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

Highlights

- Interventions, enabling cycling against traffic, identified on 508 one-way streets
- Contraflow cycling does not increase cyclist crash or casualty rates
- Crash rates are identical whether the cyclist is travelling with flow or contraflow
- All UK one-way streets should be evaluated to allow contraflow cycling
- Legislation mandating two-way cycling would improve cycling networks and routes

Abstract

Contraflow cycling on one-way streets is a cost-effective 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 10m 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 cycling volume and injury severity reporting.

There were 1633 crashes involving pedal cyclists: 824 pre-contraflow, 831 contraflow and 8 following contraflow removal. There was negligible change in adjusted overall crash rates or pedal cyclist casualty killed or seriously injured rate 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.

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Keywords

- Infrastructure
- Contraflow
- One-way streets
- Crash
- Cycling

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 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 the UK Cycling Infrastructure Design Guidance states that 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

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(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; UDV, 2016) 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 (Ryley and Davies, 1998) 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.

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). Initially a TRO proposal is consulted upon with the public and interested parties then subsequently a TRO is issued to introduce and implement the change (The Local Authorities' Traffic Orders Regulations, 1996). Both the consultation and introduction TRO must be published and made available locally. 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 London Gazette (TSO, 2022a) 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 many 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 10m 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 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), nature of TRO action (e.g. two-way to one-way) 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.

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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 intervention dates. We focussed 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 location and date of contraflow interventions using the online search facility of The Gazette (TSO, 2022b). 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) were used to identify relevant TROs. 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 bodies not listed in the dropdown 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. For each road segment that received contraflow treatments, the following data was recorded: borough name, issuing organisation (if not the borough), road name, description of contraflow spatial extent (e.g. 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, type of order (Permanent or Experimental) and action (consultation, introduction or revocation) were recorded (Table A1). Additional TRO actions, such as whether a one-way street or a contraflow bus lane was concomitantly introduced, were collected where clearly specified in the TRO. 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. As some TROs are consulted upon but not introduced and others are introduced and then removed, we wanted

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to cross-reference each road segment to ensure it existed or had existed at some point as a contraflow. We utilised The Gazette (if there was only a consultation TRO), the London Cycling Infrastructure Database (CID, TFL, 2019a) and OpenStreetMap (OSM, OpenStreetMap contributors, 2022) for this purpose. 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.

2.2.1.1 Validating data completeness

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.

2.2.1.2 Spatial data

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.

2.2.1.3 Data cleaning

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 (e.g. checking that a road segment is not incorrectly labelled as introducing both a cycle lane and cycle track); 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 UK road traffic crash data (DfT, 2022a), known as STATS19, corresponding to the years of our road segment data collection (1998 to 2019 inclusive) using the stats19 R package (Lovelace et al., 2019). 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.

2.2.3 Cyclist volume data

We obtained data of the volume of pedal cycles crossing traffic counter 'cordons' into central, inner and outer London during the study period (TFL, 2019c; TFL, 2021). As some pedal cycle counts are only performed biennially, interpolation was used to impute count data for the

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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 TFL 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 crashes associated with contraflows

Spatial joins were used to identify all crashes involving pedal cycles that occurred within 10m of contraflow interventions. Where crashes could be spatially associated with more than one road segment, they were allocated to the nearest road segment. The 10m distance was chosen as it takes into account the multiplicity of street designs that contraflow cycling on one-way streets may encompass, ranging from a minimum width of 2.6m for a narrow one-way street to 8.15m allowing a one way lane (3.65m) and a contraflow bus lane with contraflow cycle lane (4.5m) (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, 2011b, 2005). This distance was visually validated by checking that the 10m buffer covering the road segment in OSM (highway width is determined by OSM highway type (Allan et al., 2022)).

2.3.2 Characterisation of the 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 crash we identified the vehicles involved and the casualties injured.

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.

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STATS19 contains a variable that indicates whether a crash is within 20m of a junction or roundabout. We reduced this distance to 10m 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 10m of these intersections.

2.3.3 Estimating crash and pedal cyclist 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' (Equation 1).

Equation 1: Raw pre-contraflow crash rate (crashes per 100 years of exposure) =

$$\frac{\text{Total number of crashes occurring on road segments during the pre-contraflow period}}{\text{(Total number of days during the 22 years that road segments were pre-contraflow/365) * 100}}$$

However, during the study period the amount of cycling changed significantly i.e. 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 (e.g. Equation 2) and then calculated the adjusted crash rate (e.g. Equation 3). Crash rates calculated in this manner are referred to as adjusted rates as opposed to raw rates in this paper.

Equation 2: Adjusted number of crashes occurring pre-contraflow by year [i] and cordon [j] =

$$\frac{\text{Raw number of crashes occurring pre-contraflow in year [i] and cordon [j]}}{\text{index of cycling volume in year [i] and cordon [j]}}$$

Equation 3: Adjusted pre-contraflow crash rate (crashes per 100 years of exposure) =

$$\frac{\text{Total adjusted number of crashes occurring pre-contraflow)}}{\text{(Total number of days during the 22 years that road segments were pre-contraflow/365) * 100}}$$

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.

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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 have limited the casualty rate analysis to 2005-2019 as recommended by the Department for Transport (DfT, 2021b, 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 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 Availability of code and datasets

The road segment dataset that we collected is available at ONLINE LOCATION TO BE CONFIRMED.
All code used in the analysis is available at ONLINE GITHUB LOCATION TO BE CONFIRMED.

3. Results

3.1 Road segments with contraflow cycling

We identified 508 unique road segments that had TROs published between 1st January 1998 and 31st December 2019 (inclusive) to introduce contraflow cycling in inner London boroughs. These road segments measure 64.4km in total length. Ten road segments had contraflow cycling removed (Figure 1c). 318 road segments had additional actions beyond introducing contraflow cycling in the TRO. Actions 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. Specific physical contraflow cycling infrastructure was introduced on some road segments consisting of cycle lanes (139, 27.4%), segregated cycle lanes (19, 3.7%) and cycle tracks (7, 1.4%). Contraflow cycling was allowed on a footway in seven (1.4%) segments.

The road segments are spatially concentrated in central London (Figure 1b). There is considerable variation between the 14 London boroughs with City of London (the smallest

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borough in terms of geographic area) introducing the most (93) whilst Tower Hamlets introduced just five during the study period (Figure 1d, Table A2).

There are differences between boroughs in terms of when they introduced contraflow cycling (Figure 1c and 1d). In the first five years of the study period Southwark, Camden and Kensington and Chelsea introduced the most contraflow segments. During the subsequent five years, growth in numbers was mainly achieved by the City of London and Southwark. Prior to the relaxation of traffic sign legislation in 2011, Southwark, Camden, Lambeth, Kensington and Chelsea and Lewisham were driving growth in contraflow introduction. In the year following the legislative change 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. Others appear to be starting an upward trend in the latter study period such as Wandswoth, Greenwich and Islington.

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.

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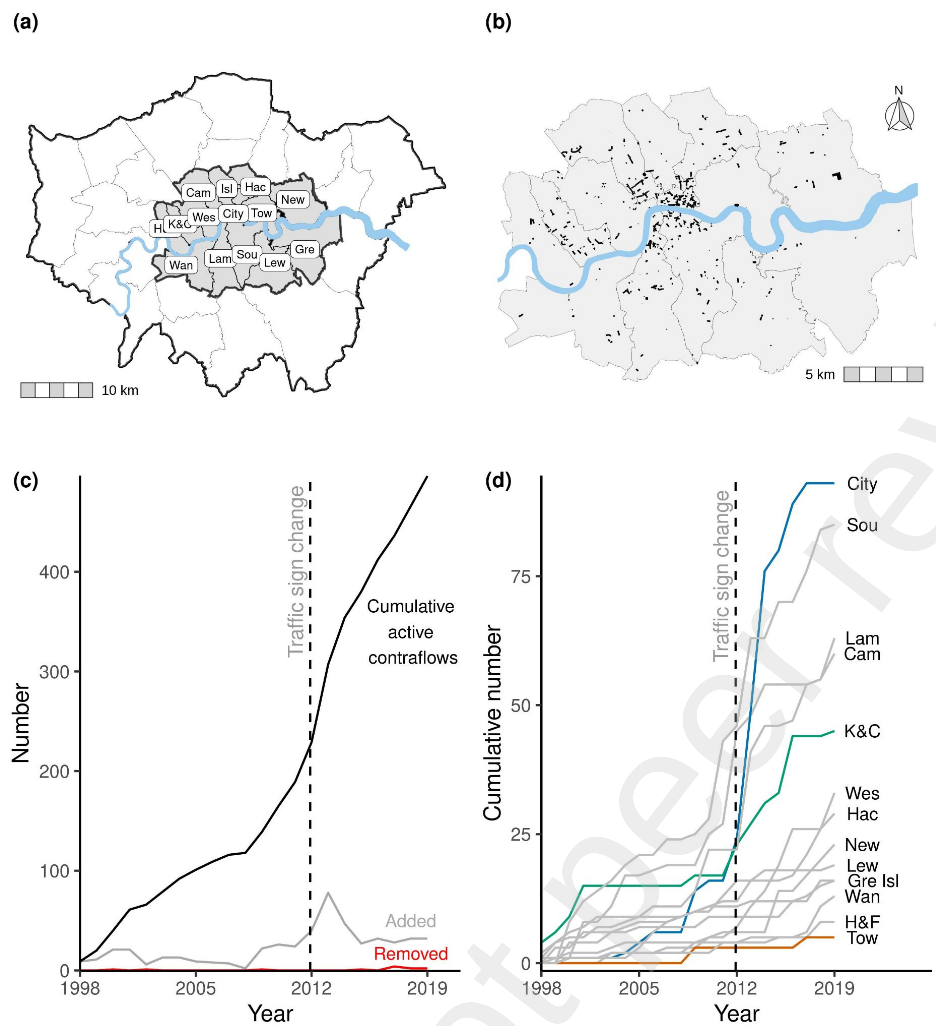

Figure 1: Road segments with contraflows introduced a) Map of London showing location of inner London boroughs used in the study; b) Map of inner London boroughs showing the location and spatial extent of road segments; c) Line chart showing number of contraflows added, removed and active over time; and d) Line chart showing cumulative number of contraflows introduced over time by borough.

The dashed line shows when traffic sign change was introduced.

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

We identified 304,456 crashes in inner London boroughs or within 150m of their boundaries between 1st January 1998 and 31st December 2019 (inclusive). 7458 of these crashes were within 10m of a road segment and 1774 involved pedal cycles. 1663 of these occurred on road segments that had a contraflow start date and thus it could be determined whether the crash occurred prior to (n = 824) or during (n = 831) the period when contraflow cycling was legally allowed or after contraflow cycling was rescinded (n = 8). The remaining analysis is focussed on

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these 1663 crashes where we can determine the crash timescale in relation to the road segment status. We will refer to this 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. This contrasts with that of crashes that occurred after contraflow cycling is removed but this is likely affected by the small numbers of crashes in this time period. Irrespective of crash segment status, the mean number of vehicles involved per crash was 1.9 and 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 but up to 12.5% had pedestrian casualties. Fortunately, very few crashes were fatal and less than 14.1% considered serious. Over 90% of crashes occurred within 20m of a junction or roundabout, which is much greater than one would expect given that only 62% of road segment length is within 20m of a junction (Table A3). Over 75% occurred on single carriageway roads and over 55% occurred on A roads. Crashes tended to occur in daylight hours, in fine weather and on dry roads although nearly a quarter occurred in darkness. Most crashes occurred in rush hours during the working week.

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Characteristics		Crash segment status		
		Pre-contraflow	Contraflow	Contraflow removed
Number of crashes		824	831	8
Mean number of vehicles (SD)		1.9 (0.3)	1.9 (0.4)	1.9 (0.4)
Mean number of casualties (SD)		1.0 (0.3)	1.1(0.2)	1.1 (0.4)
Involving cyclist casualties		788 (95.6)	774 (93.1)	7 (87.5)
Involving pedestrian casualties		43 (5.2)	69 (8.3)	1 (12.5)
Mean road segment speed limit in mph (SD)		29.9 (1.5)	27.5 (4.5)	30.0 (0.0)
Crash severity	Fatal	6 (0.7)	4 (0.5)	0 (0.0)
	Serious	102 (12.4)	117 (14.1)	1 (12.5)
	Slight	716 (86.9)	710 (85.4)	7 (87.5)
Police officer attended the scene	Yes	552 (67.0)	545 (65.6)	6 (75.0)
	No	204 (24.8)	223 (26.8)	2 (25.0)
	No - accident was self-reported [1]	5 (0.6)	61 (7.3)	0 (0.0)
	Data missing	63 (7.6)	2 (0.2)	0 (0.0)
Junction details	At or within 20 metres of a junction or roundabout	757 (91.9)	759 (91.3)	8 (100.0)
	Not at or within 20 metres of a junction or roundabout	66 (8.0)	68 (8.2)	0 (0.0)
	Unknown	1 (0.1)	4 (0.5)	0 (0.0)
First road class [2]	A	522 (63.3)	462 (55.6)	6 (75.0)
	B	66 (8.0)	56 (6.7)	0 (0.0)
	C	147 (17.8)	214 (25.8)	0 (0.0)
	Unclassified	89 (10.8)	99 (11.9)	2 (25.0)
Road type	Single carriageway	622 (75.5)	614 (73.9)	7 (87.5)
	One way street	43 (5.2)	128 (15.4)	1 (12.5)
	Dual carriageway	58 (7.0)	58 (7.0)	0 (0.0)
	One way street/Slip road	91 (11.0)	8 (1.0)	0 (0.0)
	Unknown	5 (0.6)	12 (1.4)	0 (0.0)
	Roundabout	4 (0.5)	11 (1.3)	0 (0.0)
	Slip road	1 (0.1)	0 (0.0)	0 (0.0)
Light conditions	Daylight	648 (78.6)	627 (75.5)	8 (100.0)
	Darkness	176 (21.4)	204 (24.5)	0 (0.0)
Weather conditions	Fine	748 (90.8)	737 (88.7)	8 (100.0)
	Rain, snow, fog or other	62 (7.5)	81 (9.7)	0 (0.0)
	Unknown	14 (1.7)	13 (1.6)	0 (0.0)
Road surface conditions	Dry	724 (87.9)	710 (85.4)	7 (87.5)
	Wet, icy or muddy	97 (11.8)	113 (13.6)	1 (12.5)

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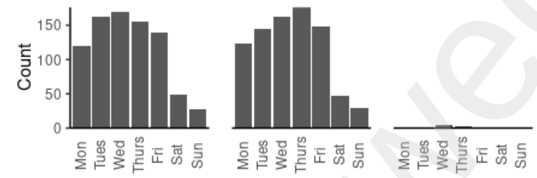
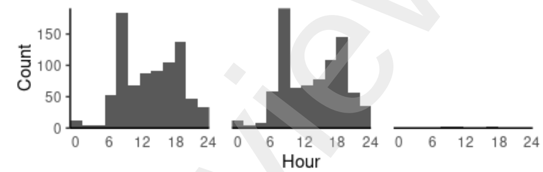
	Unknown	3 (0.4)	8 (1.0)	0 (0.0)
Day of week				
Hour of day				

[1] Self-reporting of road traffic crashes was introduced by the Metropolitan Police (not the City of London Police) in October 2016 (DfT, 2020e)

[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).

Table 1: Characteristics of crashes involving pedal cycles within 10m 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 with the exception of the additional TRO actions that are derived from the TRO dataset. Data is presented as ‘number (percentage)’ unless otherwise stated.

Figure 2 shows the1663 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. Only 317 (62%) out of the 508 road segments had a crash within 10m. 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 242 crashes on these 9 road segments despite this action only affecting 11 (2.2%) of all road segments. 84 (34.7%) crashes occurred before and 158 (65.3%) occurred after the new contraflow bus lane was introduced. For road segments that were two-way, 184 (57.0%) crashes occurred before they became one-way streets with contraflow cycling and 138 (42.7%) occurred afterwards with a further single crash occurring following contraflow removal. For the existing one-way streets, 556 (50.6%) crashes occurred before contraflow cycling, 535 (48.7%) occurred after and 7 (0.6%) occurred following contraflow removal.

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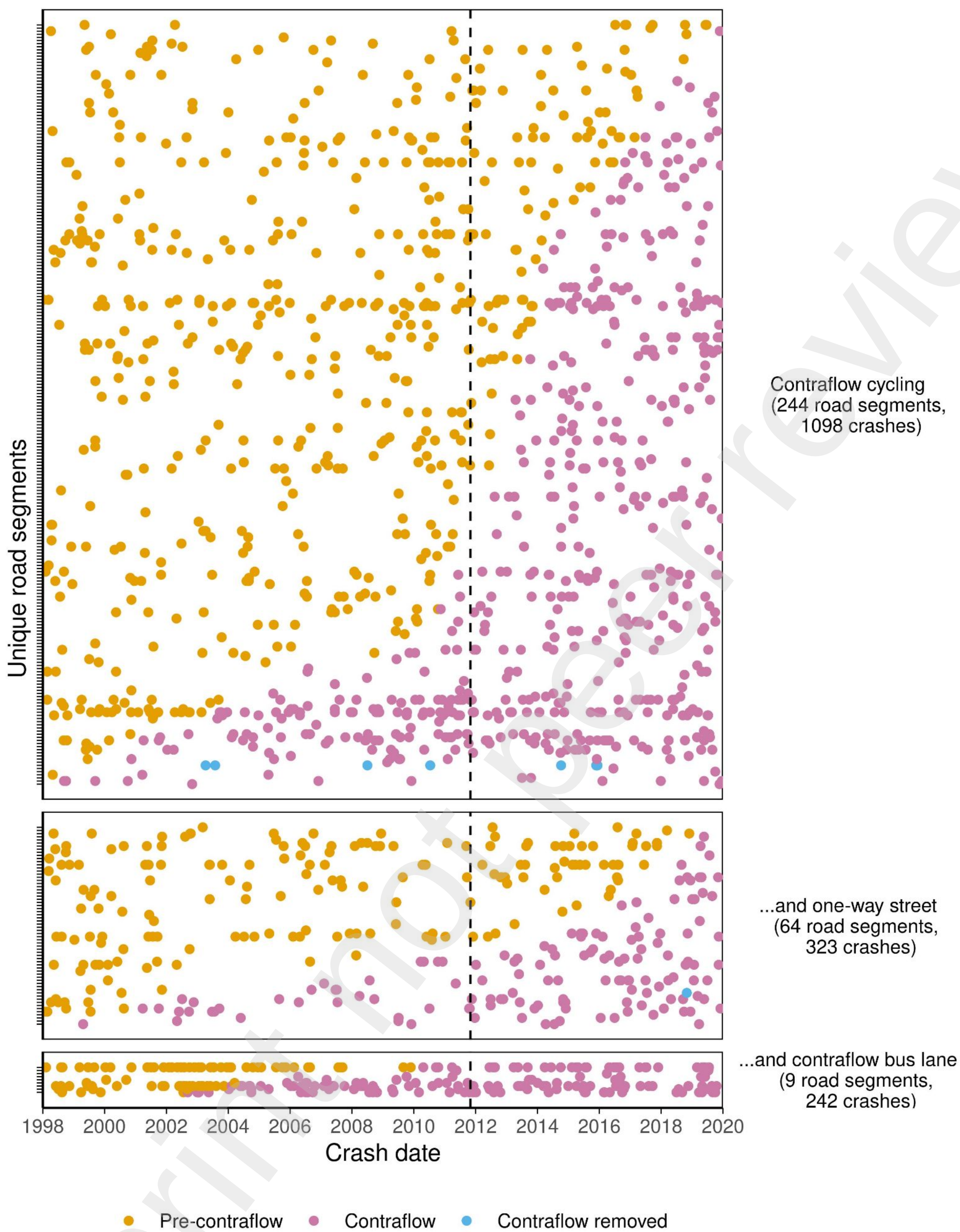

Figure 2: Dot visualisation of all crashes involving pedal cycles within 10m of a road segment by: unique road segment (vertical position); date of crash (horizontal position); crash segment status (colour); and additional TRO action (pane)

The dashed line shows when the traffic sign change was introduced. Colour palette sourced from Wong (2011) to promote visual accessibility.

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3.3 Casualties and vehicles

The 1633 crashes within 10m of a road segment resulted in 1733 casualties of which 1582 were cyclists, 116 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 58 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 220 seriously injured casualties of whom 84% were cyclists and 15% pedestrians and 1503 slightly injured casualties with cyclists accounting for 92% and pedestrians 6%. As injury severity gets milder there are more non-cyclist and non-pedestrian casualties, probably reflecting their vehicle protection.

The crashes involved 3175 vehicles (Table 2) with the majority being two vehicle crashes (1452 crashes) and the vehicles located on the main carriageway (2810, 88.5%). All crashes involved at least one pedal cycle (a requirement for inclusion). Unsurprisingly, cars were the most frequent other type of vehicles involved followed by light goods vehicles and taxis. Interestingly, given that many crashes occurred near road segments with contraflow bus lanes, buses only made up a small percentage of the vehicles and the vehicles themselves were rarely located in bus lanes.

Characteristics			**Crash segment status**		
			Pre-contraflow	**Contraflow**	**Contraflow removed**
Total number of casualties			855	869	9
Casualty type	Cyclist		790 (92.4)	785 (90.3)	7 (77.8)
	Pedestrian		45 (5.3)	70 (8.1)	1 (11.1)
	Motorcyclist		10 (1.2)	9 (1.0)	0 (0.0)
	Car		8 (0.9)	2 (0.2)	0 (0.0)
	Other		2 (0.2)	3 (0.3)	1 (11.1)
Casualty severity [1]	Fatal	Cyclist	6 (0.7)	3 (0.3)	0 (0.0)
		Pedestrian	0 (0.0)	1 (0.1)	0 (0.0)
	Serious	Cyclist	88 (10.3)	96 (11.0)	1 (11.1)
		Pedestrian	12 (1.4)	20 (2.3)	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	696 (81.4)	686 (78.9)	6 (66.7)
		Pedestrian	33 (3.9)	49 (5.6)	1 (11.1)
		Motorcyclist	9 (1.1)	8 (0.9)	0 (0.0)
		Car	7 (0.8)	2 (0.2)	0 (0.0)
		Other	2 (0.2)	3 (0.3)	1 (11.1)
Total number of vehicles			1597	1563	15
Vehicle type	Pedal cycle		829 (51.9)	847 (54.2)	8 (53.3)

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	Car	461 (28.9)	410 (26.2)	2 (13.3)
	Light Goods Vehicle	104 (6.5)	90 (5.8)	1 (6.7)
	Taxi	85 (5.3)	97 (6.2)	2 (13.3)
	Bus, coach or minibus	41 (2.6)	45 (2.9)	1 (6.7)
	Motorcycle	40 (2.5)	31 (2.0)	0 (0.0)
	Heavy Goods Vehicle	31 (1.9)	34 (2.2)	1 (6.7)
	Other or unknown	6 (0.4)	9 (0.6)	0 (0.0)
Vehicle located in a restricted lane	On main carriageway (not in restricted lane)	1513 (94.7)	1284 (82.1)	13 (86.7)
	Cycle lane (on main carriageway)	37 (2.3)	86 (5.5)	0 (0.0)
	Bus lane	24 (1.5)	18 (1.2)	0 (0.0)
	Footway (pavement)	7 (0.4)	6 (0.4)	0 (0.0)
	Cycleway or shared use footway (not part of main carriageway)	1 (0.1)	6 (0.4)	0 (0.0)
	Other or unknown	15 (0.9)	163 (10.4)	2 (13.3)

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

Table 2: Characteristics of casualties and vehicles in crashes involving pedal cycles within 10m 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)'.

3.4 Pedal cycle direction

Utilising the STATS19 vehicle direction variables, the spatial 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. Table 3 shows the number of crashes by pedal cycle direction and crash segment status. It also presents the data by whether the crashes occurred on a road segment that had been a one-way or two-way street and their proximity to a junction or roundabout. We can see that the highest proportion across all categories is for 'direction not compatible' and that this proportion is greatest for crashes within 10m of a junction or roundabout. This indicates that these pedal cyclists are turning or involved in a junction or roundabout rather than travelling on the main part of the road segments.

Focusing on those road segments that had been one-way streets, we can see that there are pre-contraflow crashes where cyclists are travelling illegally contraflow but this proportion is less than the with-flow crashes. Looking at segments that did have two-way cycling, the proportion of crashes where the pedal cyclist is travelling contraflow is consistent with that of one-way streets - around 20-25%. Where the contraflow is removed, none of these eight crashes had a pedal cycle direction.

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Pre-TRO status	Proximity to junction or roundabout		More than 10m from a junction or roundabout (OSM determined)			Within 10m 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		127	128	4	429	407	3
	Pedal cycle 1 direction	With flow	33 (26.0)	36 (28.1)	0 (0.0)	53 (12.4)	67 (16.5)	0 (0.0)
		Contraflow (illegal)	20 (15.7)	-	0 (0.0)	51 (11.9)	-	0 (0.0)
		Contraflow	-	32 (25.0)	-	-	87 (21.4)	-
		Direction not compatible	72 (56.7)	46 (35.9)	4 (100.0)	323 (75.3)	208 (51.1)	3 (100.0)
		Unknown (self reported)	2 (1.6)	14 (10.9)	0 (0.0)	2 (0.5)	45 (11.1)	0 (0.0)
	Pedal cycle 2 direction	With flow	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (10.0)	0 (0.0)
		Contraflow (illegal)	1 (100.0)	-	0 (0.0)	2 (66.7)	-	0 (0.0)
		Contraflow	-	0 (0.0)	-	-	3 (30.0)	-
		Direction not compatible	0 (0.0)	0 (0.0)	0 (0.0)	1 (33.3)	3 (30.0)	0 (0.0)
		Unknown (self reported)	0 (0.0)	1 (100.0)	0 (0.0)	0 (0.0)	3 (30.0)	0 (0.0)
Two way	Number of crashes		85	115	1	183	181	0
	Additional TRO action from two-way to...	One-way street	59 (69.4)	47 (40.9)	1 (100.0)	125 (68.3)	91 (50.3)	0 (0.0)
		One-way street with contraflow bus lane	26 (30.6)	68 (59.1)	0 (0.0)	58 (31.7)	90 (49.7)	0 (0.0)
	Pedal cycle 1 direction	With flow	17 (20.0)	40 (34.8)	0 (0.0)	26 (14.2)	37 (20.4)	0 (0.0)
		With flow (opposite)	24 (28.2)	0 (0.0)	0 (0.0)	29 (15.8)	0 (0.0)	0 (0.0)
		Contraflow	-	24 (20.9)	-	-	36 (19.9)	--
		Direction not compatible	42 (49.4)	44 (38.3)	0 (0.0)	126 (68.9)	81 (44.8)	0 (0.0)
		Unknown (self reported)	2 (2.4)	7 (6.1)	1 (100.0)	2 (1.1)	27 (14.9)	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)	0 (0.0)	0 (0.0)
		Contraflow	-	2 (66.7)	-	-	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)	1 (33.3)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)

Table 3: Pedal cycle direction in crashes involving pedal cycles within 10m 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

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. The category 'Unknown (self reported)' only became available for crashes occurring after 2016 and reported to the Metropolitan Police when self-reporting of crashes became possible (DfT, 2020e). Data is presented as 'number (percentage)'.

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3.5 Changes to 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. Figure 3a shows the number of pedal cycles counted crossing cordons around outer, inner and central London over time(cordons shown in Figure 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 5.5% occurring outside the inner cordon, 42.0% occurring between the inner and central cordons and 52.4% occurring within the central cordon (Figure 3b). This change in exposure of cyclists to infrastructure is important when considering the crash risk to which they may be subjected.

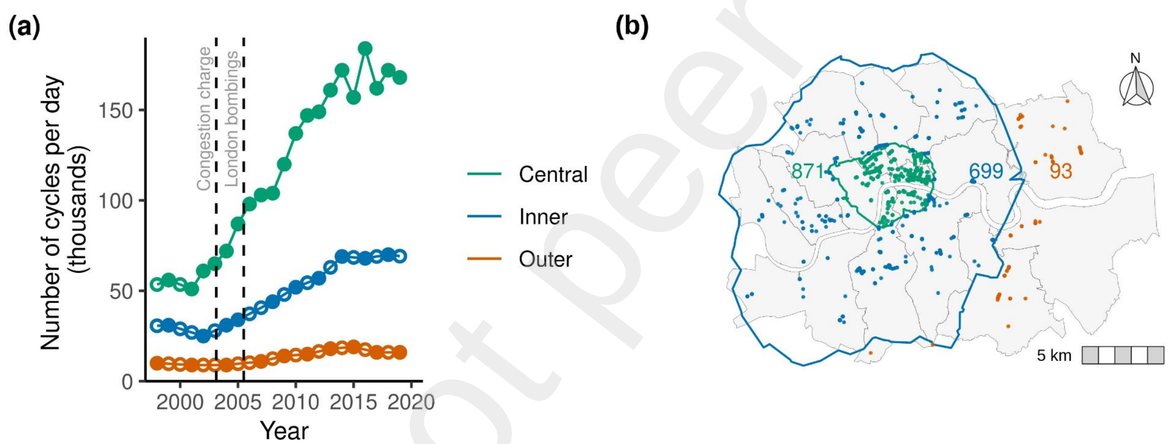

Figure 3: a) Cordon counts of number of cyclists over time and b) Spatial location of crashes and cordons (central and inner)

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 a cordon. Count data sources: TFL (2019b) and TFL (2021a). Colour palette: Wong (2011).

3.6 Crash rates involving pedal cycles

In table A4 we present crash numbers, rates and their 95% confidence intervals for crashes involving pedal cycles within 10m 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 cycling volume baselined to 1998. We have predominantly included the adjusted rates in our visualisation (Figure 4). This allows easier interpretation of the rates, so for example, the overall adjusted pre-contraflow crash rate is 9.4 which means that we would expect 9.4 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.

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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 = 12.6, 95% confidence interval 11.9-13.2 v contraflow crash rate = 21.8, 20.7-22.9, Figure 4, Table A4). However, once the number of crashes are adjusted to take into account the change in volume of cycling there is no statistically significant change in the crash rates when contraflows are implemented (9.4, 8.9-9.9 v 10.1, 9.6-10.7). 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, the adjusted crash rate within 10m of these intersections is more than double that for crashes occurring over 10m away. This is true irrespective of whether they occur in the pre-contraflow (7.1, 6.5-7.6 v 2.3, 2.0-2.6) or contraflow period (7.1, 6.6-7.6 v 3.1, 2.7-3.4). There is a small difference in the non-junction related crash rates between the pre- and contraflow time periods (2.3, 2.0-2.6, n = 152 v 3.1, 2.7-3.4, n = 117).

Examining the adjusted crash rates by TRO action demonstrates differences. There is no statistically significant change in crash rate when contraflow cycling is introduced on existing one-way streets (7.7, 7.1-8.3 v 8.5, 7.9-9.1) but there is a statistically significant difference when two-way streets are converted to one-way with contraflow cycling - the crash rate falls by a third from 10.9 (9.3-12.5, n = 139) to 7.4 (6.1-8.7, n = 68). There is also a statistically significant drop, again by a third, in crash rates when two-way streets are converted to one-way with contraflow bus lanes and cycling from 89.9 (70.1-109.0, n = 75) to 53.9 (45.0-62.3, n = 85).

Comparing 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, 1.3-1.8). This illegal contraflow crash rate is lower than that when people are legally allowed to cycle contraflow (2.4, 2.0-2.7). 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 (2.3, 2.0-2.7 v 2.4, 2.0-2.7) and this is true even for raw rates. The crash rate for those whose direction is not compatible, i.e. they are not travelling along the road but are turning off or crossing the road, is double that of those travelling along the road segment irrespective of whether occurring in pre-contraflow (6.3, 5.8-6.8, n = 413) or contraflow (4.6, 4.2-5.1, n = 176) 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.

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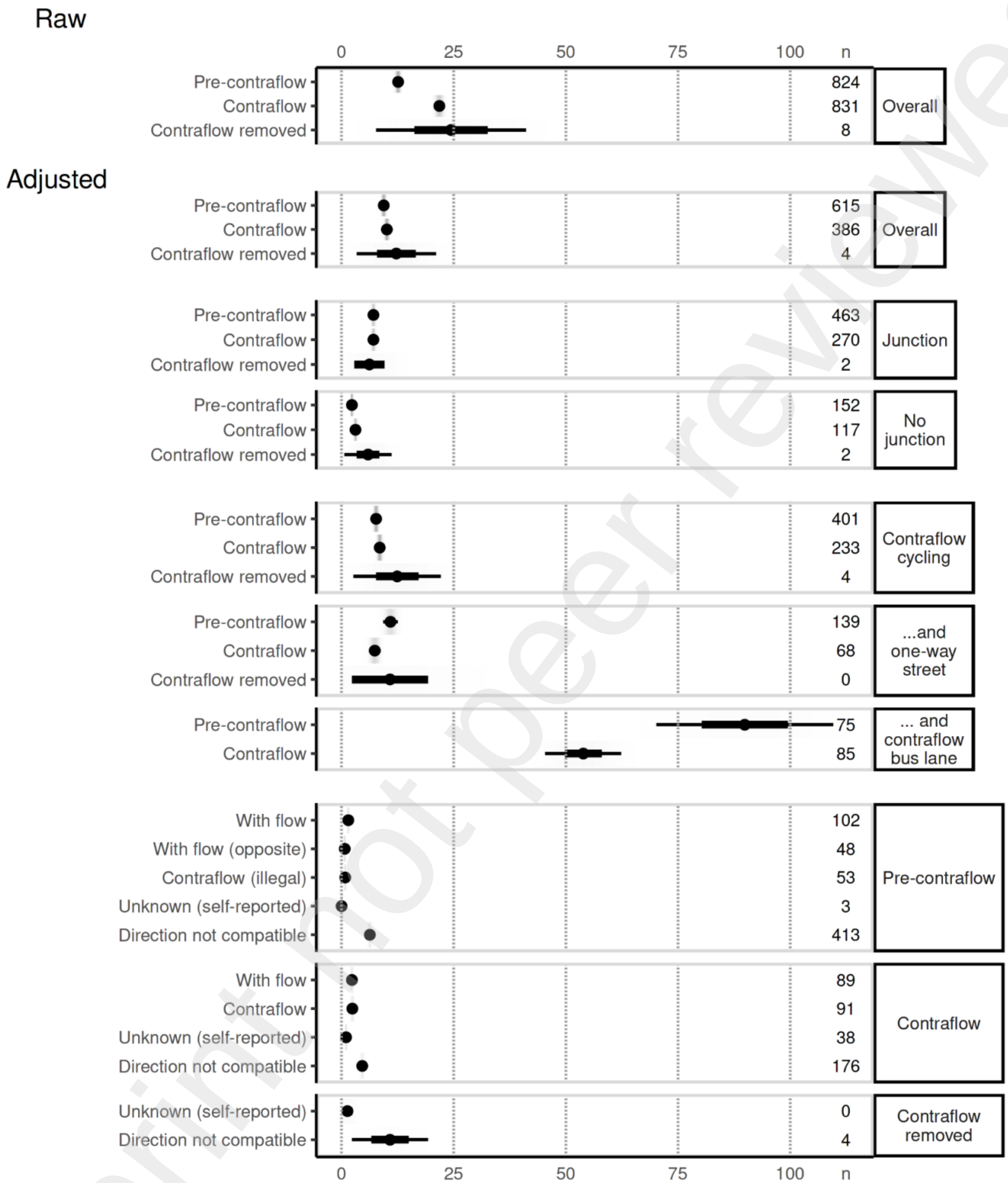

Figure 4: Crash rates involving pedal cyclists per 100 years of exposure by crash segment status

Rates are presented as raw and adjusted for annual cycle volume (1998 index) as: overall; by proximity to junctions or roundabouts (within 10m); by action; 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.

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3.7 Pedal cyclist casualty rates

In table A5 we present pedal cyclist casualties numbers, rates and their 95% confidence intervals for crashes involving pedal cycles within 10m 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 cycling volume baselined to 1998. They are visualised in Figure 5.

Our analysis shows there is no difference in fatal pedal cyclist injury rates when contraflows are introduced. The raw rates suggests that seriously injured pedal cyclist casualties double when contraflows are introduced (pre-contraflow = 1.2, 0.9-1.6 v contraflow = 2.3, 1.8-2.8) and that slight injuries increase by a third (11.6, 10.6-12.6 v 16.8, 15.9-17.7). 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 a third when contraflows are introduced. However, when the changes in cycling volume are taken into consideration there is an effect. The difference in rates of pedal cyclist casualties seriously injured is no longer statistically significant when contraflow cycling is introduced (0.7, 0.5-0.9 v 1.0, 0.8-1.2) and the difference between the slightly injured rates is small (5.7, 5.2-6.1, n = 184 v 6.9, 6.5-7.3, n = 262). This equates to one additional pedal cyclist casualty being slightly injured per 100 years of exposure to the contraflow road segments.

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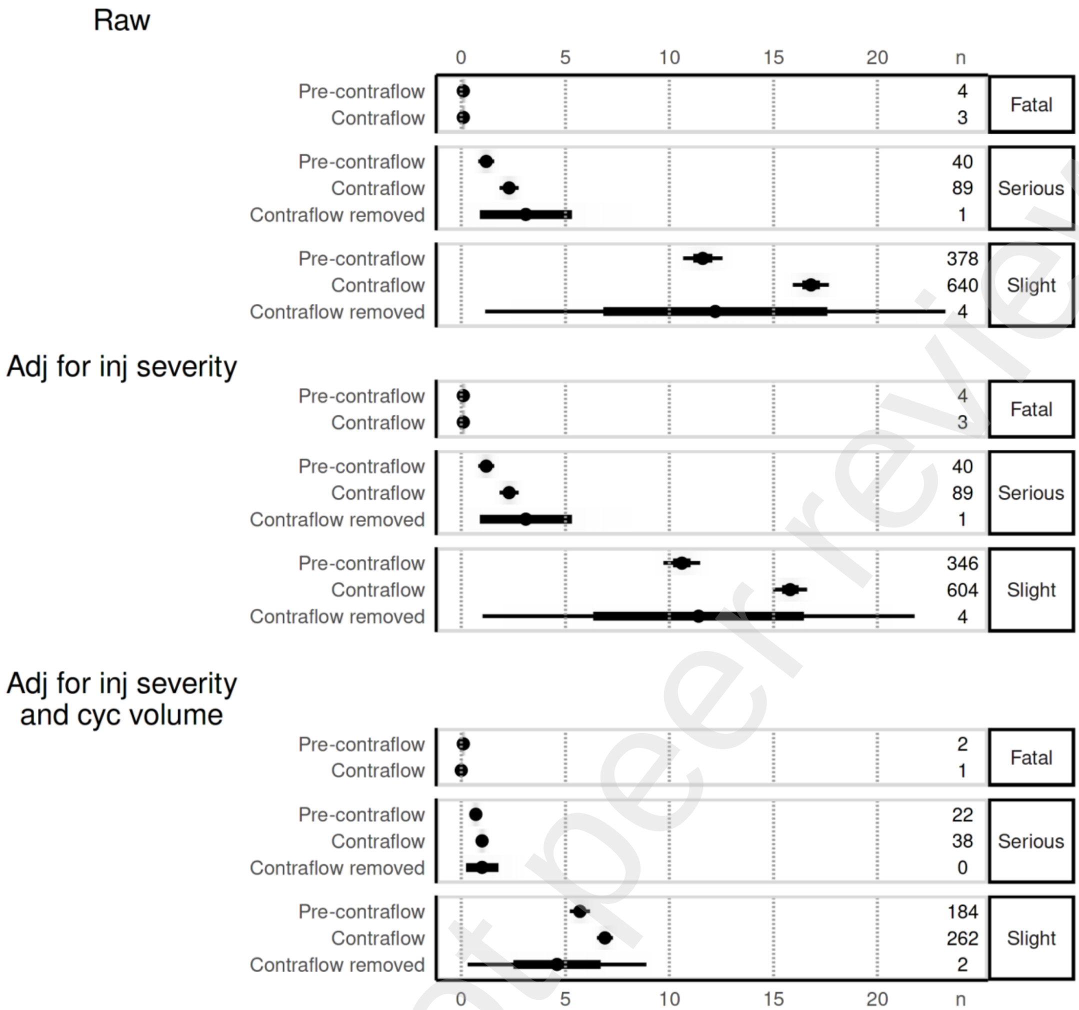

Figure 5: Pedal cyclist casualty rates per 100 years of exposure by crash segment status and injury severity, 2005-2019

Rates are presented as raw, adjusted for change in injury severity classification; and adjusted for change in injury severity classification and cycle 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.

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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. 1663 crashes involving pedal cycles occurred within 10m of the 473 segments with a contraflow start date, although 102 of these road segments were not associated with any crashes. 824 crashes occurred prior to contraflow cycling being implemented, 831 occurred after the contraflow cycling was allowed and 8 occurred following its removal. Over 90% 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 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 10m 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 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, for example, 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 or severely injured cyclist casualty rate when contraflows are introduced and only a small increase in the slightly injured rates.

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. 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.

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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 10m 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 crash rates of 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, 2017). Previous UK research has found that bus lanes are associated with both increasing (Kapousizis et al., 2021) or decreasing cycling injury risk (Adams and Aldred, 2020; Aldred et al., 2018). However, none of these studies have focussed on contraflow bus lanes where we found the crash risk was a third lower after their introduction.

These findings need to be considered in real world terms. When we consider the overall adjusted crash rates where the pre-contraflow crash rate is 9.4 and the contraflow rate is 10.1, this equates to a crash occurring on such a road segment once every 11 or ten years, respectively. Whilst the adjusted pedal cyclist severe injury rates of 0.7 during the pre-contraflow and 1.0 during the contraflow period correspond to seven and ten (respectively) cyclist casualties being seriously injured per 1000 years of exposure.

4.3 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 work 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 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

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road segments as opposed to those interacting with junctions and negates any crashes that may have been erroneously included by our 10m 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 has changed unless a new TRO exists. We attempted to mitigate this 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.

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); casualty severity reporting; and use of self-reporting (DfT, 2020e). We have addressed these issues by validating pedal cycle direction against road axes, using 10m 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 occuring 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. This 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 open cycling volume data we have for 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

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over the 22 year period making this the most comprehensive data analysis of UK pedal cyclist crash risks on contraflows.

4.4 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. 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 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 (ANONYMOUS REFERENCE), 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.

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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)

5. 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 risk is 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), including information on route substitution, as well as detailed datasets on the exact nature of contraflow interventions and the surrounding active travel environment.

Acknowledgements and Licences

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The Gazette, Office of National Statistics and UK Road Traffic crash data:

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http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3

OpenStreetMap data:

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Appendices

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

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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_contraflo w_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

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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

Table A1: TRO data collection dataset

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 A2: Number (%) of contraflow cycling road segments introduced by borough

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Number of road segments with a crash	317
Total length of these road segments within 20m of a junction*	28340.06m
Total length of these road segments	45727.27m
Proportion of road segment length within 20m of a junction	62%

* Junctions extracted from OSM January 2019 data

Table A3: Calculation of proportion of road segment length within 20m of a junction

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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		824	2396119	12.6 (11.9 - 13.2)
		Contraflow		831	1392487	21.8 (20.7 - 22.9)
		Contraflow removed		8	11949	24.4 (9.2 - 42.8)
	Adjusted	Pre-contraflow		615	2396119	9.4 (8.9 - 9.9)
		Contraflow		386	1392487	10.1 (9.6 - 10.7)
		Contraflow removed		4	11949	12.2 (4.2 - 22.2)
By junction status	Raw	Pre-contraflow	Junction or roundabout within 10m	612	2396119	9.3 (8.7 - 9.9)
		Contraflow		588	1392487	15.4 (14.4 - 16.5)
		Contraflow removed		3	11949	9.2 (3.1 - 21.4)
		Pre-contraflow	No junction or roundabout in 10m	212	2396119	3.2 (2.8 - 3.6)
		Contraflow		243	1392487	6.4 (5.7 - 7.1)
		Contraflow removed		5	11949	15.3 (3.1 - 30.5)
	Adjusted	Pre-contraflow	Junction or roundabout within 10m	463	2396119	7.1 (6.5 - 7.6)
		Contraflow		270	1392487	7.1 (6.6 - 7.6)
		Contraflow removed		2	11949	6.2 (1.2 - 14.8)
		Pre-contraflow	No junction or roundabout in 10m	152	2396119	2.3 (2.0 - 2.6)
		Contraflow		117	1392487	3.1 (2.7 - 3.4)
		Contraflow removed		2	11949	5.9 (1.6 - 11.6)
By action	Raw	Pre-contraflow	Contraflow cycling only	556	1900788	10.7 (10.0 - 11.4)
		Contraflow		535	997484	19.6 (18.3 - 20.9)
		Contraflow removed		7	10398	24.6 (7.0 - 45.6)
		Pre-contraflow	One-way street and contraflow cycling	184	464771	14.5 (12.6 - 16.6)
		Contraflow		138	337250	14.9 (12.6 - 17.3)
		Contraflow removed		1	1479	24.7 (24.7 - 98.7)
		Pre-contraflow	Contraflow bus lane and contraflow cycling	84	30560	100.3 (78.8 - 120.6)
		Contraflow		158	57753	99.9 (84.7 - 113.8)
	Adjusted	Pre-contraflow	Contraflow cycling only	401	1900788	7.7 (7.1 - 8.3)
		Contraflow		233	997484	8.5 (7.9 - 9.1)
		Contraflow removed		4	10398	12.4 (4.0 - 23.4)
		Pre-contraflow	One-way street and contraflow cycling	139	464771	10.9 (9.3 - 12.5)
		Contraflow		68	337250	7.4 (6.1 - 8.7)
		Contraflow removed		0	1479	10.8 (10.8 - 43.3)
		Pre-contraflow	Contraflow bus lane and contraflow cycling	75	30560	89.9 (70.1 - 109.0)
		Contraflow		85	57753	53.9 (45.0 - 62.3)
By pedal cycle direction	Raw	Pre-contraflow	With flow	129	2396119	2.0 (1.7 - 2.3)
			With flow (opposite)	53	2396119	0.8 (0.6 - 1.0)
			Contraflow (illegal)	74	2396119	1.1 (0.9 - 1.4)
			Unknown (self-reported)	8	2396119	0.1 (0.0 - 0.2)
			Direction not compatible	565	2396119	8.6 (8.0 - 9.2)

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		Contraflow	With flow	181	1392487	4.7 (4.1 - 5.4)
			Contraflow	185	1392487	4.8 (4.2 - 5.5)
			Unknown (self-reported)	98	1392487	2.6 (2.0 - 3.1)
			Direction not compatible	383	1392487	10 (9.1 - 10.9)
		Contraflow removed	Unknown (self-reported)	1	11949	3.1 (3.1 - 12.2)
			Direction not compatible	7	11949	21.4 (6.1 - 39.7)
	Adjusted	Pre-contraflow	With flow [2]	102	2396119	1.5 (1.3 - 1.8)
			With flow (opposite) [3]	48	2396119	0.7 (0.5 - 0.9)
			Contraflow (illegal) [4]	53	2396119	0.8 (0.6 - 1.0)
			Unknown (self-reported)	3	2396119	0 (0 - 0.001)
			Direction not compatible	413	2396119	6.3 (5.8 - 6.8)
		Contraflow	With flow	89	1392487	2.3 (2.0 - 2.7)
			Contraflow	91	1392487	2.4 (2.0 - 2.7)
			Unknown (self-reported)	38	1392487	1.0 (0.8 - 1.2)
			Direction not compatible	176	1392487	4.6 (4.2 - 5.1)
		Contraflow removed	Unknown (self-reported)	0	11949	1.3 (1.3 - 5.4)
			Direction not compatible	4	11949	10.8 (3.5 - 20.4)

[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 A4: Crash rates involving pedal cyclists within 10m of road segments per 100 years of exposure to road segment status

Rates are presented as raw and adjusted for annual cycle volume (1998 index) as: overall; by proximity for junction or roundabout (within 10m); by action; and by pedal cycle direction. 95% confidence intervals generated by bootstrapping 1000 resamples with replacement.

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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	1186657	0.1 (0.0 - 0.2)
		Serious	40	1186657	1.2 (0.9 - 1.6)
		Slight	378	1186657	11.6 (10.6 - 12.6)
	Contraflow	Fatal	3	1392488	0.1 (0.0 - 0.2)
		Serious	89	1392488	2.3 (1.8 - 2.8)
		Slight	640	1392488	16.8 (15.9 - 17.7)
	Contraflow removed	Serious	1	11949	3.1 (3.1 - 9.3)
		Slight	4	11949	12.2 (3.1 - 24.4)
Adjusted for change in injury severity classification	Pre-contraflow	Fatal	4	1186657	0.1 (0.0 - 0.2)
		Serious	40	1186657	1.2 (0.9 - 1.6)
		Slight	346	1186657	10.6 (9.7 - 11.5)
	Contraflow	Fatal	3	1392488	0.1 (0.0 - 0.2)
		Serious	89	1392488	2.3 (1.8 - 2.8)
		Slight	604	1392488	15.8 (15.0 - 16.7)
	Contraflow removed	Serious	1	11949	3.1 (3.1 - 9.3)
		Slight	4	11949	11.4 (2.8 - 22.8)
Adjusted for change in injury severity classification and annual cycle volume (1998 index)	Pre-contraflow	Fatal	2	1186657	0.1 (0.0 - 0.2)
		Serious	22	1186657	0.7 (0.5 - 0.9)
		Slight	184	1186657	5.7 (5.2 - 6.1)
	Contraflow	Fatal	1	1392488	0.0 (0.0 - 0.1)
		Serious	38	1392488	1.0 (0.8 - 1.2)
		Slight	262	1392488	6.9 (6.5 - 7.3)
	Contraflow removed	Serious	0	11949	1.0 (1.0 - 3.2)
		Slight	2	11949	4.6 (0.9 - 9.2)

[1] Number of crashes rounded to nearest integer

Table A5: 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 annual cycle volume (1998 index). 95% confidence intervals generated by bootstrapping 1000 resamples with replacement.

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