall when contraflow cycling is introduced if more accurate spatio-temporal cycling volume data was available. We recommend all one-way streets are evaluated for contraflow cycling but encourage judicious junction design and recommend UK legislative change for mandatory-two-way cycling on one-way streets unless exceptional circumstances exist.

1. Introduction

Contraflow cycling is where cycling can occur in both directions along a street that is one-way for motor vehicles. Allowing contraflow cycling on one-way streets can improve the cycling experience as it enables cyclists to utilise quieter roads, reduces the distance and energy required to travel between two points, reduces the route planning necessary to accommodate differences in outward and return journeys (PRESTO, 2010) and increases the connectivity of their routes (Putta and Furth, 2021). It is a low-cost intervention compared to other cycling infrastructure such as segregated cycle lanes or junction remodelling (Taylor and Hiblin, 2017). It increases the amount of cycling (Bjørnskau et al., 2012; Pritchard et al., 2019; Ryley and Davies, 1998), results in re-routing onto the new infrastructure (Pritchard et al., 2019) and off main roads (Alrutz et al., 2002) and reduces cycling on pavements (Alrutz et al., 2002; Bjørnskau et al., 2012; UDV, 2016). Concentrations of one-way streets, such as those found in urban environments, that do not allow contraflow cycling violate core design principles for cycling infrastructure networks and routes by reducing coherence, directness, attractiveness and comfort (DfT, 2020a). This discourages people from

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Available online 15 November 2022

cycling and challenges ambitions to increase cycling participation (DfT, 2020b).

In the United Kingdom (UK) the introduction of contraflow cycling on one-way streets is often controversial (e.g. Bloxham, 2008; Pettitt, 2011; Taylor, 2008) with planned schemes cancelled due to public opposition (e.g. Ryley and Davies, 1998; Roberts, 2020) and people cycling the 'wrong way' down one-way streets pilloried, including the former Prime Minister (BBC News, 2008). In contrast, in Europe such schemes are standard practice (UDV, 2016; Depoortere, 2019) and UK Cycling Infrastructure Design Guidance states that contraflow cycling should be implemented unless it is unfeasible for financial, operational or safety reasons (DfT, 2020a).

A key concern expressed in the UK is that contraflow cycling may increase road traffic crashes. Reasons suggested for this by Police Scotland include: narrow road widths resulting in close passing between motor vehicles and contraflow pedal cycles; reduced eye contact between motor vehicle drivers and contraflow cyclists, particularly when motor vehicles are exiting parking spaces or where the direction of the one-way street changes; and omission of specific infrastructure such as painted cycle lanes or junction changes (Police Scotland, 2021). This concern is at odds with the evidence-base on contraflow cycling. Allowing contraflow cycling on one-way streets does not increase road traffic crashes (Alrutz et al., 2002; Ryley and Davies, 1998; Vandenbulcke et al., 2014). Instead it has been shown to reduce cyclist crash risk (Chalanton and Dupriez, 2014; Vandenbulcke et al., 2014; UDV, 2016) and may reduce crash numbers, density and severity (Alrutz et al., 2002). Contrary to the opinion expressed above, conflicts and crashes have been shown to be greater for cyclists travelling with motor vehicle flow on one-way streets rather than contraflow (Alrutz et al., 2002; Chalanton and Dupriez, 2014) whilst motorists have been shown to reduce vehicle speed when encountering contraflow cyclists on narrow one-way streets and increase speeds as the road widens (Alrutz et al., 2002; UDV, 2016). However, this evidence base is predominantly based in mainland Europe, using short time scales (three to four years) and a few hundred crashes. The sole UK observational study examined five contraflow one-way streets with one day of video counts pre- and post-implementation and an analysis of crash data for three years before and eight months after introduction (Ryley and Davies, 1998). They found that cycling flow increased by 54 % after introduction (partially attributed to seasonal variation) with no crashes reported on these streets before or after contraflow cycling.

To enable contraflow cycling on one-way streets in the UK the local transport authority must issue statutory orders known as Traffic Regulation Orders (TRO) (Road Traffic Regulation Act 1984, 1984). Initially a TRO proposal is consulted upon with the public and interested parties then subsequently a TRO is issued to introduce the change (The Local Authorities' Traffic Orders Regulations, 1996). This process was made easier for transport authorities in 2011 when changes to contraflow traffic sign legislation (DfT, 2011a) increased clarity for all road users (Sewell and Nicholson, 2010) and reduced the administrative burden.

London provides a unique environment to improve the existing evidence base and provide meaningful evidence in the UK context of the impact of introducing contraflow cycling on road traffic crashes. Firstly, there are numerous one-way streets with contraflow cycling. Secondly, the TRO for the roads that allow contraflow cycling, including the crucial implementation date, is published in The Gazette (TSO, 2022b) and available online. Thirdly, the volume of cycling has increased dramatically (Tfl, 2019a) so the exposure of cyclists to contraflows is higher than in other UK locations. Fourthly, there is open data available for all road traffic crashes (DfT, 2022a). Finally, all of this data and information is available for decades thus providing long time-scales and large volumes of data for examination.

This paper presents an analysis of the impact of contraflow cycling on road traffic crashes using a before and after method. We identify road segments that implement contraflow cycling over a 22 year period in inner London and examine road traffic crashes involving pedal cycles occurring within 10 m of these road segments prior to and following contraflow cycling introduction. After describing the road segments, crashes, casualties and vehicles involved, we calculate crash rates using time exposed to the road segment as the denominator. We then present crash rates where the number of crashes has been adjusted for the change in cyclist volume using manual cordon counts indexed to the baseline year. Here we specifically focus on aspects such as proximity to junctions (a known risk factor for pedal cycle crashes e.g. Aldred et al., 2018; Kapousizis et al., 2021), significant change to the road segments (for example, two-way street to one-way with contraflow cycling) and pedal cyclist direction (with or contraflow). Finally we examine the pedal cyclist casualty rates to investigate whether introducing contraflow cycling has an impact on injury severity and thus associated costs and consequences.

2. Methods

2.1. Study period and location

London was chosen as the study location for the reasons outlined above: it is a large city with good data on road traffic crashes and casualties, cycling levels, and contraflow infrastructure, including introduction dates. We focused on the 14 London boroughs that constitute central and inner London (GLA, 2021) as these are where the majority of one-way streets with contraflow cycling are located and have the highest cycling participation (Tfl, 2019a). The start date of the study period, 1st January 1998, was selected as this is the date the first electronic TRO records became available online in The Gazette. The end date, 31st December 2019, was chosen as it is the last day of the year prior to the COVID-19 pandemic, which had a significant impact on UK transport (DfT, 2022b; Hadjidemetriou et al., 2020) and road traffic crashes (DfT, 2021a).

2.2. Data

2.2.1. Road segments that allow contraflow cycling

We collected primary data on the road segments with contraflow introduction from the TROs identified using the online search facility of The Gazette (TSO, 2022b). For each road segment, the following data was recorded: borough name, road name, description of contraflow spatial extent (for example, between junctions X and Y), contraflow start and/or stop date. We consider these variables to define the 'uniqueness' of a road segment. For each TRO, details including ID, date of publication and action (consultation, introduction or revocation) were recorded (Table A1). Significant changes to the road segments such the introduction of a one-way street or a contraflow bus lane and whether additional cycling infrastructure such as segregated cycle lanes were proposed were collected where clearly specified in the TRO. As some TROs are consulted upon but not introduced or introduced and removed, we cross-referenced each road segment to ensure it existed or had existed using The Gazette (if there was only a consultation TRO), the London Cycling Infrastructure Database (CID, Tfl, 2019b) and OpenStreetMap (OSM, OpenStreetMap contributors, 2022). We also used these sources to validate that all road segments were true one-way streets with contraflow cycling rather than 'false' one-way streets where motor vehicles can travel in both directions but only pedal cycles are able to enter at both ends of the segment.

We validated the completeness of our road segment data by identifying all roads that allow contraflow cycling in the CID and OSM and then using these road names as free text searches in The Gazette to identify any TROs that may have been missed by the initial search. The detected TROs were reviewed and managed as described in the previous section.

Spatial data for each road segment was obtained from the CID or OSM when present in these datasets. If not present, segments were visualised in OSM and their spatial data constructed from connecting discrete OSM point locations that represent the spatial extent specified in the TRO.

Following the primary data collection we performed various validation checks to ensure the data was correct. These included ensuring: uniqueness of each road segment; no duplication of data; that variables do not contradict each other; and that dates are appropriate and within the study period. We reviewed missing data to ensure it was truly missing, visualised the data on maps and examined road segment lengths to ensure these were correct and appropriate. Where any concerns were identified we returned to the TRO, CID or OSM to validate or correct the data.

2.2.2. UK road traffic crash data

We obtained the official UK road traffic crash data (DfT, 2022a), known as STATS19, corresponding to the years of our road segment data collection (1998 to 2019 inclusive). This data contains "All road accidents involving human death or personal injury occurring on the Highway … and notified to the police within 30 days of occurrence, and in which one or more vehicles are involved" (DfT, 2011b, pg. 4). It contains in depth data that describes the crash, its circumstances, the vehicles involved and the casualties. We excluded crashes that were 'self-reported' as this facility was introduced late in the study period (2016) and use of this data is not recommended when comparing across years (DfT, 2020e).

2.2.3. Cyclist volume data

We obtained the official manual count data of the volume of pedal cycles crossing traffic counter 'cordons' into central, inner and outer London during the study period from Transport for London publications (TFL, 2019c; TFL, 2021). As some official counts are only performed biennially, interpolation was used to impute count data for the missing years. The only exception to this was 2019 inner cordon count data. As there was no 2020 inner cordon count data, the 2019 inner cordon count data was estimated by calculating the mean difference in percentage change for central and outer counts and applying this to the 2018 inner count. Spatial data for traffic counter cordons was generated in QGIS by geo-referencing a static map (TFL, 2022) and creating spatial polygons representing the cordons.

2.3. Data analysis

2.3.1. Identifying pedal cycle crashes associated with contraflows

Spatial joins were used to identify all crashes involving pedal cycles that occurred within 10 m of contraflow interventions. Where crashes could be spatially associated with more than one road segment, they were allocated to the nearest road segment. The 10 m distance was chosen as it takes into account the multiplicity of street designs that contraflow cycling on one-way streets may encompass (DfT, 2020a); differences in road segment spatial geometry collection (e.g. CID v OSM); and changes in the positional accuracy of crash data location over time (DfT, 2005; DfT, 2011b). This distance was visually validated by checking that the 10 m buffer covered the road segment in OSM (highway width is determined by OSM highway type (Allan et al., 2022).

2.3.2. Categorising pedal cycle crashes

We limited crashes to those linked to a road segment with a known contraflow start date. Using the start date along with the date the contraflow was removed (if appropriate), each crash was categorised as occurring during the pre-contraflow, contraflow or contraflow removed time period. For each pedal cyclist crash we identified the vehicles involved, casualties injured and whether the cyclist was travelling 'with flow' or 'contraflow'. We removed crashes that met the definition of a single bicycle crash (all crash types in which only the cyclist is involved, Schepers et al., 2015) as they are likely to be under-reported in crash datasets (Davidson, 2005; Jeffrey et al., 2009; Juhra et al., 2012).

STATS19 contains a variable that indicates whether a crash is within 20 m of a junction or roundabout. We reduced this distance to 10 m to have a greater sample of crashes occurring away from intersections. We utilised the trafficalmr R package to identify all road junctions and roundabouts in inner London in 2019 and used this to determine if a crash occurred within or beyond 10 m of these intersections.

2.3.3. Estimating pedal cyclist crash and casualty rates

To estimate the crash rate we used the number of crashes that occurred during the 22 year study period prior to, during or after the contraflow was removed (numerator) and divided it by the duration of time exposed to unique road segments in that status during that 22 year period (denominator). This duration of time exposure for each road segment in the three possible statuses was calculated in days from the study start date, contraflow start date, contraflow stop date (if removed) and study end date. For example, the pre-contraflow crash rate is the total number of crashes that occurred on road segments with contraflow start dates prior to contraflow cycling being introduced divided by the total amount of time all the road segments with contraflow start dates were 'pre-contraflow' (Eq. (1)).

$$\textit{Raw precontraflow crash rate (crashes per 100 years of exposure)} = \frac{\textit{Total number of crashes occurring on road segments during the precontraflow period}}{(\textit{Total number of days during the 22 years that road segments were precontraflow}/365) \times 100} \quad (1)$$

However, during the study period the amount of cycling changed significantly. This means the total exposure of pedal cyclists to the road segments is likely to have changed and that the number of crashes that occurred in 1998 is not comparable to that of 2019. To account for this we created an index of cycling volume baselined to 1998 for each of the three cordon counts (outer, inner and central London). We adjusted the annual number of crashes occurring in each cordon location by the cordon-specific cycling volume index for that year (Eq. (2)) and then calculated the adjusted crash rate (Eq. (3)). Crash rates calculated in this manner are referred to as adjusted rates as opposed to raw rates in this paper.

$$\textit{Adjusted number of crashes occurring precontraflow by year } [i] \textit{ and cordon } [j] = \frac{\textit{Raw number of crashes occurring precontraflow in year } [i] \textit{ and cordon } [j]}{\textit{Index of cycling volume in year } [i] \textit{ and cordon } [j]} \quad (2)$$

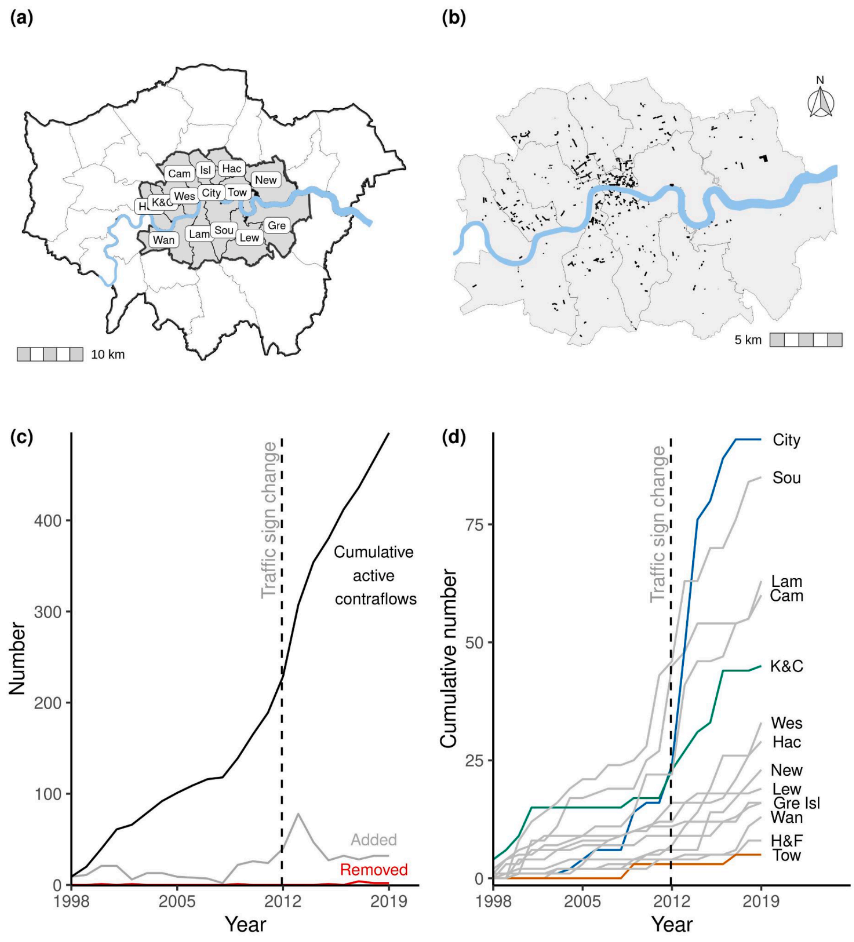


Fig. 1. Road segments with contraflows introduced a) Map of London showing location of inner London boroughs used in the study; b) Map of inner London boroughs showing the location and spatial extent of road segments; c) Line chart showing number of contraflows added, removed and active over time; and d) Line chart showing cumulative number of contraflows introduced over time by borough. The dashed line shows when traffic sign change was introduced.

$$\textit{Adjusted precontraflow crash rate}\ (\textit{crashes per}\ 100\ \textit{years of exposure}) = \frac{\textit{Total adjusted number of crashes occurring precontraflow}}{(\textit{Total number of days during the}\ 22\ \textit{years that road segments were precontraflow}/365) \times 100} \quad (3)$$

Pedal cyclist casualty rates were calculated using the same approach as the crash rates. However, because there were changes in the way that ‘severe’ and ‘slight’ casualty injuries were classified during the study period, we limited the casualty rate analysis to 2005–2019 data as recommended by the Department for Transport (DfT, 2021b; DfT, 2020c). We calculated raw rates and then calculated rates adjusted for the change in severity categorisation using crash-specific, casualty-level adjustment probabilities produced for this purpose (DfT, 2020d). Finally we calculated casualty rates adjusted for both change in injury severity categorisation and change in cordon cycling volume.

2.3.4. Estimating uncertainty of rates

We wanted to estimate the uncertainty around our rates. To achieve this we utilised the bootstrapping method and generated 1000 random resampled datasets from our crash and casualty datasets. The resampling was done with replacement to generate bootstrap datasets that were of the same size as the original datasets (Efron and Tibshirani, 1986). For each bootstrapped sample we derived the relevant raw and adjusted rates. We then calculated the standard error from the standard deviation of our bootstrap sampling distribution of rates and a 95 % confidence interval for the rate by calculating the 2.5 % and 97.5 % percentiles of the bootstrap sampling distribution.

2.3.5. Replication materials

There is additional information about the methods used in Appendix A. The road segment dataset that we collected is available at https://github.com/PublicHealthDataGeek/Contraflow_cycling_safety. Code used in the analysis is available at https://github.com/PublicHealthDataGeek/Contraflow_cycling_safety.

3. Results

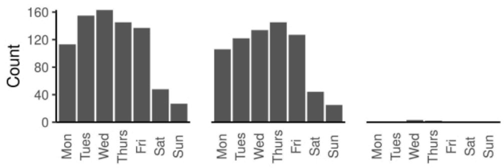
3.1. Road segments with contraflow cycling

We identified 508 unique road segments that had TROs published

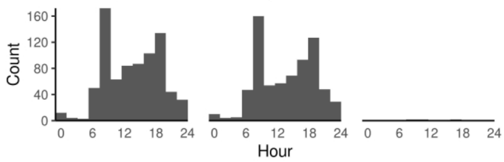
Table 1
Characteristics of crashes involving pedal cycles within 10 m of road segments by crash segment status occurring between 1st January 1998 and 31st December 2019 (inclusive). These characteristics are derived from the STATS19 dataset. Data is presented as 'number (percentage)' unless otherwise stated.

Characteristics		Crash segment status		
		Pre-contraflow	Contraflow	Contraflow removed
Number of crashes		788	703	7
Total number of vehicles		1550	1352	13
Mean number of vehicles per crash (SD)		2.0 (0.3)	1.9 (0.3)	1.7 (0.4)
Total number of casualties		819	740	8
Mean number of casualties per crash (SD)		1.0 (0.3)	1.1 (0.2)	1.1 (0.4)
Crashes involving cyclist casualties		753 (95.6)	652 (92.7)	6 (85.7)
Crashes involving pedestrian casualties		42 (5.3)	63 (9.0)	1 (14.3)
Mean road segment speed limit in mph (SD)		29.9 (1.3)	27.8 (4.2)	30.0 (0.0)
Crash severity	Fatal	6 (0.8)	4 (0.6)	0 (0.0)
	Serious	90 (11.4)	98 (13.9)	1 (14.3)
	Slight	692 (87.8)	601 (85.5)	6 (85.7)
Vehicles involved in crash with the pedal cycle [1]	Car	448 (56.9)	361 (51.4)	2 (28.6)
	Light Goods Vehicle	99 (12.6)	75 (10.7)	0 (0.0)
	Taxi	79 (10)	86 (12.2)	2 (28.6)
	Single pedal cycle – no additional vehicle	40 (5.1)	62 (8.8)	1 (14.3)
	Bus, coach or minibus	40 (5.1)	40 (5.7)	1 (14.3)
	Motorcycle	36 (4.6)	29 (4.1)	0 (0.0)
	Heavy Goods Vehicle	31 (3.9)	34 (4.8)	1 (14.3)
	Other vehicle type	6 (0.8)	5 (0.7)	0 (0.0)
	Two pedal cycles	3 (0.4)	9 (1.3)	0 (0)
	Two motor vehicles	6 (0.8)	2 (0.3)	0 (0)
Police officer attended the scene	Yes	531 (67.4)	517 (73.5)	6 (85.7)
	No	194 (24.6)	184 (26.2)	1 (14.3)
	Data missing or out of range	63 (8.0)	2 (0.3)	0 (0.0)
Junction details	At or within 20 m of a junction or roundabout	726 (92.1)	656 (93.3)	7 (100.0)
	Not at or within 20 m of a junction or roundabout	62 (7.9)	47 (6.7)	0 (0.0)
First road class [2]	A	498 (63.2)	383 (54.5)	6 (85.7)
	B	64 (8.1)	43 (6.1)	0 (0.0)
	C	141 (17.9)	193 (27.5)	0 (0.0)
	Unclassified	85 (10.8)	84 (11.9)	1 (14.3)
Road type	Single carriageway	602 (76.4)	533 (75.8)	7 (100.0)
	One way street	36 (4.6)	99 (14.1)	0 (0.0)
	Dual carriageway	56 (7.1)	52 (7.4)	0 (0.0)
	One way street slip road	88 (11.2)	8 (1.1)	0 (0.0)
	Unknown	3 (0.4)	1 (0.1)	0 (0.0)
	Roundabout	3 (0.4)	10 (1.4)	0 (0.0)
Light conditions	Daylight	618 (78.4)	530 (75.4)	7 (100.0)
	Darkness	170 (21.6)	173 (24.6)	0 (0.0)
Weather conditions	Fine	715 (90.7)	631 (89.8)	7 (100.0)
	Rain, snow, fog or other	61 (7.7)	67 (9.5)	0 (0.0)
	Unknown	12 (1.5)	5 (0.7)	0 (0.0)
Road surface conditions	Dry	692 (87.8)	607 (86.3)	6 (85.7)
	Wet, icy or muddy	96 (12.2)	96 (13.7)	1 (14.3)

Day of week



Hour of day



[1]Each crash involves a pedal cyclist. Crashes may involve one or more pedal cycles and one or more other vehicles. 'Single bicycle crashes' that involve a single pedal cycle and a single pedal cyclist casualty are excluded from this analysis.
[2]A roads are major roads providing large-scale transport connections and B roads connect different areas and A to C roads. C roads are smaller roads whilst unclassified are local roads for local traffic (DfT, 2012).

between 1st January 1998 and 31st December 2019 (inclusive) to introduce contraflow cycling in inner London boroughs. These road segments measure 64.4 km in total length. Ten road segments had contraflow cycling removed (Fig. 1c). Significant changes to the roads included the conversion of 115 (22.6 %) segments from two-way for vehicles to one-way and the introduction of contraflow bus lanes on 11 (2.2 %) segments. Some TROs mentioned that one or more specific types of additional cycling infrastructure was to be introduced on road segments, namely cycle lanes (139, 27.4 %), segregated cycle lanes (19, 3.7 %) and cycle tracks (7, 1.4 %) (see Fig. A1 for images of UK infrastructure). Contraflow cycling was allowed on a footway in seven (1.4 %) segments.

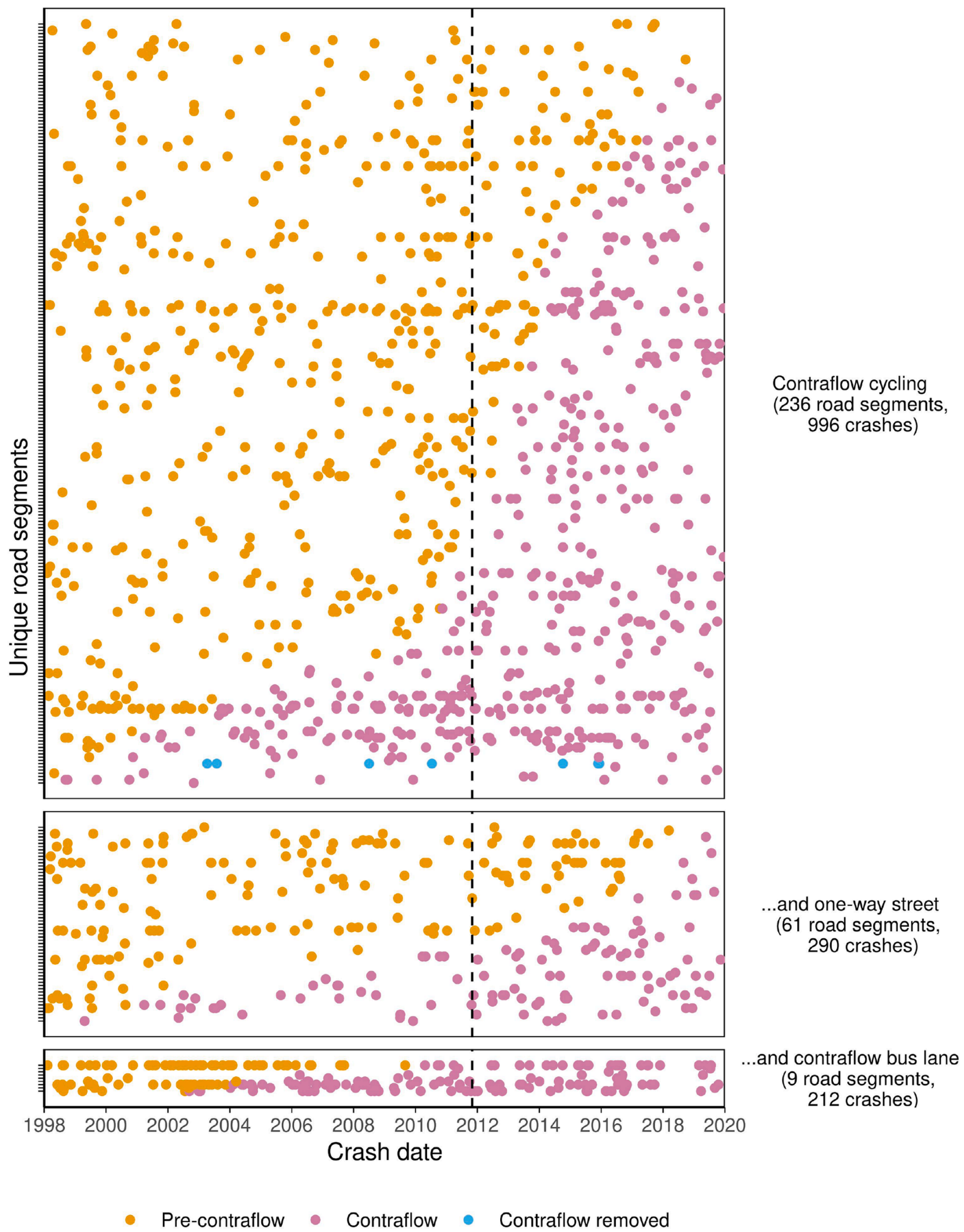


Fig. 2. Dot visualisation of all crashes involving pedal cycles within 10 m of a road segment by: unique road segment (vertical position); date of crash (horizontal position); crash segment status (colour); and significant change to road segment (pane). The dashed line shows when the traffic sign change was introduced. Colour palette sourced from Wong (2011) to promote visual accessibility.

The road segments are spatially concentrated in central London (Fig. 1b). There is considerable variation between the 14 London boroughs with City of London (the smallest borough in terms of geographic area) introducing the most (93) whilst Tower Hamlets introduced just five during the study period (Fig. 1d, Table B1). There are differences between boroughs in terms of when they introduced contraflow cycling (Fig. 1c and 1d). Immediately prior to and in the year following the relaxation of traffic sign legislation in 2011, there was significant expansion in many boroughs and exponential growth in City, Southwark and Lambeth. Two boroughs have consistent low-levels of contraflow introduction; Tower Hamlets and Hammersmith and Fulham.

For 35 road segments, a contraflow start date could not be identified (6.9 %). This is because these road segments have a 'Consultation' but not a 'Introduction' TRO. They are known to exist through validation with the CID and/or OSM. However, this means that these segments are not used in our crash analysis as we are unable to identify whether a crash occurred before or after contraflow implementation.

3.2. *Road traffic crashes involving pedal cycles within 10 m of road segments*

We identified 1498 crashes involving pedal cycles within 10 m of a road segment identified in section 3.1 that had a contraflow start date (n = 306) between 1st January 1998 and 31st December 2019 (inclusive).

Table 2
Characteristics of casualties in crashes involving pedal cycles within 10 m of road segments by crash segment status occurring between 1st January 1998 and 31st December 2019 (inclusive). These characteristics are all determined from the STATS19 dataset. Data is presented as 'number (percentage)'.

Characteristics			Crash segment status		
			Pre-contraflow	Contraflow	Contraflow removed
Total number of casualties			819	740	8
Casualty type	Cyclist		755 (92.2)	662 (89.5)	6 (75.0)
	Pedestrian		44 (5.4)	64 (8.6)	1 (12.5)
	Motorcyclist		10 (1.2)	9 (1.2)	0 (0.0)
	Car driver or passenger		8 (1.0)	2 (0.3)	0 (0.0)
	Other		2 (0.2)	3 (0.4)	1 (12.5)
Casualty severity [1]	Fatal	Cyclist	6 (0.7)	3 (0.4)	0 (0.0)
		Pedestrian	0 (0.0)	1 (0.1)	0 (0.0)
	Serious	Cyclist	76 (9.3)	79 (10.7)	1 (12.5)
		Pedestrian	12 (1.5)	19 (2.4)	0 (0.0)
		Motorcyclist	1 (0.1)	1 (0.1)	0 (0.0)
		Car	1 (0.1)	0 (0.0)	0 (0.0)
	Slight	Cyclist	673 (82.2)	580 (78.4)	5 (62.5)
		Pedestrian	32 (3.9)	45 (6.1)	1 (12.5)
		Motorcyclist	9 (1.1)	8 (1.1)	0 (0.0)
		Car	7 (0.9)	2 (0.3)	0 (0.0)
		Other	2 (0.2)	3 (0.4)	1 (12.5)

[1] In November 2015 London Police Forces moved to injury-based classifications systems for casualty severity to standardise the severity assessment. (DfT, 2021b). Adjustment probabilities have been developed so that severity can be compared across the years (DfT, 2020c; DfT, 2020e). The data presented in this table is unadjusted.

Of these crashes, 788 occurred before whilst 703 occurred during the time period when contraflow cycling was legally allowed and a further 7 occurred after contraflow cycling was rescinded. Our remaining analysis is focused on these 1498 crashes where we have determined the crash timescale in relation to the road segment status, referred to as 'crash segment status'.

Table 1 shows the characteristics of the crashes by crash segment status. In general, the characteristics of crashes that occurred before or when contraflow cycling is allowed are very similar. The mean number of vehicles involved per crash was 1.9–2.0, the mean number of casualties was 1.0–1.1 and the mean road speed limit was 30 mph or less (the normal speed limit for UK built-up areas (DfT, 2022c)). The vast majority of crashes resulted in cyclist casualties with less than 10 % having pedestrian casualties. Fortunately, very few crashes were fatal and less than 14 % considered serious. The commonest other single vehicles involved in these crashes with pedal cyclists are cars, taxis and light goods vehicles which account for around three-quarters of crashes. Over 92 % of crashes occurred within 20 m of a junction or roundabout despite only 63 % of road segment length being within 20 m of a junction (Table B2). Over 75 % occurred on single carriageway roads and over 54 % occurred on A roads. Crashes tended to occur in daylight hours (over 75 %), in fine weather (90 %) and on dry roads (86 %). Most crashes occurred in rush hours on weekdays. It is hard to draw any conclusions about crashes that occurred after contraflow cycling is removed due to the small numbers.

Fig. 2 shows the 1498 crashes involving pedal cycles, each represented as a dot, arranged vertically by road segment and ordered from left-to-right as they occurred over time (please see Fig. B1 and Table B3 for a breakdown by additional cycling infrastructure mentioned in the TRO, for example cycle lanes). Only 306 (60 %) out of the 508 road segments had a crash within 10 m. Some road segments have a greater number of crashes, represented by more dots along their horizontal row. This is particularly obvious for crashes associated with road segments where contraflow bus lanes are introduced with contraflow cycling (lowest pane). There were 212 crashes on these 9 road segments despite this action only affecting 11 (2.2 %) of all road segments. 80 (37.7 %) crashes occurred before and 132 (62,3%) occurred after the new contraflow bus lane was introduced. For road segments that were two-way, 176 (60.7 %) crashes occurred before they became one-way streets with contraflow cycling and 114 (39.3 %) occurred afterwards. For the existing one-way streets, 532 (53.4 %) crashes occurred before contraflow cycling, 457 (45.9 %) occurred after and 7 (0.7 %) occurred following contraflow removal.

3.3. Casualties

The 1498 crashes within 10 m of a road segment resulted in 1567 casualties of which 1423 were cyclists, 109 were pedestrians, 19 were motorcyclists, 10 were car occupants and six were 'other' (Table 2). The majority of crashes resulted in just one casualty (96 %) but 57 crashes had two casualties and three crashes had three, four and eight casualties each. There were 10 fatalities, nine of whom were cyclists with 60 % of these occurring in the pre-contraflow period. There were 189 seriously injured casualties of whom 83 % were cyclists and 16 % pedestrians and 1368 slightly injured casualties with cyclists accounting for 92 % and pedestrians 6 %. Only 9 % of non-cyclist, non-pedestrian casualties experienced a serious injury from the crashes with the rest being slightly injured.

3.4. Pedal cycle direction

Utilising the STATS19 vehicle direction variables, the spatial

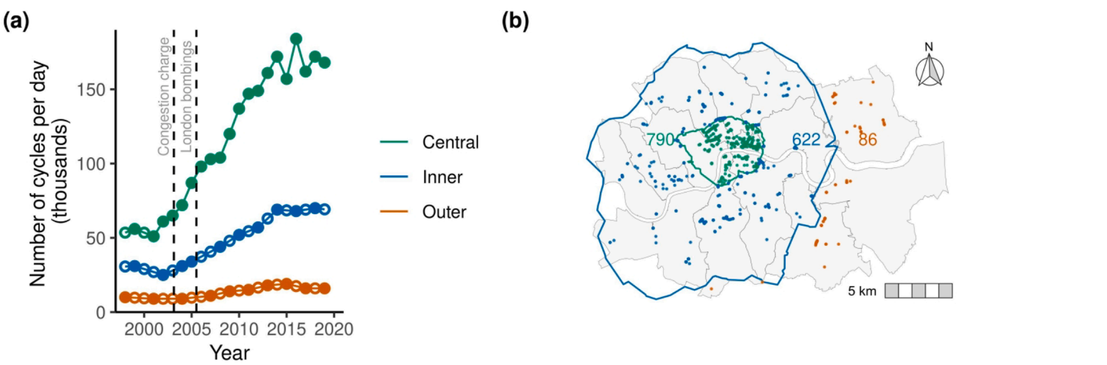


Fig. 3. a) **cordon counts of number of cyclists over time and b) spatial location of crashes and the central and inner cordon s.** Circle points (a) indicate values interpolated from data whereas dots (a) show actual count data. Numbers in (b) show the number of crashes occurring within each cordon. Count data sources: TFL (2019e) and TFL (2021). Colour palette: Wong (2011).

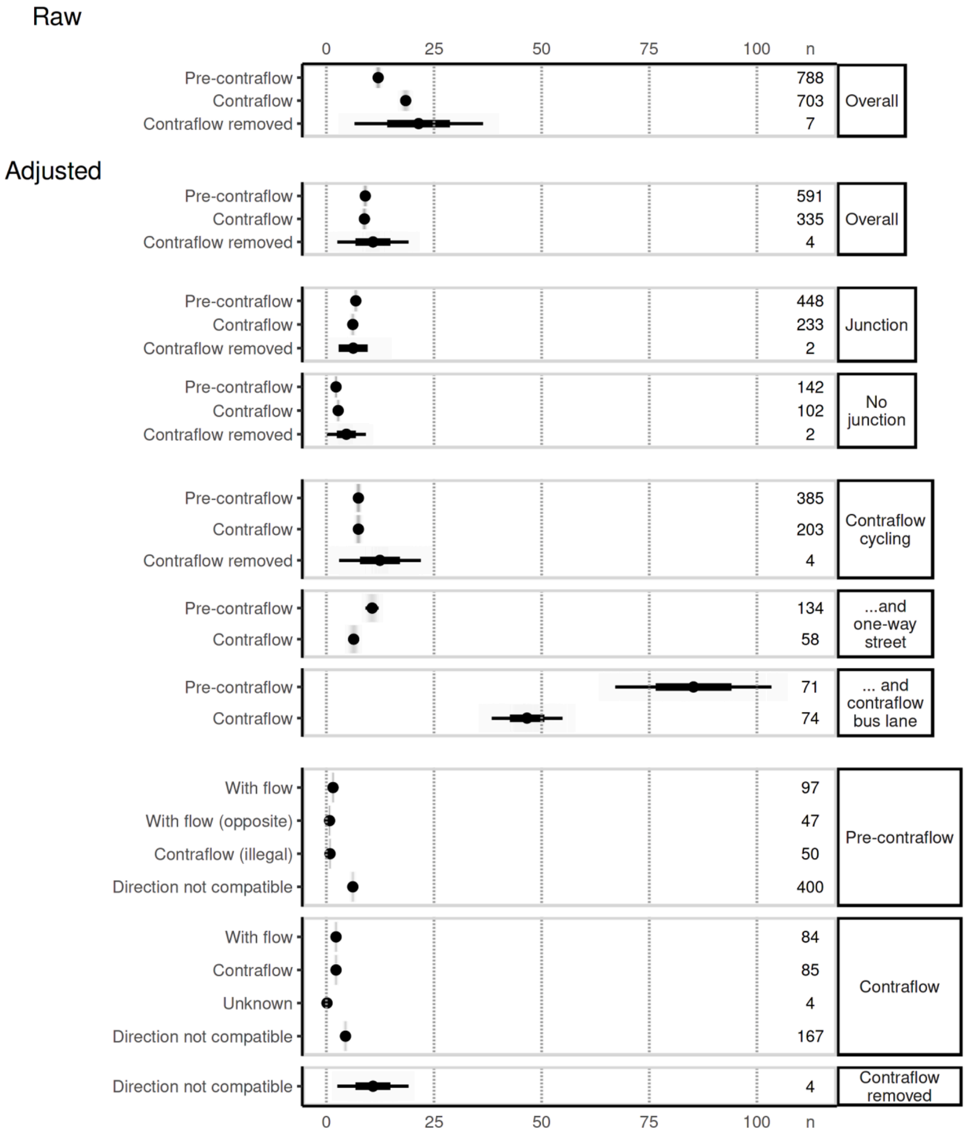


Fig. 4. Crash rates involving pedal cyclists per 100 years of exposure by crash segment status. Rates are presented as raw and adjusted for cordon cycling volume (1998 index) as: overall; by proximity to junctions or roundabouts (within 10 m); by significant change to road segments; and by pedal cycle direction. Visualisation shows point estimates for rates with 95 % confidence intervals generated by bootstrapping. n represents the number of crashes, rounded to the nearest integer for adjusted data.

orientation of the road segment, the crash location and the crash segment status, we could determine whether the pedal cycle was travelling with or against the motor vehicle traffic flow. This data is shown in Table B4. The commonest pedal cycle direction is 'direction not compatible' and that this proportion is greatest for crashes within 10 m of a junction or roundabout (up to 76 %). This indicates that these pedal cyclists are turning rather than travelling with or contraflow along the road segment.

Focusing on road segments that had been one-way streets, there are pre-contraflow crashes where cyclists are travelling illegally contraflow but this proportion is lower than the with-flow crashes, for example it is 15.3 % v 27.1 % for crashes more than 10 m from a junction. Looking at segments that were two-way streets, the proportion of crashes where the pedal cyclist is travelling contraflow is similar to that of one-way streets - around 21–28 %. Where the contraflow was removed, none of the seven crashes had a pedal cycle direction.

3.5. Changes to cordon cycling volume over time

The number of people cycling and thus the number of people potentially exposed to cycling on roads with contraflows in London has changed during the study time period. Fig. 3a shows the number of pedal cycles counted crossing cordons around outer, inner and central London over time (cordons shown in Fig. 3b). This demonstrates a large increase in the number of pedal cycles entering London with the volume doubling (inner) and tripling (central) over time. The number of crashes within our study area also varies in relation to these cordons with 5.7 % occurring outside the inner cordon, 42.0 % occurring between the inner

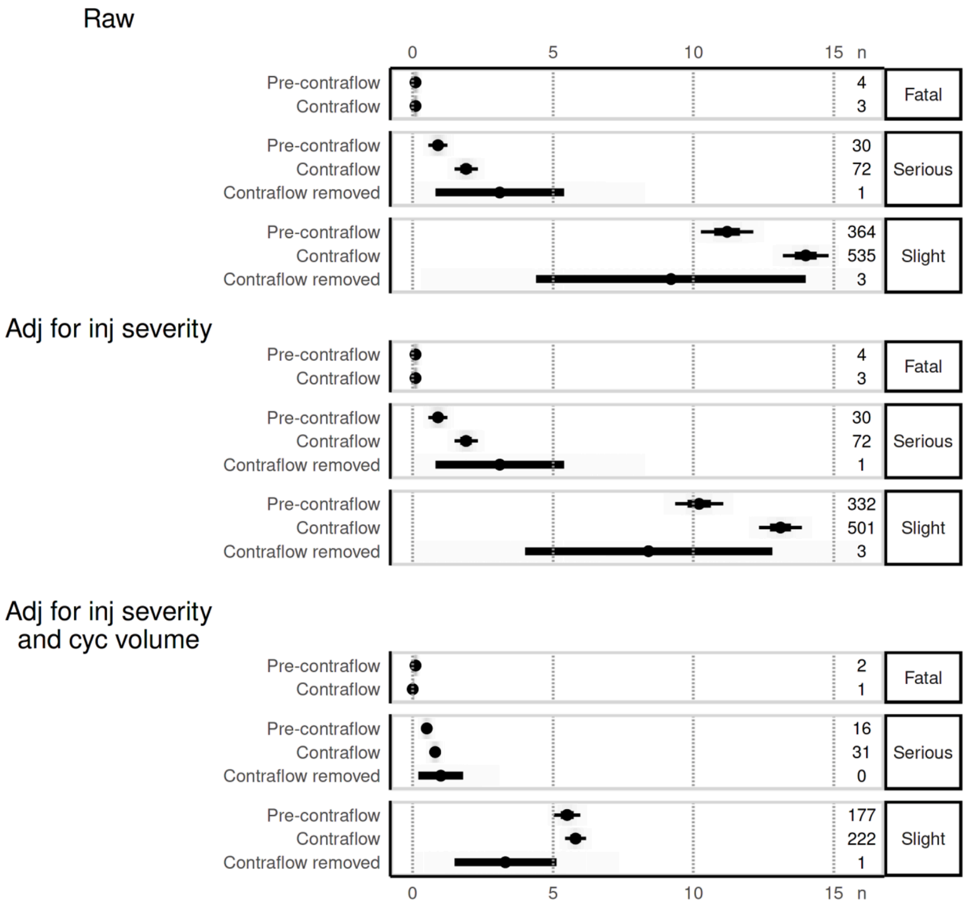


Fig. 5. Pedal cyclist casualty rates per 100 years of exposure by crash segment status and injury severity, 2005–2019. Rates are presented as raw, adjusted for change in injury severity classification; and adjusted for change in injury severity classification and cordon cycling volume (1998 index). Visualisation shows point estimates for rates with 95 % confidence intervals generated by bootstrapping. n represents the number of pedal cyclist casualties, rounded to the nearest integer for adjusted data.

and central cordons and 52.7 % occurring within the central cordon (Fig. 3b). This change in exposure of cyclists to infrastructure is important when considering the crash risk to which they may be subjected.

3.6. Pedal cycle crash rates

In Table B5 we present crash numbers, rates and their 95 % confidence intervals for crashes involving pedal cycles within 10 m of a road segment. These rates are expressed per 100 years of exposure to the road segment status (i.e. pre-contraflow, contraflow or following removal) as raw and adjusted for change in cordon cycling volume baselined to 1998 (we have predominantly included the adjusted rates in our visualisation, Fig. 4). This allows easier interpretation of the rates, so for example, the overall adjusted pre-contraflow crash rate is 9.0 which means that we would expect 9.0 crashes involving pedal cyclists to occur during 100 years of use of these road segments given the levels of cycling that have occurred over the study period.

Examining the overall crash rate shows that when raw numbers are utilised there appears to be a higher crash rate when contraflows are implemented (pre-contraflow crash rate = 12.0, 95 % confidence interval 11.4–12.6 v contraflow crash rate = 18.4, 17.4–19.4, Fig. 4, Table B5). However, once the number of crashes are adjusted to take into account the change in cordon cycling volume there is no statistically significant change in the crash rates when contraflows are implemented (9.0, 8.5–9.5 v 8.8, 8.2–9.3). This pattern - raw crash rates suggesting a difference between the pre and contraflow periods that is removed after accounting for change in cycling volume - exists for most rate comparisons. It is hard to draw any conclusions about the impact of removing contraflow cycling as the number of crashes on these segments are in single digits and therefore the confidence intervals around these crash rates are extremely wide.

Focusing now on crashes near junctions or roundabouts, there is no statistical difference in the cordon cycling volume adjusted crash rates occurring within or beyond 10 m of a junction between the pre- or contraflow time periods. However, the adjusted crash rate within 10 m of junctions is more than double that for crashes occurring over 10 m away. This is true irrespective of whether they occur in the pre-contraflow (6.8, 6.4–7.3 v 2.2, 1.9–2.5) or contraflow period (6.1, 5.6–6.6 v 2.7, 2.3–3.1).

Examining the cordon cycling volume adjusted crash rates by significant change to road segment demonstrates differences. Whilst there is no statistically significant change in crash rate when contraflow cycling is introduced on existing one-way streets (both rates are 7.4, 6.8–8.0), there is a statistically significant difference when two-way streets are converted to one-way with contraflow cycling - the crash rate falls by over a third from 10.6 (8.9–12.0) to 6.3 (5.2–7.6). There is also a statistically significant drop, again by over a third, in crash rates when two-way streets are converted to one-way with contraflow bus lanes and cycling from 85.3 (67.2–104.5) to 46.6 (39.5–55.4).

Comparing cordon cycling volume adjusted crash rates by pedal cycle direction shows that in the pre-contraflow period the crash rate involving pedal cycles travelling contraflow illegally on one-way streets is 0.8 (0.6–1.0) and is comparable to those travelling with flow in the opposite direction on two-way streets (0.7, 0.5–0.9) but lower than those travelling with flow (1.5, 1.2–1.8). This illegal contraflow crash rate is lower than that when people are legally allowed to cycle contraflow (2.2, 1.9–2.6). Examining the crash rate when contraflow cycling is allowed, the rate of crashes involving pedal cyclists travelling with the motor vehicle flow is identical to the crash rate of those travelling against the flow (both rates are 2.2, 1.9–2.6) and this is true even for raw rates (4.5, 3.9–5.2). The adjusted crash rate for those whose direction is not compatible, i.e. they are turning, is double that of those travelling along the road segment irrespective of whether occurring in pre-contraflow (6.1, 5.6–6.5) or contraflow (4.4, 3.9–4.8) period. These pedal cyclist direction rates confirm the earlier finding that pedal cyclists travelling on segments between junctions experience lower crash rates than those near junctions or roundabouts but additionally show that turning pedal cyclists experience lower crash rates after contraflow introduction.

3.7. Pedal cyclist casualty rates

In Table B6 we present pedal cyclist casualties numbers, rates and their 95 % confidence intervals for crashes involving pedal cycles within 10 m of a road segment by injury severity for the years that severity adjustment factors are available (2005–2019). Again, these rates are expressed per 100 years of exposure to the road segment status. They are presented as raw rates and rates adjusted for change in classification of injury severity and change in cordon cycling volume baselined to 1998. The casualty rates for the 1012 pedal cyclist casualties injured between 2005 and 2019 are visualised in Fig. 5.

Our analysis shows there is no difference in fatal pedal cyclist injury rates when contraflows are introduced. The raw rates suggest that seriously injured pedal cyclist casualties double when contraflows are introduced (pre-contraflow = 0.9, 0.6–1.3 v contraflow = 1.9, 1.5–2.3) and that slight injuries increase by nearly a third (11.2, 10.3–12.2 v 14.0, 13.2–14.8). Adjusting for the change in injury severity classification only alters the casualty rates for those with slight injuries. It reduces the slight casualty rate but does not alter the suggestion that they increase by nearly a third when contraflows are introduced. However, when the changes in cordon cycling volume are taken into consideration the findings change. There is no statistically significant difference in rates of pedal cyclist casualties that are seriously (0.5, 0.3–0.7 v 0.8, 0.6–1.0) or slightly injured (5.5, 5.0–6.0 v 5.8, 5.5–6.2) when contraflow cycling is introduced.

4. Discussion

4.1. Summary of key findings

During the 22 year study period, 508 road segments in inner London had contraflow cycling introduced with 10 having it removed. 1498 crashes involving pedal cycles occurred within 10 m of the 473 segments with a contraflow start date, although 167 of these road segments were not associated with any crashes. 788 crashes occurred prior to contraflow cycling being implemented, 703 occurred after the contraflow cycling was allowed and 7 occurred following its removal. Over 92 % of crashes occurred close to junctions or roundabouts.

Crash rates calculated using raw numbers suggest contraflow cycling increases crashes involving pedal cyclists. However, when the rate is adjusted using cordon cycling count data to take into account the significant changes in cycling volume that has occurred in London during the 22 years, there is no difference in overall crash rates before or after contraflow cycling is introduced.

The presence of a junction or roundabout within 10 m is associated with a doubling of the crash rate whilst converting a two-way street to one-way and contraflow cycling, with or without a contraflow bus lane, is associated with a reduction in the crash rate by over a third. The crash rate when pedal cyclists are cycling contraflow is identical to those travelling with the flow of motor vehicles. However, the crash rate when pedal cyclists are travelling in directions that are not compatible with the road segment, i.e. they are turning, is double that of cyclists travelling in compatible directions. Illegal contraflow cycling crash rates are no different than those cycling with flow. The pedal cyclist direction rates confirm the earlier finding that pedal cyclists travelling on segments between junctions experience lower crash rates than those near junctions or roundabouts but additionally demonstrate turning pedal cyclists experience lower crash rates after contraflow introduction.

Our casualty analysis demonstrates that there is no difference in the fatal, severely or slightly injured cyclist casualty rate when contraflows are introduced once change in cordon cycling volume and injury severity reporting changes are taken into account.

4.2. Interpretation of findings and contextualisation with the literature

Our findings corroborate existing evidence suggesting that there is no increase in crash risk when contraflow cycling is introduced on one-way streets (Vandenbulcke et al., 2014; Chalanton and Dupriez, 2014; UDV, 2016). It may even be true that the crash rate falls when contraflow cycling is introduced. This could be the case as contraflow interventions attract more cycling and route substitution onto the new infrastructure (Pritchard et al., 2019), raising the question of whether 'safety in numbers' effects apply to contraflows (Elvik and Goel, 2019). However, more data on cycling levels on specific road segments, including those with contraflows, are needed before conclusions on this question can be answered. If higher cycling volumes than we included in our adjustment are found on contraflows this would further reduce estimates of crash rates on contraflows.

In contrast to the existing evidence (Alrutz et al., 2002; Chalanton and Dupriez, 2014), we did not find any difference in crash rates for those travelling with or against motor traffic on road segments with contraflows. This may be explained by different approaches to calculating crash rates. We used the time duration of exposure to the different contraflow states to allow for the fact that some road segments were 'pre-contraflow' for most of the 22 years whilst others were 'contraflow' for a substantial period whereas Alrutz et al. (2002) and Chalanton and Dupriez (2014) use total length of contraflow segments and express their crash rates as 'per kilometre'. Alrutz et al. (2002) only included crashes that were indisputably on a contraflow road segment whereas Chalanton and Dupriez (2014) utilised a 10 m buffer to identify crashes. In common with both the contraflow cycling and wider cycling infrastructure literature, including that focussed on London (e.g. Collins and Graham, 2019; Adams and Aldred, 2020), we identify proximity to junctions or roundabouts as being a significant cyclist crash association.

We found that converting a two-way road to one-way with contraflow cycling was associated with reduced adjusted crash rates of over a third. This contrasts with research from the USA where two-way streets are considered safer. However, this also reflects contrasting street designs: in the USA one-way streets tend to be wide, multilane structures thus conversion to two-way improves safety (Riggs and Gilderbloom, 2016; Riggs and Gilderbloom, 2017). Previous UK research has found that bus lanes are associated with both increasing (Kapousizis et al., 2021) and decreasing cycling injury risk (Adams and Aldred, 2020; Aldred et al., 2018). However, none of these studies have focused on contraflow bus lanes where we found the adjusted crash rate was over a third lower after their introduction.

Our findings need to be considered in real world terms. The overall adjusted crash rates where the pre-contraflow crash rate is 9.0 and the contraflow rate is 8.8, this equates to a crash occurring on such a road segment once every 11 years, respectively. Whilst the adjusted severe pedal cyclist injury rates of 0.5 during the pre-contraflow and 0.8 during the contraflow period correspond to a single severely injured pedal cyclist every 200 (pre-contraflow) or 125 (contraflow) years of exposure to such road segments.

5. Strengths and limitations

Our study is the first large data analysis of crashes occurring on road segments before and after contraflow cycling has been implemented, to the best of our knowledge. It examines a substantial time period (22 years) and large physical area (inner London) with hundreds of road segments. We utilised The Gazette (TSO, 2022a) where it is legally mandatory for London transport authorities to publish information on certain road infrastructure changes and the official UK road traffic crash datasets, both of which should be considered the gold standard for this data. In line with accepted practice, we have adjusted the crash rate for cycling exposure both in terms of duration of exposure to the specific road segment status and cycling volume (Vanparijs et al., 2015). We used a recognised statistical technique (bootstrapping) to vary crashes by year and crash timescale in order to estimate uncertainty of our crash rates and generate confidence intervals.

We believe our pedal cycle direction crash rate analysis provides the most compelling evidence about safety of contraflows themselves as it identifies cyclists most likely to be travelling on the road segments as opposed to those interacting with junctions and negates any crashes that may have been erroneously included by our 10 m buffering process. We also believe this is the first analysis of the impact of introducing contraflow bus lanes and the first use of injury adjustment factors for UK road traffic crashes.

Our approach is not without limitations. First, we assumed that the road segment data coded and provided in The Gazette is high-quality data and as such is accurate, complete, reliable, relevant and timely (Wand and Wang, 1996). We have assumed that: all contraflows that were implemented have a TRO that can be detected using the 'contraflow' search term; the TRO content contains accurate information about the contraflow order including location, action and whether consulting, introducing or rescinding an order etc; and the contraflow start date is accurate. Furthermore we have assumed that none of the infrastructure had been changed further unless a new TRO exists. We attempted to mitigate these issues by validating the TRO data against other datasets such as the CID and OSM and identifying contraflows in the CID and OSM and cross-referencing them with The Gazette. It would have strengthened the analysis if we had been able to consider the additional cycling infrastructure, for example, cycle lanes, in our rate calculations as such infrastructure may have affected crashes. This is something that none of the previous contraflow studies had examined (Pritchard et al., 2019; Ryley and Davies, 1998; Alrutz et al., 2002; Bjørnskau et al., 2012; Chalanton and Dupriez, 2014; UDV, 2016). However, there are considerable unmeasured aspects of such infrastructure in our data; for example, whether it was installed, positional uncertainty and measurement uncertainty. This lack of data coupled with the challenge of how to include this 'exposure' in our rate calculation meant we were unable to consider this aspect.

Second, the UK road traffic crash dataset has limitations. Concerns exist around the accuracy of data on vehicle direction of travel and geospatial crash location (Anderson, 2003; DfT, 2021c; Imprialou and Quddus, 2019) and casualty severity reporting (DfT, 2020e). We have addressed these issues by validating pedal cycle direction against road axes, using 10 m buffers around the road segments and adjusting casualties using the official severity probabilities. It is known that there is under-reporting of crashes involving pedal cycles (e.g. Ward et al., 2005; Jeffrey et al., 2009) and so our rates may not reflect the true number of these crashes occurring on London roads.

Third, we have not adjusted for all potential confounders. For example, road traffic crashes involving pedal cyclists are affected by weather, light conditions, road conditions, driver behaviour and road speed (Knowles et al., 2009; Prati et al., 2018; Young and Whyte, 2020). However, our descriptive tables suggest that the crashes, casualties and vehicles occurring pre and during the contraflow period are comparable despite occurring at different points during our 22 year study period.

Fourth, whilst we have adjusted for change in cycling volume, our cycling volume data is based on cordon traffic counters not individual road segment cycling volume. This data does not accurately reflect cyclist spatial distribution or volume (von Stülpnagel et al., 2022). It also does not take into account potential increases in cycling volume on the contraflow segment as a consequence of this infrastructure being introduced (Pritchard et al., 2019). We have also assumed a linear relationship between crash risk and cycling volume but this does not make allowances for the safety-in-numbers effect that suggests this relationship may not be linear (Aldred et al., 2018; Elvik and Goel, 2019). Obtaining and utilising quality cyclist exposure data is difficult (Vanparijs et al., 2015) and the cordon traffic counters are the best official open cycling volume data we have for the full duration of the study period. Additionally, using a long study period, multiple road segments, official data sets, adjusting over time and aggregating the rates means that any confounders or systematic biases are likely to even out over the 22 year period making this the most comprehensive data analysis of UK pedal cyclist crash risks on contraflows.

5.1. Implications for policy and future research

Our research provides strong evidence that all UK one-way streets should allow contraflow cycling unless there are compelling reasons against this position. This is already recommended by the Department for Transport (DfT, 2020a) and provides a cost-effective alternative to more substantial cycling infrastructure changes. We recommend all UK local transport authorities review their one-way (for motor traffic) streets with a view to allowing contraflow cycling and examine their two-way streets for potential to reconfigure to one-way streets or contraflow bus lanes with contraflow cycling. Our results suggest that safe junction design should be a priority. We call on national governments to consider implementing legislative change making it mandatory for one-way streets to be two-way for pedal cyclists unless there are exceptional conditions. Such laws have been introduced in Belgium (Depoortere, 2019). More broadly, large scale investment in contraflows will strengthen cycling networks and routes by not only improving the coherence, directness, attractiveness and comfort but also their safety, increasing their level of compliance with design guidance (DfT, 2020a).

The substantial benefits of preventing crashes involving pedal cyclists are felt by health services, businesses and the economy as well as individuals, families and communities. The value of preventing urban crashes are estimated to be £2.5 million for fatal, £280,000 for severe and £28,000 for slight crashes whilst the average value of preventing a pedal cyclist casualty is £90,000 (2022 estimates, DfT, 2022d). Our findings suggest that introducing contraflow cycling is an intervention that may improve road safety and could reduce crash and casualty costs particularly if it attracts more cyclists who then benefit from a safety-in-numbers effect. However, our analysis does not consider crashes or casualties that occur on nearby streets that might have been used by cyclists in the pre-contraflow period because there was no contraflow cycling allowed on their direct route. If these adjacent street crashes and casualties were considered then additional benefits may be accrued. This is because pre-contraflow routes may have included busier and faster nearby roads with concomitant greater number of crashes and casualties whilst when contraflow cycling is introduced there is greater route directness and route substitution from the nearby streets onto the new contraflows that may decrease crashes on these adjacent streets.

Our research has highlighted the difficulties and importance in obtaining good quality data and evidence around cycling infrastructure to challenge arguments that are not evidence-based. It may be that other beliefs and assumptions in this arena are unfounded and under-researched. This may be due to the long time duration required to generate enough exposure and crashes and hindered by lack of open granular data such as actual road speeds, cycling volumes and motor vehicle volumes. Building on our previous call for open data inventories of cycling infrastructure (Tait et al., 2022), our research demonstrates their importance and utility to build the evidence base around cycling infrastructure. We welcome the proposed new requirement for English transport authorities to publish standardised open TRO data (DfT, 2022e) as this will enable many types of cycling infrastructure to be evaluated more easily using the approaches we have demonstrated.

We have shown the importance of using an appropriate denominator in the calculation of crash rates. When we accounted for the change in cycling volume we found no evidence that contraflow cycling increases crash risk. However, our denominator lacked granularity or specificity for contraflows. We believe our findings could be reproduced and strengthened by performing the analysis with better cyclist volume data but to achieve this there must be better monitoring of cyclist volume. This could be realised through traditional manual counting or newer technologies such as machine learning analysis of video camera images (e.g. Foroozandeh Shahraki et al., 2017; Edwardes et al., 2021) augmented with emerging data sources (Alattar et al., 2021) such as crowdsourced data to improve the spatial and temporal granularity (Conrow et al., 2018; Kwigizile et al., 2022).

6. Conclusion

This is the first large-scale analysis of the impact of introducing contraflow cycling on one-way streets. We have found no evidence that contraflow cycling infrastructure alters the crash or casualty rate for pedal cyclists and it may be protective. Crash rates are consistent whether the cyclist is travelling with or contraflow. Transport authorities should consider implementing contraflow cycling on all one-way streets and consider conversion of appropriate two-way streets to one-way with contraflow cycling to improve cycling networks and routes. As crash rates are elevated at junctions and when cyclists are turning, careful junction design must form part of any such improvement. Governments with suitable styles of one-way streets should explore legislative options to make them two-way for pedal cyclists by default.

Our analysis was only possible after intensive primary data collection from TROs that identified contraflow cycling infrastructure and their introduction dates and association of this data with spatial road segment data and spatio-temporal pedal cycle crashes and casualties. We have demonstrated an approach that can be replicated, strengthened and applied to other areas of cycling infrastructure evaluation that are urgently needed through the use of new datasets such as the proposed digital TRO dataset. Further research on contraflows should utilise new ways to collect cyclist levels (exposure) and utilise site-specific cycling volume data to improve rate calculation. Such research should also investigate the impact of different types of cycling infrastructure implemented on contraflows and evaluate impact on cycling volume including route substitution onto the new contraflows. This research would be strengthened through detailed datasets on the exact nature of contraflow interventions and the surrounding active travel environment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data and code that form this analysis is available at: https://github.com/PublicHealthDataGeek/Contraflow_cycling_safety.

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TfL data: Powered by TfL Open Data. Contains OS data © Crown copyright and database rights 2016 and Geomni UK Map data © and database rights [2019].

The Gazette, Office of National Statistics and UK Road Traffic crash data: Licensed under the Open Government Licence v3.0. http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3.

OpenStreetMap data: © OpenStreetMap contributors and available under Open Database Licence. Contains Ordnance Survey data © Crown copyright and database right 2010-19. https://www.openstreetmap.org/copyright.

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Appendix A. Additional information about the methods

Road segments that allow contraflow cycling

Relevant TROs were identified by searching The Gazette for Road Traffic Regulation Act Notices (notice code 1501) (TSO, 2022c) containing the text 'contraflow' or 'contra-flow' (lower case text search returned the same results as upper case or capitalised words). Search results were limited to those in the study time period and location. We utilised the following search terms to identify TROs issued by relevant

Table A1
TRO data collection dataset.

Variable name	Variable description	Source
unique_row_ID	Unique ID for row in dataframe	Created
Borough	Borough name	TRO content
Organisation	Organisation involved (borough, Transport for London, Corporation of London	TRO content
road_name	Road name	TRO content
unique_contraflow_ID	Unique ID for the contraflow segment. Unique means unique in terms of road name, road contraflow limits, borough, contraflow start date, contraflow stop date and the type of action in terms of introducing: one way street, contraflow cycling, contraflow cycle lane, contraflow cycle track, contraflow cycling in footway, a contraflow bus lane, contraflow cycling in a bus lane or segregated contraflow cycle lane.	Created
road_limits_char	Describes the extent of the contraflow segment e.g. entire length of named road or length of named road between junctions A and B	TRO content
order_action	Text string that describes action: enable contraflow cycling, contraflow cycle track, contraflow lane, contraflow cycling in bus lane	TRO content
introduces_one_way_street	TRUE if TRO specifies that one way working/one way street introduced at the same time	TRO content
Introduces_cf_Cyclelane	TRUE if TRO states a contraflow cycle lane will be introduced	TRO content
Introduces_cf_Cycletrack	TRUE if TRO states a contraflow cycle track will be introduced	TRO content
Introduces_cf_footway	TRUE if TRO specifically mentions allowing contraflow cycling on the footway or if when looking at OpenStreetMap the area is pedestrianised	TRO content
introduces_contraflow_bus_lane	TRUE if TRO specifies that contraflow bus lane introduced at the same time	TRO content
Enables_cf_cycling_in_bus_lane	TRUE if TRO states cycling will be allowed in a contraflow bus lane	TRO content
Introduces_cf_seg_cyclelane	TRUE if TRO states contraflow cycle lane will be segregated	TRO content
FEATURE_ID	CID contraflow ID that spatially matches the contraflow	CID (identified spatially)
osm_id	OSM contraflow that spatially matches the contraflow	OSM (identified spatially)
spatial_data_ok	TRUE if all spatial dimensions of contraflow covered by OSM or CID data, FALSE if it isn't	Decision on examining spatial data
sp_d_not_ok_create_new	TRUE if spatial dimensions of contraflow not covered by CID/OSM data and need to create new spatial object (lat and long for linestring of spatial object recorded, if line bends then create new line for each part of linestring	Decision on examining spatial data
point_1	lat long of point 1	OSM (identified spatially)
point_2	lat long of point 2	OSM (identified spatially)
contraflow_start_date	Date contraflow becomes operational	TRO content
Evid_contraflow_exists	TRUE if have OSM or later TRO that says the contraflow exists, FALSE if no evidence - these ones will probably be deleted	CID, OSM, TRO content
contraflow_stop_date	Date contraflow is revoked	TRO content
notice_id_1	ID for first TRO (the earliest TRO regarding the contraflow)	Gazette listing
publication_date_1	Publication date of first TRO (defined by content of TRO or if not in content then the 'date of publication in the gazette)	TRO content (some cases Gazette listing)
pub_date_1_source_TRO	TRUE if the date of publication is contained within the body text of the TRO. FALSE means no date is contained within the body text of the TRO and instead date of publication in the Gazette is taken as the date	TRO content
tro_type_1	Type of TRO: Permanent or Experimental	TRO content
tro_action_1	Action of TRO: Consultation, Introduction, Revocation	TRO content
notice_id_2	ID for second TRO	Gazette listing
publication_date_2	Publication date of second TRO (defined by content of TRO or if not in content then the 'date of publication in the gazette)	TRO content (some cases Gazette listing)
pub_date_2_source_TRO	TRUE if the date of publication is contained within the body text of the TRO. FALSE means no date is contained within the body text of the TRO and instead date of publication in the Gazette is taken as the date	TRO content
tro_type_2	Type of TRO: Permanent or Experimental	TRO content
tro_action_2	Action of TRO: Consultation, Introduction, Revocation	TRO content
notice_id_3	ID for third TRO	Gazette listing
publication_date_3	Publication date of third TRO (defined by content of TRO or if not in content then the 'date of publication in the Gazette)	TRO content (some cases Gazette listing)
pub_date_3_source_TRO	TRUE if the date of publication is contained within the body text of the TRO. FALSE means no date is contained within the body text of the TRO and instead date of publication in the Gazette is taken as the date	TRO content
tro_type_3	Type of TRO: Permanent or Experimental	TRO content
tro_action_3	Action of TRO: Consultation, Introduction, Revocation	TRO content

Fig. A1. Types of UK cycling infrastructure (images taken from TFL 2019d).

bodies not listed in the drop-down borough search option: 'Transport for London', 'Corporation of London', 'City of London' and 'City of Westminster'.

Each TRO description was read to identify new contraflow cycling interventions on specific road segments and their details Table A1. Some TRO specified that additional cycling infrastructure was due to be introduced. Fig. A1 illustrates the UK types of additional cycling infrastructure that may be introduced (NB images do not necessarily show how such infrastructure would look on a contraflow street).

Changes to unique segments, for example upgrading to segregated contraflow cycle lanes, were captured as separate data observations. Subsequent TROs, for example a second TRO ordering the introduction of contraflow cycling following a consultation TRO, were also captured and linked to previous TRO.

Cyclist volume data

Manual cordon count data for all types of traffic has been collected since 1971 by Transport for London (TFL, 2012). 3 cordons exist covering central, inner and outer London. Counts are taken on every road site crossing the cordon. They are performed four times each hour between 6am and 10 pm on weekdays. Some additional counts have been made on weekends to enable comparison between weekdays and weekends, Central cordon counts are performed in autumn whilst inner and outer cordon counts are performed in the summer. For our study period the following cyclist cordon counts data was available (TFL, 2019c; TFL, 2021). Central cordon data was available for the year 1999 and then for all years between 2001 and 2019. For the inner London cordon, counts were available for the years 1999, 2002, 2004, 2005, 2008 and biannually until 2018 that whilst outer cordon counts were available for the years 1998, 2001, 2004, and biannually from 2007 to 2019.

Pedal cycle direction

We utilised the following method to identify the direction the pedal cycle was travelling in relation to whether this was 'with flow' or 'contraflow'. The direction the pedal cycle was travelling in was obtained from the STATS19 variables "vehicle direction from' and 'vehicle direction to'. We identified the traffic flow direction on the road segments from the TRO and/or OSM. Where the pedal cycles' direction from and to matched the axis of the road segment traffic flow then the pedal cycle flow was defined as either: 'with flow'; 'with flow (opposite)' when travelling in the opposite direction on a pre-contraflow or contraflow removed road segment that was two-way; 'contraflow (illegal)' when travelling against the flow on a one-way street prior to contraflow introduction; or 'contraflow' when travelling contraflow when contraflow cycling was allowed. Where a pedal cycle direction did not match the axis, for example, travelling perpendicular or the 'from' matched but the 'to' did not these were labelled as 'Direction not compatible' and assumed to be travelling on other road segments (such as at a crossing) or turning on or off the road segment. For road segments that had more than one axis, for example, those that have a bend, the road segment and crashes were visually mapped to identify the axis at the crash location and the appropriate flow was then attributed.

When calculating crash rates by pedal cycle direction, we included all pedal cycles where we have a vehicle direction. This means that in the small number of crashes where two pedal cycles were involved, these are both included in the numerator.

Appendix B. Additional results tables

(See Fig. B1 and Tables B1 – B6).

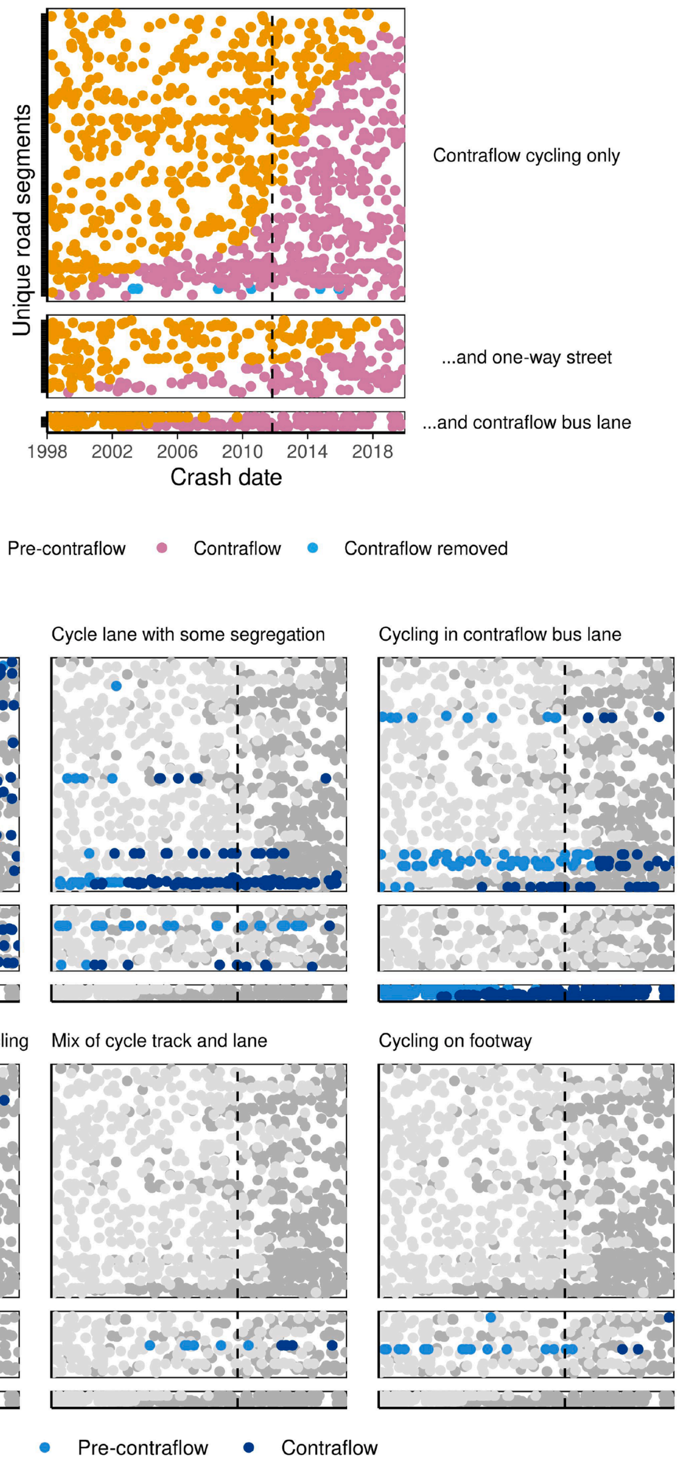

Fig. B1. Dot visualisation of all crashes involving pedal cycles within 10 m of a road segment by unique road segment (vertical position); date of crash (horizontal position); crash segment status (colour); and significant change to road segments (pane). Top visualisation represents all crashes. Lower visualisations highlight crashes by additional cycling infrastructure mentioned in Traffic Regulation Order. The seven contraflow removed crashes have been omitted to aid visualisation.

Table B1
Number (%) of contraflow cycling road segments introduced by borough.

Borough	Number (%)
City of London	93 (18.3)
Southwark	85 (16.7)
Lambeth	63 (12.4)
Camden	60 (11.8)
Kensington and Chelsea	45 (8.9)
Westminster	33 (6.5)
Hackney	29 (5.7)
Newham	23 (4.5)
Lewisham	19 (3.7)
Greenwich	16 (3.1)
Islington	16 (3.1)
Wandsworth	13 (2.6)
Hammersmith and Fulham	8 (1.6)
Tower Hamlets	5 (1.0)

Table B2
Calculation of proportion of road segment length within 20 m of a junction.

Number of road segments with a crash	306
Total length of these road segments within 20 m of a junction*	27564 m
Total length of these road segments	43805 m
Proportion of road segment length within 20 m of a junction	63 %

* Junctions extracted from OSM January 2019 data.

Table B3
Number of unique road segments where contraflow cycling was introduced by significant change to road segments, additional cycling infrastructure, whether they had a crash on the road segment or not and crash segment status; and number of crashes by significant change to road segments, additional cycling infrastructure and crash segment status.

Significant change to road segment	Additional cycling infrastructure mentioned in Traffic Regulation Order	Number of unique road segments (proportion of total number of segments)					Number of crashes		
		Total	Any crash	Crash segment status			Crash segment status		
				Pre-contraflow	Contraflow	Contraflow removed	Pre-contraflow	Contraflow	Contraflow removed
Contraflow cycling only	No additional action	265	167 (63)	137 (51.7)	92 (34.7)	0 (0)	346	204	0
	Cycle lane	71	48 (67.6)	29 (40.8)	33 (46.5)	1 (1.4)	83	96	7
	Cycle lane with some segregation	14	12 (85.7)	8 (57.1)	11 (78.6)	0 (0)	26	108	0
	Cycling in contraflow bus lane	9	7 (77.8)	7 (77.8)	6 (66.7)	0 (0)	64	42	0
	Cycle track and cycling on footway	3	2 (66.7)	2 (66.7)	2 (66.7)	0 (0)	13	7	0
One-way street and contraflow cycling	No additional action	59	38 (64.4)	34 (57.6)	17 (28.8)	0 (0)	84	40	0
	Cycle lane	32	16 (50)	8 (25)	12 (37.5)	0 (0)	41	55	0
	Cycle lane with some segregation	5	3 (60)	2 (40)	3 (60)	0 (0)	28	10	0
	Cycling on footway	2	2 (100)	2 (100)	2 (100)	0 (0)	17	3	0
	Cycle track and cycling on footway	1	1 (100)	0 (0)	1 (100)	0 (0)	0	1	0
	Cycle track and lane	1	1 (100)	1 (100)	1 (100)	0 (0)	6	5	0
Contraflow bus lane and contraflow cycling	Cycling in contraflow bus lane	11	9 (81.8)	6 (54.5)	9 (81.8)	0 (0)	80	132	0

Table B4
Pedal cycle direction in crashes involving pedal cycles within 10 m of road segments by crash segment status occurring between 1st January 1998 and 31st December 2019 (inclusive) by crash segment status, pre-TRO road status and proximity to junctions or roundabouts.

Pre- TRO status	Proximity to junction or roundabout		More than 10 m from a junction or roundabout (OSM determined)			Within 10 m of a junction or roundabout (OSM determined)		
	Crash segment status		Pre - contraflow	Contraflow	Contraflow removed	Pre - contraflow	Contraflow	Contraflow removed
One way	Number of crashes		118	109	4	414	348	3
	Pedal cycle 1 direction	With flow	32 (27.1)	34 (31.2)	0 (0.0)	51 (12.3)	66 (19.0)	0 (0.0)
		Contraflow (illegal)	18 (15.3)	–	0 (0.0)	48 (11.6)	–	0 (0.0)
		Contraflow	–	30 (27.5)	–	–	82 (23.6)	–
		Direction not compatible	68 (57.6)	43 (39.4)	4 (100.0)	315 (76.1)	196 (56.3)	3 (100.0)
		Unknown	0 (0.0)	2 (1.8)	0 (0.0)	0 (0.0)	4 (1.1)	0 (0.0)
	Pedal cycle 2 direction	With flow	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (14.3)	0 (0.0)
		Contraflow (illegal)	1 (100.0)	–	0 (0.0)	2 (66.7)	–	0 (0.0)
		Contraflow	–	0 (0.0)	–	–	3 (42.9)	–
		Direction not compatible	0 (0.0)	0 (0.0)	0 (0.0)	1 (33.3)	3 (42.9)	0 (0.0)
		Unknown	0 (0.0)	1 (100.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Two way	Number of crashes		80	98	0	176	148	0
	Additional TRO action from two-way to…	One-way street	56 (70.0)	39 (39.8)	1 (100.0)	120 (68.2)	75 (50.7)	0 (0.0)
		One-way street with contraflow bus lane	24 (30.0)	59 (60.2)	0 (0.0)	56 (31.8)	73 (49.3)	0 (0.0)
	Pedal cycle 1 direction	With flow	16 (20.0)	36 (36.7)	0 (0.0)	25 (14.2)	34 (23.0)	0 (0.0)
		With flow (opposite)	23 (28.7)	–	0 (0.0)	29 (16.5)	–	0 (0.0)
		Contraflow	–	21 (21.4)	–	–	33 (22.3)	–
		Direction not compatible	41 (51.2)	41 (41.8)	0 (0.0)	122 (69.3)	78 (52.7)	0 (0.0)
		Unknown	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	3 (2.0)	0 (0.0)
	Pedal cycle 2 direction	With flow	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
		With flow (opposite)	0 (0.0)	–	0 (0.0)	0 (0.0)	–	0 (0.0)
		Contraflow	–	2 (100.0)	–	–	1 (50.0)	–
		Direction not compatible	0 (0.0)	0 (0.0)	0 (0.0)	1 (100.0)	1 (50.0)	0 (0.0)
		Unknown (self reported)	0 (0.0)	0 (0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)

No crashes involved more than two pedal cycles. Direction not compatible means that the direction the pedal cycle was travelling from and to is not compatible with the road segment direction. '-' indicates that this type of direction is not possible given the road segment status and crash timescale. Data is presented as 'number (percentage)'.

Table B5
Pedal cyclist crash rates within 10 m of road segments per 100 years of exposure to road segment status. Rates are presented as raw and adjusted for cordon cycling volume (1998 index) as: overall; by proximity for junction or roundabout (within 10 m); by significant change to road segment; and by pedal cycle direction. 95 % confidence intervals generated by bootstrapping 1000 resamples with replacement.

Analysis	Rate type	Crash segment status	Sub-analysis	Number of crashes [1]	Time duration of segment exposure (days)	Crash rate per 100 years of exposure to road segment at that status (95 % confidence interval)
Overall	Raw	Pre-contraflow		788	2,396,119	12.0 (11.4–12.6)
		Contraflow		703	1,392,487	18.4 (17.4–19.4)
		Contraflow removed		7	11,949	21.4 (9.2–39.7)
	Adjusted	Pre-contraflow		591	2,396,119	9.0 (8.5–9.5)
		Contraflow		335	1,392,487	8.8 (8.2–9.3)
		Contraflow removed		4	11,949	10.8 (3.8–19.9)
By junction status	Raw	Pre-contraflow	Junction or roundabout within 10 *m*	590	2,396,119	9.0 (8.4–9.5)
		Contraflow		496	1,392,487	13.0 (12.1–13.9)
		Contraflow removed		3	11,949	9.2 (3.1–21.4)
		Pre-contraflow	No junction or roundabout in 10 *m*	198	2,396,119	3.0 (2.6–3.4)
		Contraflow		207	1,392,487	5.4 (4.8–6.2)
		Contraflow removed		4	11,949	12.2 (3.1–24.4)
	Adjusted	Pre-contraflow	Junction or roundabout within 10 *m*	448	2,396,119	6.8 (6.4–7.3)
		Contraflow		233	1,392,487	6.1 (5.6–6.6)
		Contraflow removed		2	11,949	6.2 (1.2–15)
		Pre-contraflow	No junction or roundabout in 10 *m*	142	2,396,119	2.2 (1.9–2.5)
		Contraflow		102	1,392,487	2.7 (2.3–3.1)
		Contraflow removed		2	11,949	4.6 (1.0–9.7)
By significant change to road segment	Raw	Pre-contraflow	Contraflow cycling only	532	1,900,788	10.2 (9.5–10.9)
		Contraflow		457	997,484	16.7 (15.4–18)
		Contraflow removed		7	10,398	24.6 (10.5–45.6)
		Pre-contraflow	One-way street and contraflow cycling	176	464,771	13.8 (12.0–15.5)
		Contraflow		114	337,250	12.3 (10.3–14.5)
		Pre-contraflow	Contraflow bus lane and contraflow cycling	80	30,560	95.5 (75.2–115.9)
		Contraflow		132	57,753	83.4 (70.8–98.6)
	Adjusted	Pre-contraflow	Contraflow cycling only	385	1,900,788	7.4 (6.8–8.0)
		Contraflow		203	997,484	7.4 (6.8–8.0)
		Contraflow removed		4	10,398	12.4 (4.4–22.9)
		Pre-contraflow	One-way street and contraflow cycling	134	464,771	10.6 (8.9–12.0)
		Contraflow		58	337,250	6.3 (5.2–7.6)
		Pre-contraflow	Contraflow bus lane and contraflow cycling	71	30,560	85.3 (67.2–104.5)
		Contraflow		74	57,753	46.6 (39.5–55.4)
By pedal cycle direction	Raw	Pre-contraflow	With flow [2]	124	2,396,119	1.9 (1.6–2.2)
			With flow (opposite) [3]	52	2,396,119	0.8 (0.6–1.0)
			Contraflow (illegal) [4]	69	2,396,119	1.1 (0.8–1.3)
			Direction not compatible	548	2,396,119	8.3 (7.8–8.9)
		Contraflow	With flow	171	1,392,487	4.5 (3.9–5.2)
			Contraflow	172	1,392,487	4.5 (3.9–5.2)
			Direction not compatible	362	1,392,487	9.5 (8.6–10.4)
			Unknown	10	1,392,487	0.3 (0.1–0.4)
		Contraflow removed	Direction not compatible	7	11,949	21.4 (9.2–39.7)
	Adjusted	Pre-contraflow	With flow [2]	97	2,396,119	1.5 (1.2–1.8)
			With flow (opposite) [3]	47	2,396,119	0.7 (0.5–0.9)
			Contraflow (illegal) [4]	50	2,396,119	0.8 (0.6–1.0)
			Direction not compatible	400	2,396,119	6.1 (5.6–6.5)
		Contraflow	With flow	84	1,392,487	2.2 (1.9–2.6)

(*continued on next page*)

Table B5 (*continued*)

Analysis	Rate type	Crash segment status	Sub-analysis	Number of crashes [1]	Time duration of segment exposure (days)	Crash rate per 100 years of exposure to road segment at that status (95 % confidence interval)
			Contraflow	85	1,392,487	2.2 (1.9–2.6)
			Direction not compatible	167	1,392,487	4.4 (3.9–4.8)
			Unknown	4	1,392,487	0.1 (0.0–0.2)
		Contraflow removed	Direction not compatible	4	11,949	10.8 (3.8–19.9)

[1]Number of crashes rounded to nearest integer.
[2]This includes all one and two-way roads in the pre-contraflow period.
[3]This only includes two-way roads in the pre-contraflow period.
[4]This only includes one-way roads in the pre-contraflow period.

Table B6
Pedal cyclist casualty rates per 100 years of exposure by road segment status and injury severity, 2005–2019. Rates are presented as raw, adjusted for change in injury severity classification; and adjusted for change in injury severity classification and cordon cycling volume (1998 index). 95 % confidence intervals generated by bootstrapping 1000 resamples with replacement.

Analysis	Crash segment status	Injury severity	Number of pedal cyclist casualties [1]	Time duration of segment exposure (days)	Pedal cyclist casualty rate per 100 years of exposure to road segment at that status (95 % confidence interval)
Raw	Pre-contraflow	Fatal	4	1,186,657	0.1 (0.0–0.3)
		Serious	30	1,186,657	0.9 (0.6–1.3)
		Slight	364	1,186,657	11.2 (10.3–12.2)
	Contraflow	Fatal	3	1,392,488	0.1 (0.0–0.2)
		Serious	72	1,392,488	1.9 (1.5–2.3)
		Slight	535	1,392,488	14.0 (13.2–14.8)
	Contraflow removed	Serious	1	11,949	3.1 (3.1–12.2)
		Slight	3	11,949	9.2 (3.1–21.4)
Adjusted for change in injury severity classification	Pre-contraflow	Fatal	4	1,186,657	0.1 (0.0–0.3)
		Serious	30	1,186,657	0.9 (0.6–1.3)
		Slight	332	1,186,657	10.2 (9.4–11.1)
	Contraflow	Fatal	3	1,392,488	0.1 (0.0–0.2)
		Serious	72	1,392,488	1.9 (1.5–2.3)
		Slight	501	1,392,488	13.1 (12.4–13.9)
	Contraflow removed	Serious	1	11,949	3.1 (3.1–12.2)
		Slight	3	11,949	8.4 (2.7–19.4)
Adjusted for change in injury severity classification and annual cycle volume (1998 index)	Pre-contraflow	Fatal	2	1,186,657	0.1 (0.0–0.2)
		Serious	16	1,186,657	0.5 (0.3–0.7)
		Slight	177	1,186,657	5.5 (5.0–6.0)
	Contraflow	Fatal	1	1,392,488	0.0 (0.0–0.1)
		Serious	31	1,392,488	0.8 (0.6–1.0)
		Slight	222	1,392,488	5.8 (5.5–6.2)
	Contraflow removed	Serious	0	11,949	1.0 (1.0–4.2)
		Slight	1	11,949	3.3 (0.8–7.7)

[1] Number of casualties rounded to nearest integer.

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Chapter 4

Paper 3: Build it but will they come? Exploring the impact of introducing contraflow cycling on cycling volumes with crowd-sourced data

Again an extract from my thesis showing how this chapter can be written and how the references appear at the end of the chapter

4.1 Abstract

Contraflow cycling on one-way streets is a low cost intervention that is safe and can improve the cycling experience. The evidence on its impact on cycling participation is patchy and based on small studies involving a few streets and short duration of follow up. In this paper, we use crowd-sourced data to assess the impact of introducing contraflow cycling on cycling volumes on multiple one-way streets. We qualitatively assess factors that are associated with change in cycling volume on such infrastructure.

Using a primary dataset of roads where contraflow cycling was introduced in inner London between April 2018 and October 2019, we matched these roads with monthly Strava Metro cycling count data before and after the intervention. We identified the count direction as either with or against motor vehicle flow. We generated expected counts adjusted for changes in Strava trips, users, seasonality and time of year by examining global change in monthly Strava counts during the study period. We used national cycle infrastructure design guidance for contraflow infrastructure and Google Street View to qualitatively assess the quality of the contraflow infrastructure.

There were 28 one-way streets and 14 two-way streets (which were converted to one-way streets) that introduced contraflow cycling. Three one-way streets experienced significant

increases in mean contraflow trips (260, 630 and 1750 percent) that were much higher than expected. They also had increased numbers of people post-implementation. A number of other streets had higher counts post-intervention. Increases in contraflow cycling were less apparent for the former two-way roads. Illegal contraflow cycling was popular on many streets pre-introduction. Qualitative assessment of 12 streets demonstrated that local context such as connectivity, protected entrances and segregation of infrastructure and external factors (e.g. construction) were important in determining whether the intervention increased contraflow cycling.

We have found that the introduction of contraflow cycling can increase cycling participation on one-way streets but that local factors are important in determining volumes. Large-scale adoption of this low cost infrastructure could significantly improve cycle routes and networks. Legislative change to make all one-way streets contraflow by default would facilitate such implementation. Further work could utilise other data sources to assess the representativeness of the Strava Metro data and to triangulate these findings.

4.2 Introduction

Contraflow cycling, where cycling occurs bidirectionally along a road that is limited to one-way for motor vehicles, can improve cycling networks and routes by making them more coherent, direct, attractive, comfortable and safe (DfT, 2020). It can improve the cycling experience by enabling cyclists to use quieter rather than busy streets; make journeys more direct thus reducing the distance, energy and time; and simplify journey planning by using the same road each way (PRESTO, 2010). Furthermore, it has been claimed to increase cycling volumes (Ryley and Davies, 1998; Bjørnskau et al., 2012; Burkin, 2019; Pritchard et al., 2019) and result in route substitution onto the new infrastructure (Pritchard et al., 2019).

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Chapter 5

Discussion

This qmd file contains both the discussion and conclusion. I dont know quite why it works like this but then labels the Conculsion as a separate chapter but it works so I have rolled with it!

5.1 Overview

In this chapter the key findings for each of the research questions are presented. The body of research is then considered in terms of the original aim by discussing infrastructure evaluation, addressing the research gaps and generating evidence for policy-makers. Limitations of the research are then presented followed by policy recommendations and proposed areas for future research. The section finishes with the Conclusion.

5.2 Key findings

This thesis sought to evaluate the impact of cycling infrastructure using large observational datasets. To do this, three research questions were developed. This section presents the key findings for each research question.

5.2.1 RQ1: What cycling infrastructure exists in London?

This question was explored in Chapter 2 in the paper *"Is cycling infrastructure in London safe and equitable? Evidence from the cycling infrastructure database"*. This was the first analysis of the London cycling infrastructure database (CID) and analysed cycling infrastructure provision and cycle lane quality. It demonstrated that the quantity and quality of infrastructure was not equal across London. People living in outer London had less infrastructure that provided safe space for cycling than inner London. This pattern persisted when adjusted for area and population but was inverted when adjusted for commuter cycling. Traffic calming was the most common infrastructure and found in 58,585 locations. Just six percent of on-road cycle lane length was physically segregated from motor traffic. Estimated mean compliance with national design guidance (DfT, 2020a) for protection of cyclists in cycle lanes from motor vehicle traffic based on segregation and road speed limits was 22%. This varied by location with 64% of inner London boroughs exceeding the mean compliance compared to just 16% of outer London boroughs. Estimated compliance was higher than perhaps the low levels of physical segregation would predict. This was due to low road speed limits making non-physical separation acceptable i.e. compliance was achieved automatically rather than through deliberately-designed infrastructure.

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5.3 Interpretation and contextualisation of the thesis

The aim of this thesis was to contribute original research evaluating the effect of cycling infrastructure on cyclist safety and participation using large, observational datasets to address research gaps in this field and generate evidence that can influence policy and have real-world impact.

5.3.1 Evaluating infrastructure

Paper 1 used a new database for London containing 234,251 cycling infrastructure objects to examine common evaluation questions such as what type, how much and where infrastructure is located. It also compared the provision of infrastructure that aimed to promote safe cycling space between areas, taking into account factors such as cycling volume, population size and area to make fairer comparisons, before evaluating the quality of infrastructure against a criteria. These comparative and evaluative approaches could be considered a form of benchmarking which is of particular interest to policy-makers (Bowerman et al., 2002; Northcott and Llewellyn, 2005; Papaioannou et al., 2006).

However, such approaches can be misleading. Paper 1 identified that just six percent of on-road cycle lane length in London was physically segregated (fully or partially) but this resulted in 22% compliance with national design standards. The global reductions in road speed limits to 20mph that have occurred across London (see Appendix C, Figure B.1) will mean that such compliance will automatically increase without any improvements in segregation from motor vehicles. So although cyclist crashes, casualties and participation may improve as speed reduction is effective (Mulvaney et al., 2015; Phillips et al., 2018), cycling safety perceptions will not improve as the infrastructure present is not segregated and, as established in the Introduction, segregation is vital to increase such perceptions (Steer Davies Gleave, 2012; Misra et al., 2015; TfL, 2017; DfT, 2020b). Furthermore, recent research has shown that 20mph speed limits have minimal impact on such perceptions (Williams et al., 2022). However, policy-makers may see that compliance with design standards has increased and believe that the infrastructure is of appropriate quality and consequently will improve cycling safety and participation.

Papers 2 and 3 used large quantities of observational data at a city-wide level over many years to evaluate whether a particular type of cycling infrastructure altered cycling crashes and volumes. This type of question is extremely important as it determines what is effective and therefore what should be prioritised and funded by policy-makers (Evaluation Task Force, 2023a; Evaluation Task Force, 2023b). The quantitative approaches taken in Papers 2 and 3 are essential and appropriate to answering such questions. The qualitative examination undertaken in Paper 3 is useful as it teases out the context in which interventions may work and why, what on paper seem to be good implementations, may not work in practice.

However, using observational data that may be new (such as the contraflow cycling infrastructure) or under-explored (e.g. Strava Metro data) and deriving data such as crash or casualty rates using denominators that are imperfect can be challenging. In particularly, this data is subject to uncertainty. Some of these uncertainties were known and quantified or accounted for whilst others could only be acknowledged. The research presented in this thesis communicates these uncertainties so that the quality and application of the evidence can be assessed by readers and others.

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Chapter 6

Conclusion

This thesis has evaluated cycling infrastructure in London using large observational data with a particular focus on cyclist safety and participation. It has discovered that there is no evidence that contraflow cycling in unsafe in the UK, contrary to widely-held beliefs, and that it can increase cycling participation. However, it has also shown that cycling infrastructure is not distributed equally across London and may not be of the quality that provides safe space for cycling or that appeals to everyone.

Ambitions for active travel to be the default choice for short urban journeys to reap the individual and population benefits will not be achieved without high-quality infrastructure that is safe, coherent, direct, comfortable, attractive and enables all to cycle. Making large datasets available to researchers could improve evaluation of cycling infrastructure in particular by knowing where, when and what infrastructure is implemented and improving estimates of cycling volumes across entire areas and time periods. However, researchers need to be aware of the limitations of such data and the methods used to evaluate infrastructure. Further research could improve such evaluation by examining route substitution, improving denominators and incorporating qualitative assessments.

The research has already had an impact through presentation of the contraflow cycling findings to influential UK government departments such as Active Travel England, the Department for Transport, Public Health Scotland and local government such as the Urban Transport Group.

Appendix A

Appendices to Paper 3 (chapter 4)

A.1 Exclusion criteria for OpenStreetMap highways

We started with the OSM lines dataset. We removed any non-highways OSM lines that were coded as: “dam”, “lock_gate”, “gate”, “handrail” or “fence”.

We removed any highways that were coded as:

- Footway
- Steps
- Elevator
- Track (this is off road, mainly for agricultural vehicles)
- Proposed (as this means they have not been built)
- Construction (as this means they are under construction)
- Bridleways (as this as usually off road tracks for horse riders)

We removed any highways where the surface was coded as:

- Gravel, fine gravel, grit or loose-surface
- Dirt
- Grass or grass-paver

A.2 Additional figures

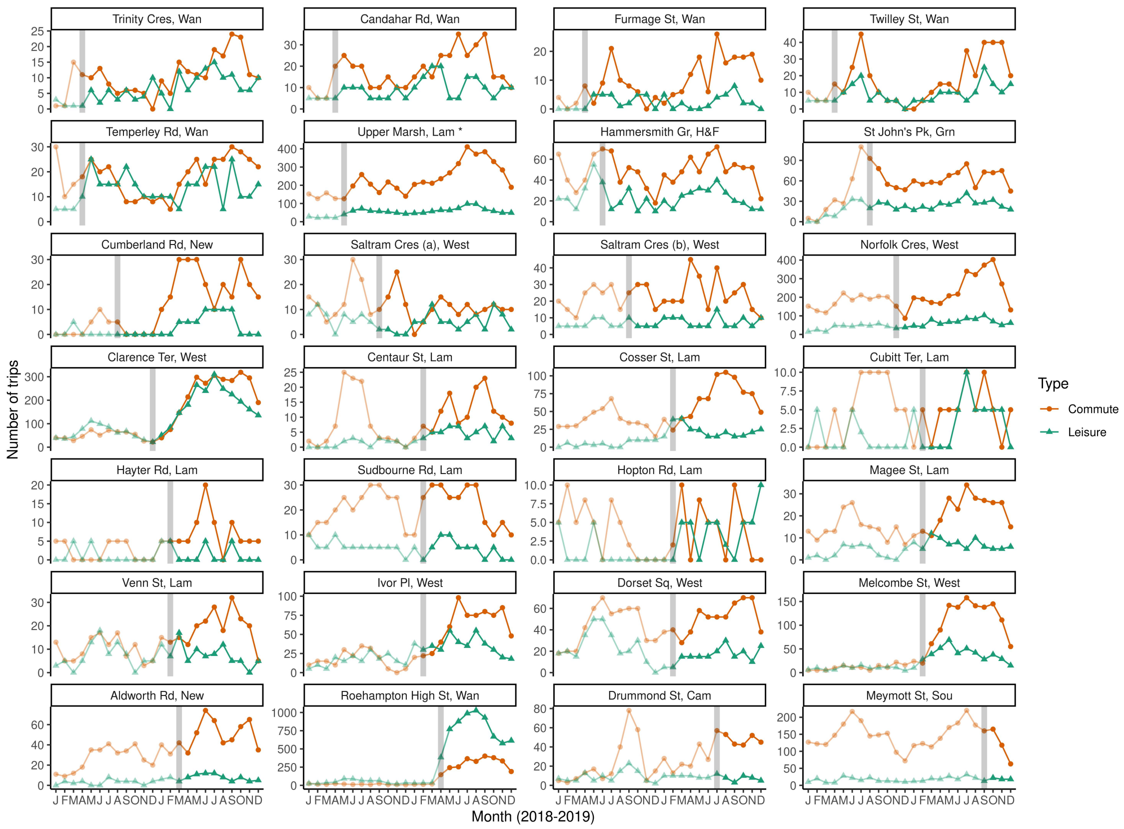

FIGURE A.1: Monthly variation in observed commute and leisure contraflow Strava trip counts on each former one-way road segments before (pale colours)and after (darker colours) contraflow introduction (month of transition shown as vertical grey line)

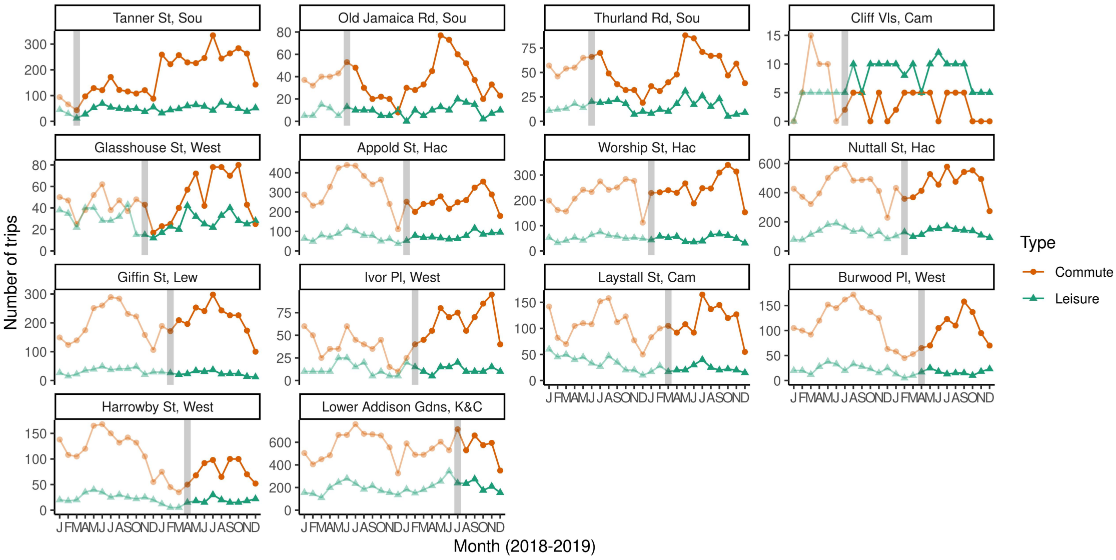

FIGURE A.2: Monthly variation in observed commute and leisure contraflow Strava trip counts on each former two-way road segments before (pale colours)and after (darker colours) contraflow introduction (month of transition shown as vertical grey line)

Appendix B

Appendices to Discussion

B.1 Additional figure

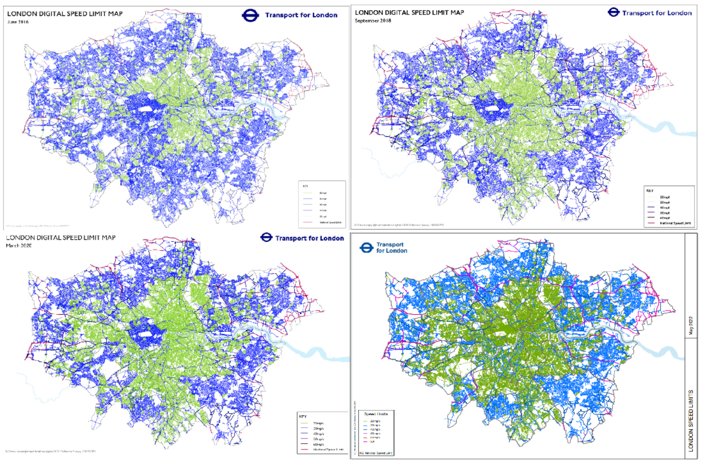

FIGURE B.1: London road speed limits 2016, 2018, 2020 and 2022 with 20mph roads coloured green (Mapping London 2020 & TfL 2022)

Mapping London 2020. Speed Limit Map. Available from: http://mappinglondon.co.uk/2017/speed-limit-map/?utm_source=dlvr.it&utm_medium=twitter

TfL 2022. London speed limits May 2022. Available from: https://content.tfl.gov.uk/london-digital-speed-limit-map.pdf