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

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ABSTRACT

Contraflow cycling on one-way streets is a safe, low cost intervention that can improve the cycling experience. The evidence of its impact on cycling participation is patchy and limited. In this paper, we use crowd-sourced data to assess the impact of introducing contraflow cycling on cycling volumes and qualitatively assess factors that are associated with impact of such infrastructure.

We matched roads where contraflow cycling was introduced in London in 2018/2019 with monthly Strava Metro cycling count data before and after the intervention. We generated expected counts adjusted for changes in Strava trips, users and seasonality by examining global change in Strava counts during the study period. We used national cycle infrastructure design guidance and Google Street View to qualitatively assess the contraflow infrastructure.

Twenty-eight one-way streets and fourteen two-way streets (converted to one-way streets) introduced contraflow cycling. Illegal contraflow cycling was popular on some streets pre-introduction. Three streets experienced significant increases in mean contraflow trips (260, 630 and 1750 percent) and people after introduction that were much higher than expected. Many other streets had higher counts post-intervention. Count increases were less apparent for the former two-way roads. Qualitative assessment demonstrated that local context such as connectivity, physical infrastructure and external factors (e.g. construction) were important in determining whether the intervention increased contraflow cycling.

We found that contraflow cycling introduction can increase cycling participation but that local factors are important in determining volumes. Large-scale adoption of such 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 confirm these findings with a more comprehensive analysis that explore multiple factors including local factors and weather conditions.

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1. 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).

However, the evidence base examining the impact on cycling volume is limited to a few streets that were existing one-way roads and a small number of locations. Studies have used short time scales (hours or months), predominantly video counts and rarely adjust for other factors that can impact cycling volume such as seasons. For example, Ryley and Davies (1998) investigated introducing contraflow cycling on three one-way roads in England. They video counted cyclists 24 hours before and after introduction, reporting a 54 percent increase in volume with a bigger increase in cyclists travelling contraflow, but did not adjust for seasonality. Bjørnskau et al. (2012) examined two streets with red contraflow cycle lanes in Oslo, Norway and used two other streets as controls. Cycle counting before and after demonstrated around a 50 percent increase in volume on the contraflow roads and a decrease on the control streets but method details were unspecified. Pritchard et al. (2019) examined replacing parking with a contraflow cycle lane on an existing contraflow cycling one-way street in Oslo. Using 113 cyclists with GPS devices and over 100 video count hours they found 50 to 100 more trips per month (seasonally-adjusted). Finally, Burkin (2019) examined one street in Somerville, USA that had contraflow cycling introduced using 10 hours of video counts and found the hourly bike count increased by 75 percent. Therefore, these claims to increase cycling volume are based on an insubstantial evidence base.

Traditionally, cycling volume has been measured by on-site manual or automatic counts performed by people or equipment such as pneumatic road tubes or via automated or manual video processing (NACTO, 2022). Each method has strengths and limitations but key challenges are accuracy, cost, granularity, coverage and capturing additional information such as rider demographics, journey purpose and bicycle type. In particular, these methods can usually only be deployed for short time periods and in a few locations. These counts can be augmented with large datasets such as census data for additional information or GPS devices and smartphone apps to increase spatial and temporal coverage and granularity (Nelson et al., 2021; NACTO, 2022).

Strava Metro is an example of crowd-sourced cycling volume 'big data'. It is large dataset of processed, aggregated, de-identified cyclist data generated by users of Strava, a GPS activity tracking product available via a device or smartphone app, who have given permission for their data to be used by authorised researchers and other parties (Strava, 2023; Strava Metro, 2023a). Strava Metro data has been used to examine cycling patterns, demand and route choice (Lee and Sener, 2021). Researchers have also used Strava Metro data to evaluate the impact of cycling infrastructure on cycling volumes (Heesch et al., 2016; Heesch and Langdon, 2016; Boss et al., 2018; Hong et al., 2020a,b). The strength of Strava Metro over traditional cycling count methods is its volume, extensive spatio-temporal coverage and spatio-temporal granularity allowing examination of cycling volumes on urban roads in many countries for all time periods. It is particular useful for roads, such as those with contraflow cycling, that are monitored less often than main roads or those with substantial cycling infrastructure.

However, whilst Strava Metro provides extensive cycling volume data some limitations do exist (Nelson et al., 2021; Lee and Sener, 2021). Firstly, users are not representative of the wider cycling population in terms of geographical coverage, demographic coverage, origins and destinations, route choice and distance travelled (Leao et al., 2019). Researchers have found that Strava users tend to be male, younger and more likely to cycle for leisure (Lee and Sener, 2021). Secondly, Strava Metro is a sampled dataset as users must opt in to data sharing thereby it does not represent all Strava users or journeys. Thirdly, there is an anonymisation process that means counts are only present if three or more trips or people cycle a road segment and counts are rounded up to the nearest five. This causes challenges when using small time scales (e.g. hourly counts) or demographic subgroups thus limiting its usefulness. Finally, the datasets are processed meaning any errors or omissions may be difficult to unearth and algorithms used for processing are opaque. Methods used by others to address some of these challenges with Strava Metro data include: using multiple data sources; comparing Strava counts to manual counts or survey data; utilising qualitative data; adjusting for temporality and change in Strava users; using modelling techniques; and consideration of appropriate data aggregation (Griffin et al., 2020; Nelson et al., 2021; Lee and Sener, 2021).

The aim of this study is to examine cycling volume when contraflow cycling is introduced across multiple locations in London, UK. A recently constructed dataset of inner London roads that introduced contraflow cycling (Tait et al., 2023; Tait, 2022) will provide the intervention sites whilst Strava Metro data, adjusted for seasonality and change in Strava users, before and after implementation will be used to consider the impact of the infrastructure on trip and unique people counts. After identifying locations that appear to have had an impact on such counts and those that have not, we will qualitatively assess the infrastructure to identify factors that may explain the differences. There are two types of interventions we will examine: existing one-way streets where contraflow cycling is introduced; and two-way streets that are converted to one-way streets with contraflow cycling. In the former, prior to intervention any contraflow cycling would be considered 'illegal' whilst in the latter contraflow cycling is legal before and after implementation. To our knowledge, there are no published studies on the latter type of intervention. Our overall approach will address key challenges with the current evidence base by using: a) large volumes of spatio-temporal cycling count data; b) many roads over a large geographical area; and c) multiple years' worth of data. Furthermore, it will address concerns in use of Strava Metro data by using monthly counts (Raturi et al., 2021) and adjusting for temporality and change in Strava users.

2. Methods

2.1. Data

2.1.1. Strava data

Strava Metro maps Strava activity data onto OpenStreetMap highways before deconstructing these roads at decision points (e.g. junctions) to create edges (Strava Metro, 2023c). Strava user activity data is matched to these edges to generate counts available to authorised users at hourly, daily, monthly or yearly periods ((Strava Metro, 2022)[1]). Trip (number of bicycle trips on that edge) and people (number of unique cyclists on that edge) counts are available in forward and reverse directions with direction defined by OpenStreetMap digitisation (Strava Metro, 2023b, data definitions in Appendix 1).

The years 2018 and 2019 were chosen as these were unaffected by the COVID-19 pandemic and are the earliest years where Strava Metro count data is available. Monthly count data was used as this maximises granularity whilst minimising data loss due to the Strava Metro anonymisation process (Raturi et al., 2021).

Using the Strava Metro Dashboard GUI we downloaded all counts for inner London in multiples of 25 square miles (the maximum download size, Strava Metro, 2022). We combined the data and removed duplicates. Where the download areas spatially overlapped, some edges (2.6 percent of total) had non-identical duplicate month counts (for example, a trip count was 30 in version one of January 2018 and 35 in version two of January 2018). Having established that the variation was very small and as it was unknown which version was the true count for these edges, we randomly selected a non-identical duplicate month count as the true count.

2.1.2. Roads with contraflow cycling

We used the primary dataset to identify roads in inner London that had contraflow cycling introduced in 2018 or 2019 (Tait et al., 2023; Tait, 2022). We kept roads that had a minimum of two monthly counts before and after contraflow implementation. This meant the roads had a contraflow start date that was between 1st March 2018 and 31st October 2019 inclusive. Key dataset variables are: road name, description of contraflow spatial extent (e.g. between junction X and Y), contraflow start date and spatial data. Roads were either existing one-way streets that had contraflow cycling introduced or were two-way streets converted to one-way streets with contraflow cycling. One road, Saltram Crescent, had two distinct sections of contraflow cycling introduced separated by a two-way road with opposite vehicle flow so were considered as two road segments.

2.2. Data analysis

Using the Strava Metro Dashboard map we identified all Strava edges that corresponded to the roads with contraflow cycling and dropped roads with less than 23 months of count data to ensure maximum data availability. Most roads were represented by multiple sequential Strava edges and the mean monthly count was calculated. Some roads were represented by one or more parallel Strava edges, for example, a road with a main carriageway and a segregated cycle lane. For these, the parallel Strava edge counts were summed and the mean Strava count then calculated.

Strava edge direction was identified by examining the edge start and end nodes in OpenStreetMap (OpenStreetMap contributors, 2023). Motor vehicle direction was also identified in OpenStreetMap. Using these two directionalities, Strava counts were classified as with or against one-way motor vehicle flow. There was one road (Upper Marsh) where motor vehicle direction reversed when contraflow cycling was introduced. To prevent misinterpretation due to this change, this road direction was not altered so that before and after counts are comparable.

2.2.1. Generating expected Strava counts that adjust for changes in Strava trips, users, seasonality and time

Cycling volume can change due to external factors such as amount of daylight, season and weather (Miranda-Moreno and Nosal, 2011; Tin Tin et al., 2012; Bean et al., 2021). Participation in Strava Metro can also change (e.g. Strava Press, 2021). Therefore, we wanted to adjust our observed monthly Strava count data to take into account these changes. To achieve this we created a Strava edge dataset that is broadly comparable to our contraflow roads using the following method. We extracted all inner London 'highways' from OpenStreetMap and removed inappropriate highways such as pavements and footpaths or incompatible surfaces (e.g. gravel) (see Appendix 2). We matched the resulting highways to our existing, inner London Strava edges and removed any edges that did not match our selected highways.

Using this dataset of broadly comparable edges, we summed the monthly edge counts to obtain total count per month for trips, trip purpose (commuting/leisure) and people. Using January 2018 as the baseline, we calculated the percentage change from this for each month and each count type.

We calculated the expected monthly count for each road segment by multiplying the observed January 2018 counts by the percentage change for that type of count and month then dividing it by 100. We applied Strava's anonymisation rules to our expected counts.

[1] The use of graph theory in transportation where roads are constructed of edges (links) and nodes (interchanges) is well established (e.g. Derrible and Kennedy (2011)). Historically, Strava Metro has made node data available (Lee and Sener, 2021) but this was not available when the research was conducted.

2.2.2. Remote qualitative assessment of contraflow cycling infrastructure

National cycle infrastructure design guidance provides advice on implementing contraflow cycling infrastructure (DfT, 2020). It suggests that contraflow cycling can be allowed without any segregation or painted cycle lanes if traffic volume and road speed are low (up to 32 km per hour (kph)) but advises that mandatory cycle lanes should be considered. Additional protection such as traffic islands at the exit are desirable and conspicuous road markings and/or coloured surfaces are advised. However, there is no prescriptive standard. Therefore, to qualitatively assess the roads we used the design principles of coherence, directness, safety, comfort and attractiveness plus accessibility of such infrastructure for all (DfT, 2020). We used OpenStreetMap to identify the roads, their locality and surrounding area to examine how the roads connect to other cycling infrastructure and places. We utilised Google Street View (Google, 2023) to assess the contraflow cycling infrastructure including its quality, road surface, lighting and general experience of cycling.

3. Results

3.1. Roads with contraflow cycling introduced in 2018–2019

We identified 28 one-way (total length 3.4 km) and 14 two-way (total length 1.5 km) roads that introduced contraflow cycling between April 2018 and October 2019 with 23 months or more Strava count data (Fig. 1 and Appendix 3). One-way roads consisted of fewer sequential Strava edges (50 percent had 1 or 2 edges) than two-way roads (29 percent had 1 or 2 edges) indicating that one-way roads had fewer junctions. One-way roads also had fewer parallel Strave edges (11 percent had parallel Strava edges) than two-way roads (43 percent had parallel Strava edges) indicating that two-way roads were more likely to have parallel infrastructure that cyclists could use such as segregated lanes, shared lanes and the main carriageway. However, the one-way roads were longer (mean length 121 m) than two-way roads (mean length 110 m). This suggests that the physical structure of two-way roads is more compact and complex than one-way roads.

3.2. Change in Strava cycle counts during the study period

Using our dataset of roads broadly comparable to the study roads, we can see that there is variation in Strava trip and people counts across the two-year period (Fig. 2). Numbers increase during the summer months and fall during winter corroborating previous Strava Metro research (Hong et al., 2020b; Venter et al., 2023). This seasonal change is more marked for certain counts: the volume of people increases more than the volume of trips, females increase more than males and leisure trips more than commuting. The greatest percentage changes are associated with change in temperature, although this may also reflect daylight duration, but appear to be less associated with percentage of rainy days.

3.3. Existing one-way streets with contraflow cycling introduced

3.3.1. Contraflow trip counts

The monthly variation in total observed and expected Strava contraflow trips on the 28 one-way streets with contraflow cycling introduction is shown in Fig. 3. The observed data are the actual Strava Metro data whilst the expected data are the expected Strava Metro data on that road if usage reflected the wider change in Strava data across Inner London roads. Contraflow trips are shown in absolute (counts, Fig. 3a) and relative (proportion of total trips, Fig. 3b) terms.

Fig. 3 shows that there is considerable variation in the volume of Strava contraflow trips between different roads. For example, Roehampton High Street has over a thousand trips per month whereas Cubitt Terrace has under 20. As expected, roads with high volumes have smoother lines compared to those with smaller volumes. On over half of roads, the observed contraflow counts increase after contraflow introduction and increase more than expected should the change reflect the wider change in Strava usage (Trinity Crescent, Candahar Road, Furmage Street, Twilley Street, Upper Marsh, Cumberland Road, Norfolk Crescent, Clarence Terrace, Centaur Street, Cosser Street, Magee Street, Ivor Place, Melcombe Street, Aldworth Road, Roehampton High Street). Dorset Square appears to be the only street where the observed contraflow cycling seems to drop after contraflow introduction. On the remaining streets contraflow introduction does not appear to be associated with cycling volume change suggesting that other factors may be important.

Focussing on the 12 roads with observed counts over 100 per month, three roads have low levels of illegal contraflow cycling relative to levels of legal contraflow cycling. Clarence Terrace, Melcombe Street and Roehampton High Street demonstrate 260, 630 and 1750 percent increases in mean observed counts post-implementation and these observed counts are high and higher than expected. These roads also show an increase in relative contraflow cycling that is higher than expected, increasing from around 3 to 39 percent on Roehampton High Street. A further five roads have a moderate increase (39–199 percent) in contraflow cycling when it is legalised (Upper Marsh, St John's Park, Norfolk Crescent, Cosser Street and Ivor Place) and their observed counts are higher than expected. However, the proportion of contraflow cycling remains fairly static for these streets. Only three roads experienced a fall in mean contraflow counts (−9 to −18 percent) after contraflow implementation: Hammersmith Grove, Saltram Crescent (a) [2] and

[2] Saltram Crescent has two distinct sections of contraflow cycling introduced separated by a two-way road with opposite vehicle flow. These were considered as two road segments and are labelled as Saltram Crescent (a) and Saltram Crescent (b) to distinguish between them.

Fig. 1. Maps showing the a) One-way roads and b) Two-way roads with contraflow cycling implemented between April 2018 and October in inner London.

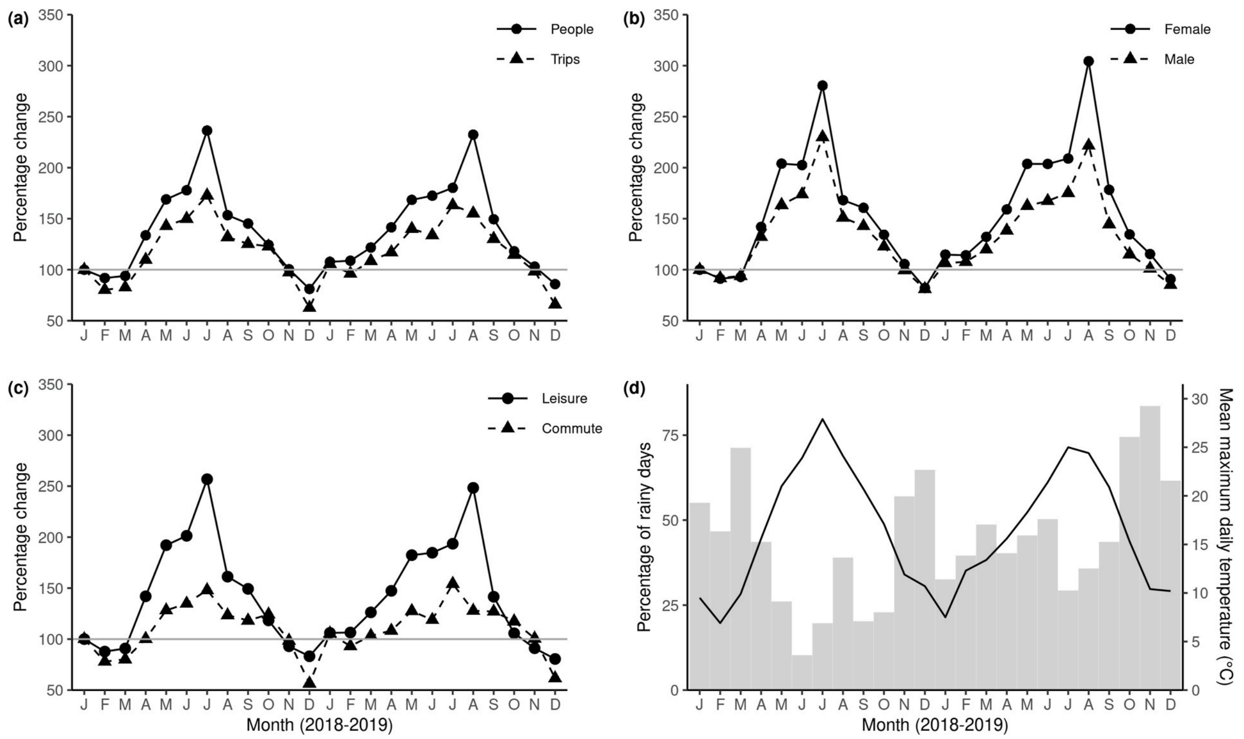

Fig. 2. Percentage change in inner London monthly Strava count baselined to January 2018 for a) total trip and unique people counts, b) unique female and male counts and c) total leisure and commute trip counts. d) Climatograph showing percentage of rainy days per month (bars) and mean maximum daily temperature (line chart) (St James's Park weather station, Westminster, London, Met Office, 2020a,b).

Meymott Street; with the former two having observed counts lower than expected. These findings again suggest that factors other than contraflow introduction may affect cycling levels. High levels of illegal contraflow cycling (best viewed in Fig. 3b) demonstrates unmet need and desire to cycle the roads in that direction prior to implementation.

Strava Metro provides commuting, defined either by the Strava user or identified by a Strava Metro model, and leisure trip counts. These show that roads are used for different journey purposes (Fig. 4). Most contraflow trips on Roehampton High Street are leisure trips whereas commuting and leisure trips are equally split for Clarence Terrace. For other roads, the trips are predominantly commutes.

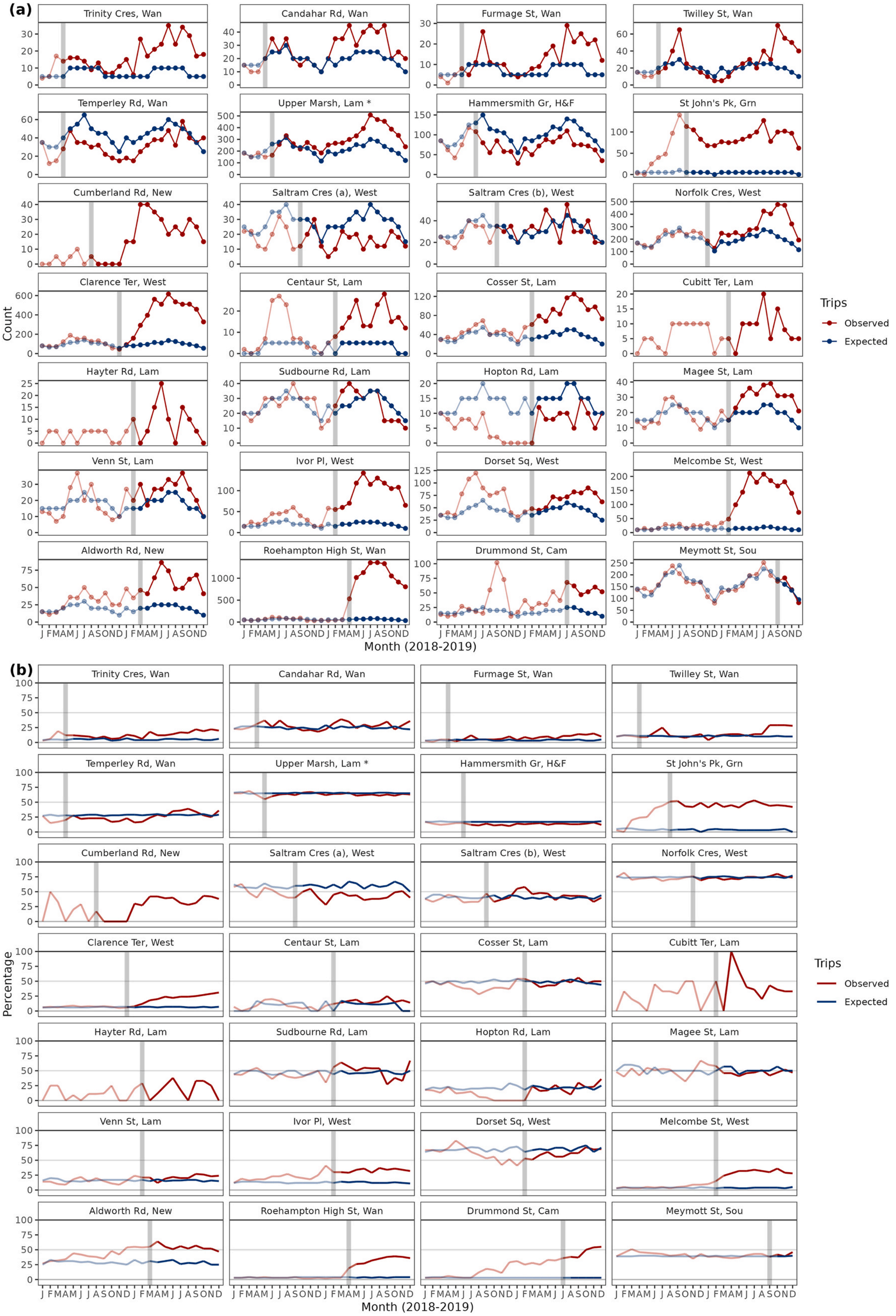

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Fig. 3. Monthly variation in observed and expected contraflow Strava trips on each existing one-way road segment before (pale colours) and after (darker colours) contraflow introduction (month of transition shown as vertical grey line): a) Total counts and b) Percentage of all trips. * Indicates the only road (Upper Marsh) that had motor vehicle direction reversed when contraflow cycling was introduced but the data here represents the real-world contraflow counts so that before and after counts are comparable.

Contraflow introduction appears to be associated with different effects on journey purpose depending on the road. Seven of the eight roads with commute or leisure monthly counts of over one hundred, show increases in mean count for both journey purposes after contraflow introduction. Roehampton High Street shows the largest mean change with commuting trips increasingly by 2029 percent and leisure by 1675 percent. Melcombe Street, Ivor Place and Clarence Terrace also have larger increases in commuting compared to leisure trips. In contrast, Upper Marsh, Norfolk Crescent and Cosser Street show larger increases in leisure than commute trips. Meymott Street experienced a drop in commuting trips and Hammersmith Grove had a drop in leisure trips whilst Saltram Crescent (a) had a drop in both types after contraflow introduction. Overall, this shows that the connectivity of roads to places of work and places people want to cycle from and to are important.

3.3.2. Contraflow unique people counts

Examining the unique people may offer insight into contraflow cycling (Fig. 5). As there are fewer unique people than trips, many of the roads have low counts, but the trends are similar to the trip counts (Fig. 3a). There are six roads where the monthly count of unique people exceeds 100. Three show large increases (310–1153 percent) in the mean number after implementation from low counts of illegal contraflow cycling and the observed counts are much higher than expected (Clarence Terrace, Melcombe Street and Roehampton High Street). Two (Upper Marsh and Norfolk Crescent) experienced a smaller increase and the observed counts are not much more than expected. Meymott Street again experienced a decrease post-implementation. These findings add credence to other factors affecting contraflow usage and that there is desire to cycle contraflow prior to implementation on many roads.

3.3.3. Examining factors that may contribute to successful contraflow implementation

To explore factors that may contribute to the success of new contraflow implementation, defined as increased contraflow cycling trips and/or people after legalising contraflow cycling, we examined the three most “successful” and the three least “successful”, assessing their infrastructure against coherence, directness, safety, comfort, attractiveness and accessibility for all and the specific design guidance for contraflow infrastructure (DfT, 2020). Data to support the qualitative assessment, such as before and after implementation images, can be found at: https://publichealthdatageek.github.io/qualitative_assessment_intro.html. Fig. 6 shows images of some of these streets in May 2023.

3.3.3.1. “Successful” implementations. Our analysis identified three roads that had large increases in contraflow cycling trips and people after contraflow introduction: Clarence Terrace, Melcombe Street and Roehampton High Street.

3.3.3.1.1. Clarence Terrace. Clarence Terrace is a short, straight 32 kph street (67 m) that forms part of the London Cycling Network. Cycling contraflow takes cyclists away from central London towards the suburbs and parks. Contraflow cyclists are protected on entry by a traffic island and then use a mandatory cycle lane distanced from motor vehicles using cross-hatched paint. It is well lit, has a good surface, clear views, only one side junction (whose entrance is the opposite side to the contraflow) and motor vehicles cannot park on the contraflow side. Overall this appears to be good infrastructure that meets national guidance.

3.3.3.1.2. Melcombe Street. Melcombe Street is a straight, short street close to Clarence Terrace with a good quality surface, clear views and 32 kph speed limit. It has similar connectivity and a protected entrance with subsequent mandatory cycle lane that is distanced from motor vehicles using a buffer strip and no same-side parking. Again this appears to be good infrastructure that meets national guidance.

3.3.3.1.3. Roehampton High Street. Cycling contraflow on Roehampton High Street connects inner London areas with affluent suburbs. It facilitates cycling in large green spaces such as Richmond Park. The 32 kph road is 330 m long with multiple, small side junctions and many shops and amenities. It is well lit with asphalt/pave surfaces and intermittent parking. The entrance is protected with a traffic island, set back side junction and green asphalt whilst the exit has a mandatory cycle lane. The rest is unprotected. Some sections are narrow that may reduce accessibility and risk conflict with motor vehicles. Overall this appears to be satisfactory infrastructure that meets guidance.

3.3.3.2. “Unsuccessful” implementations. Three streets experienced a fall in mean contraflow counts after implementation: Hammersmith Grove, Saltram Crescent (a) and Meymott Street; with the former two having observed counts lower than expected.

3.3.3.2.1. Hammersmith Grove. The Hammersmith Grove contraflow is around 100 m long, well-lit, near amenities, with a good road surface and 32 kph speed limit, however, there are numerous issues. There is no protected entrance with no indication that cyclists can cycle contraflow until painted tarmac signage metres from the junction. Multiple large planters, supporting road reallocation for pedestrians and cycle parking, interfere with contraflow cyclists’ road visuals and numerous parking spaces on both sides exist. These encourage motor vehicles to drive in the centre of the road. These factors make the road very unappealing and inaccessible so this infrastructure does not meet design standards.

3.3.3.2.2. Saltram Crescent (a). In contrast, Saltram Crescent is a residential road. It connects two cycle routes, facilitates travel towards central London, is 32 kph and has parking on both sides. There is a short mandatory cycle lane at the entrance but during the study period there was no protection and the junction was extremely wide, which may have discourage contraflow cycling.

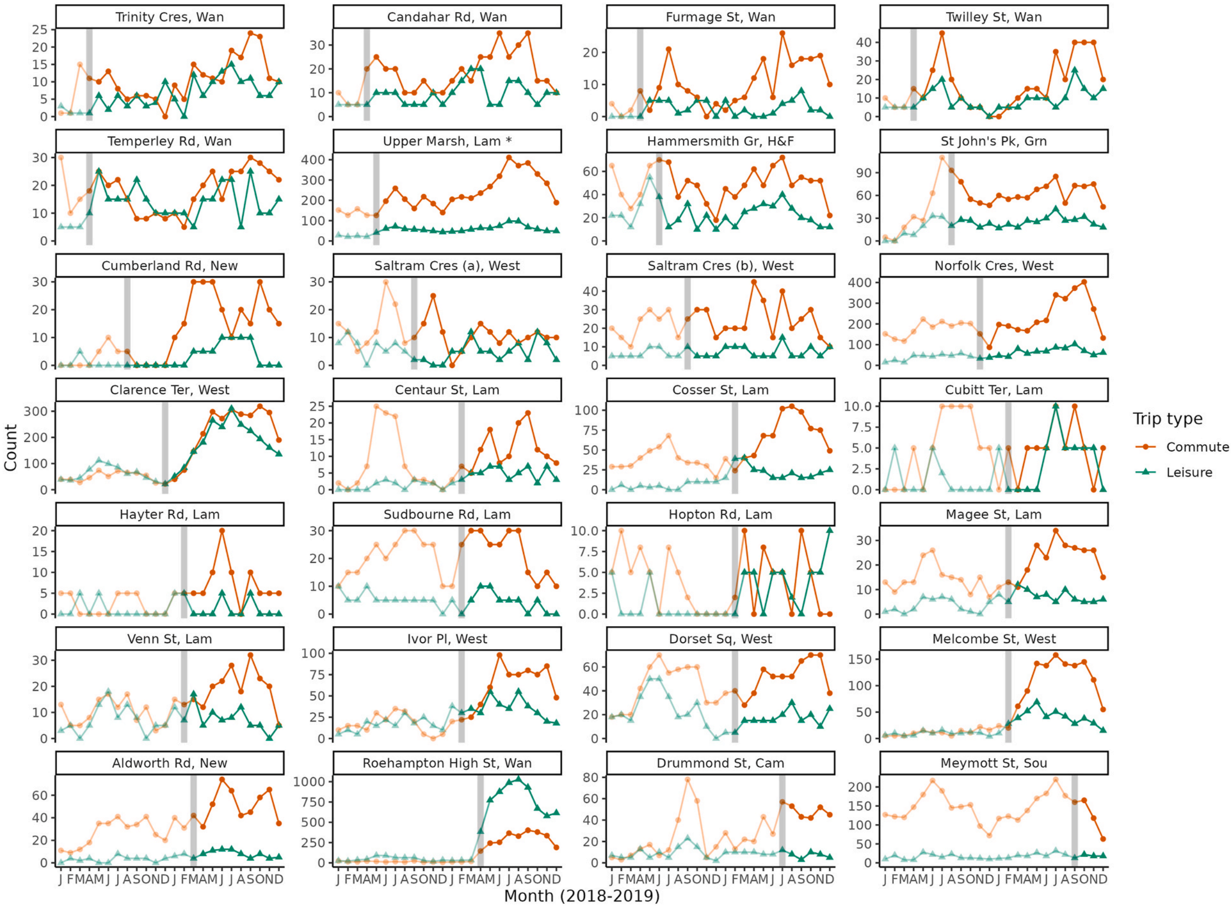

Fig. 4. Monthly variation in observed commute and leisure contraflow Strava trip counts on each former one-way road segments before (pale colours)and after (darker colours) contraflow introduction (month of transition shown as vertical grey line).

Subsequently, the entrance was upgraded with protection but, negatively, it delivers cyclists into parking spaces so it would be interesting to examine the current contraflow counts.

3.3.3.2.3. Meymott Street. Meymott Street is a short section of straight road that connects multiple cycle routes. Contraflow cycling was legally allowed towards the end of the study period but examining Google Street View images there are no indications that any infrastructure changes have occurred on the ground that facilitate or indicate to road users that it is allowed which could clearly explain why the counts are low.

3.4. Two-way streets converted to one-way with contraflow cycling

3.4.1. Contraflow trip counts

Fig. 7 shows the monthly variation in total observed and expected number of contraflow Strava trips on these fourteen streets. As these roads were two-way initially, we would expect the contraflow cycling volumes to be similar before and after contraflow implementation. This holds true for most roads but Tanner Street, Worship Street and Ivor Place experience increases of 110 percent, 50 percent and 11 percent in mean observed contraflow counts (Fig. 7a). Old Jamaica Road counts visually appear to increase but the mean count only increases by 1 percent. The observed contraflow trip counts for Tanner Street, Ivor Place and Old Jamaica Road are higher than expected. Surprisingly, Harrowby Street's mean count falls by 25 percent and Appold Street by 15 percent post-implementation with both having lower than expected counts.

The relative levels of contraflow cycling (Fig. 7b) are stable for most roads, which contrasts with existing one-way streets where there is more variation (Fig. 3b). However, the proportion of contraflow cycling has dropped post-implementation on five roads (30 percent on Old Jamaica Road and Ivor Place and around 20 percent on Harrowby Street, Giffin Street and Thurland Road) whereas only one road experienced an increase in contraflow proportion (Worship Street, 20 percent). This may suggest that converting two-way to one-way with contraflow cycling attracts cyclists to travel with flow. Overall this inconsistency in how counts change after implementation suggest that other factors are important in influencing cycling.

Examination of contraflow trips by purpose shows that these roads are overwhelmingly used for commuting trips and increases in contraflow cycling after implementation are driven by increases in commuting trips (Appendix 4, Figure A1).

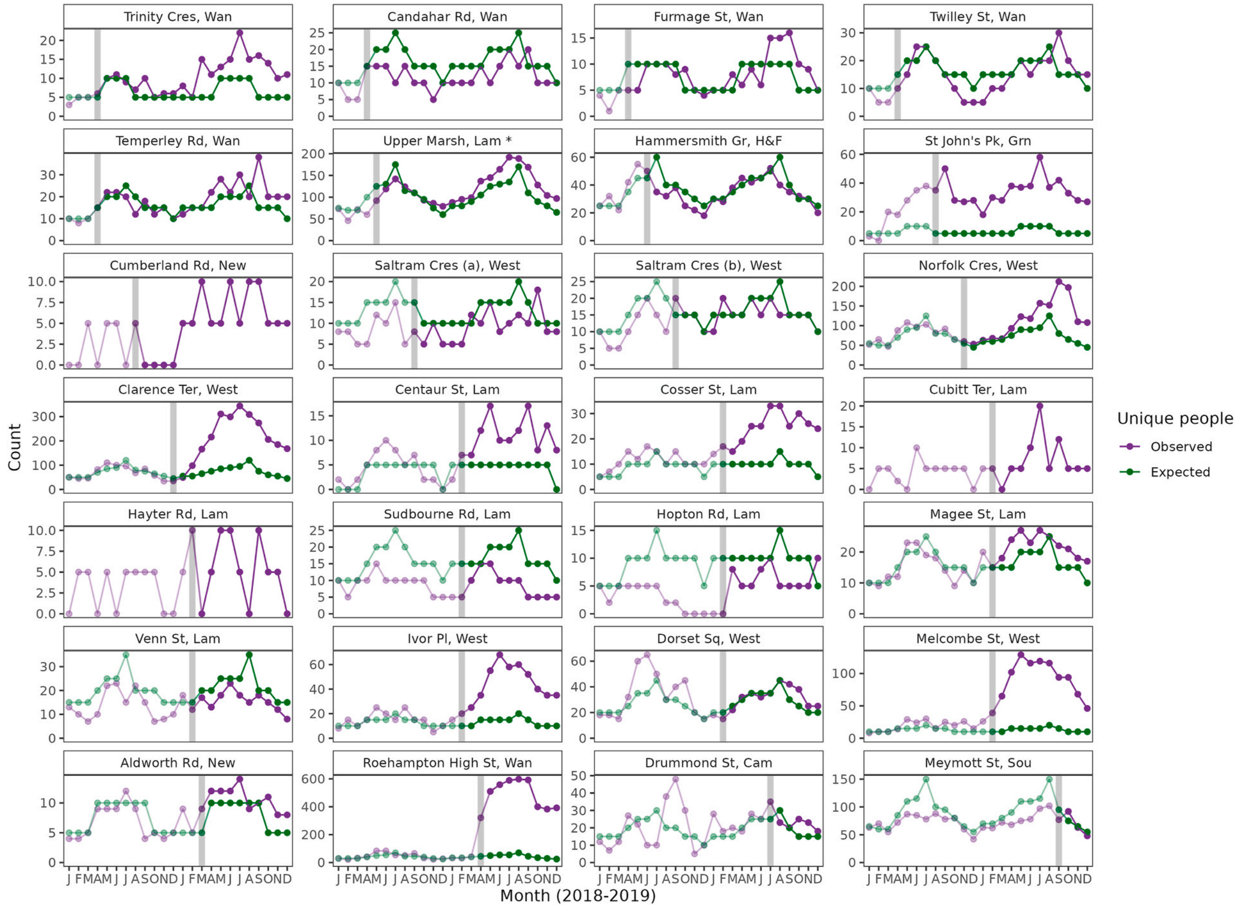

Fig. 5. Monthly variation in total observed and expected number of unique Strava users cycling contraflow on each existing one-way road segment before (pale colours) and after (darker colours) contraflow introduction (month of transition shown as vertical grey line).

3.4.2. *Contraflow unique people counts*

The patterns seen for contraflow people counts (Fig. 8) tend to mirror those seen for contraflow trip counts (Fig. 7). The mean number of contraflow cyclists increases on Tanner Street, Old Jamaica Road and Ivor Place (91 percent, 33 percent and 30 percent). However, Harrowby Street and Burwood Place, where trip counts fell, have contrasting changes in people counts: Harrowby Street experiences a 10 percent fall whilst Burwood Place experiences a 12 percent increase.

3.4.3. *Examining factors that may contribute to successful contraflow implementation*

As before, we selected two-way streets that were successful and unsuccessful to examine factors that may be contributing to these outcomes. Data to support the qualitative assessment is available at: https://publichealthdatageek.github.io/qualitative_assessment_intro.html.

3.4.3.1. "Successful" implementation. Our analysis identified three roads where contraflow cycling trips and people increased after implementation: Tanner Street, Old Jamaica Road and Ivor Place.

3.4.3.1.1. Tanner Street. Tanner Street is a long 32 kph section (280 m) that is part of Cycleway 14 and connects to other cycle routes. The contraflow entrance is wide and well protected. There is a partial bidirectional cycleway, painted cycle lanes and traffic islands. The surface is good quality, well lit with some on-road parking but not on the contraflow side. Overall this is good infrastructure that is compliant with design guidance. The delay in cycling volume increase after the contraflow start date may be explained by the lengthy construction time as it was not complete until Autumn 2018; (Mayor of London, 2018).

3.4.3.1.2. Old Jamaica Road. This 137 m 32 kph residential road has no entry protection for contraflow cyclists but does have advisory cycle lane sections. It leads to a school and connects to the cycling network. The surface is good and there is street lighting. There is parking allowed on both sides of the road but the road is wide. Assuming motor vehicle speed and flow is low, this could be satisfactory infrastructure compliant with design guidance but it could be improved with protection at the entrance.

3.4.3.1.3. Ivor Place. This is a very short (34 m) 32 kph residential contraflow that has no entry protection for cyclists. There is a short mandatory cycle lane at the exit and parking is allowed on the non-contraflow side. It is located close to other cycleways and amenities with a good surface and lighting. It appears to be satisfactory infrastructure compliant with design guidance but it could be

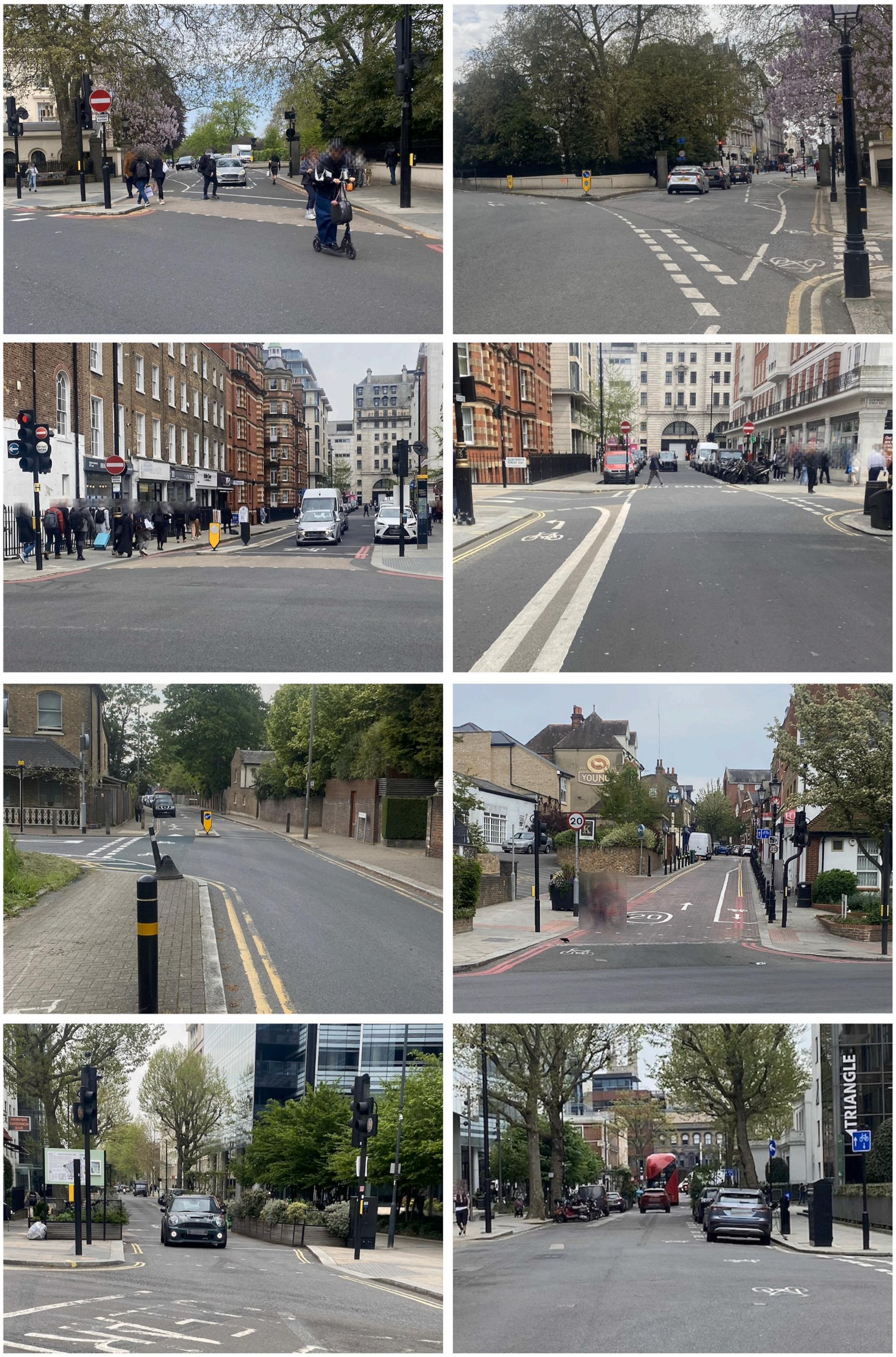

Fig. 6. Images of one-way streets that allow contraflow cycling taken in May 2023: Clarence Terrace (top row), Melcombe Street (second row), Roehampton High Street (third row), Hammersmith Grove (fourth row); left column is the contraflow entrance and right column is contraflow exit.

improved with protection at the entrance.

3.4.3.2. "Unsuccessful" implementation. Two roads were identified as experiencing falls in contraflow cycling after contraflow implementation.

3.4.3.2.1. Harrowby Street and Burwood Place. These short contraflow sections are on good tarmac and well lit. Their entrances are protected by traffic islands and there are advisory cycle lanes. They appear to be compliant with design guidance, are adjacent to each other and form part of Cycleway 27 but are 'unsuccessful'. One explanation is that Cycleway 27 is not complete. These roads form the eastern end of a section and there is a significant distance (2 km) to the next section of Cycleway 27 that is unfinished. Another explanation is that the main road separating these two streets has a severance effect on the route.

4. Discussion

4.1. Key findings

Our findings suggest that implementing contraflow cycling can increase contraflow cycling volume and attract more people to cycle on such infrastructure. This could be explained by attracting new cyclists or existing cyclists choosing to deviate from previous routes to use the infrastructure. On the existing one-way streets that had more than 100 trips per month, eight out of twelve demonstrated increases in contraflow cycling trips and seven experienced increases in the number of unique people cycling contraflow, all of which exceeded expected counts. Three experienced increases in the relative volume of contraflow trips and people. Some streets had high

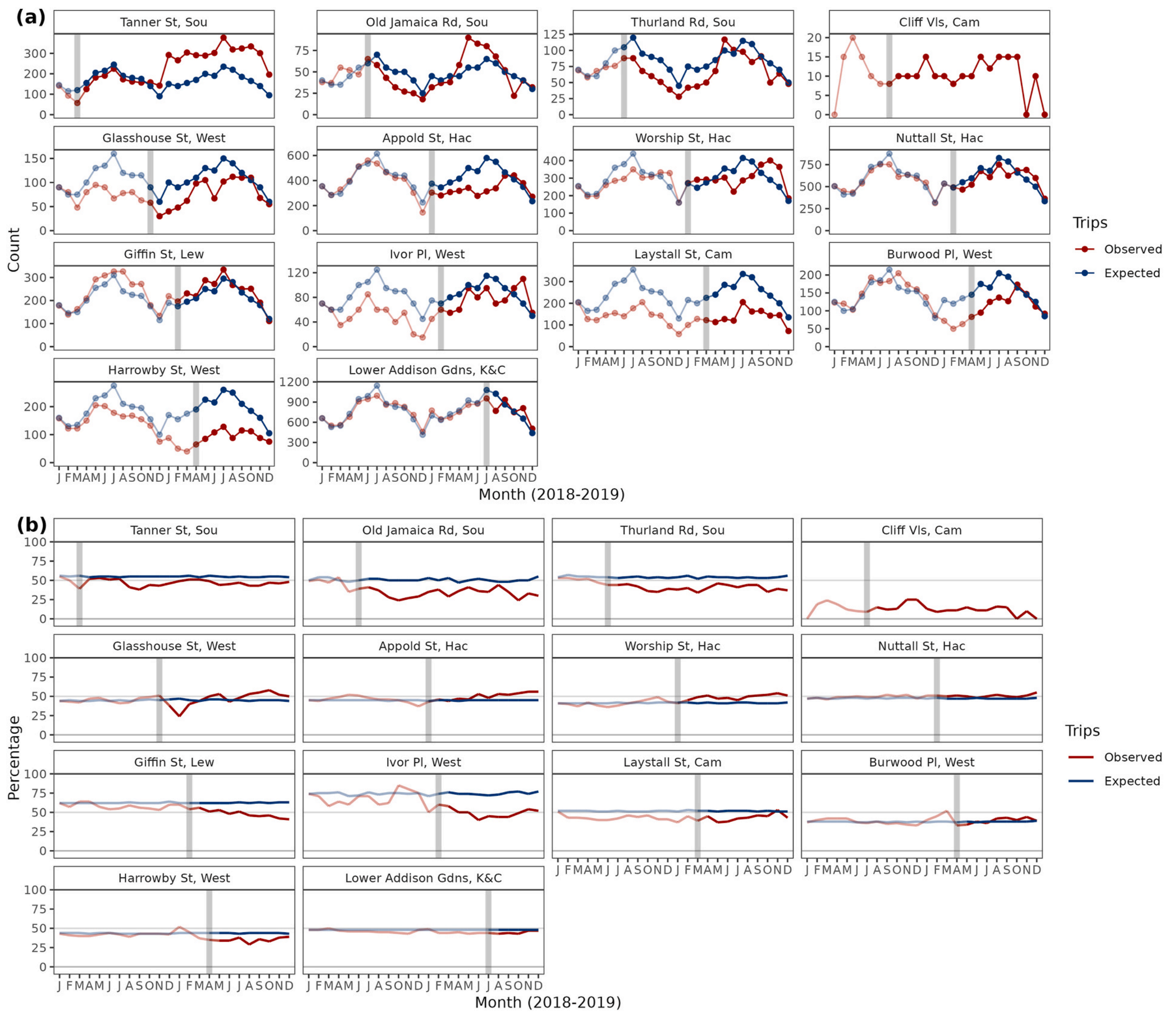

Fig. 7. Monthly variation in observed and expected contraflow Strava trips on each former two-way road segment before (pale colours) and after (darker colours) contraflow introduction (month of transition shown as vertical grey line): a) Total counts and b) Percentage of all trips.

counts of illegal contraflow cycling suggesting previous unmet demand. Others had low illegal counts then high legal counts suggesting that introducing the infrastructure increased contraflow cycling.

Despite expecting little change in contraflow cycling when two-ways streets are converted, three out of fourteen streets experienced over a ten percent increase in mean contraflow counts, all greater than expected, whilst two streets had over a ten percent fall with observed counts lower than expected. Relative contraflow counts fell on two streets that experienced increased contraflow volumes, suggesting these roads attracted with-flow cycling. However, for most streets we did not see any impact of introducing contraflow cycling.

Local context was important in determining apparent success of implementation. Connectivity to existing cycle routes appeared to unlock cycling potential and facilitating travel to and from places of interest including green spaces was important and consistent with Beecham et al. (2023). Contraflow infrastructure factors identified as necessary include protected entrances, limited on-road parking, unobscured vision and distance or separation from motor vehicles. External factors such as local construction work, infrastructure construction or delays in implementation affected success.

4.2. Interpretation of findings and contextualisation within the literature

Our findings that contraflow cycling volumes and users can increase when contraflow cycling is introduced on existing one-way streets is consistent with the current evidence base (Ryley and Davies, 1998; Bjørnskau et al., 2012; Burkin, 2019; Pritchard et al., 2019). We also found some evidence that it can increase more than with-flow cycling, consistent with previous studies (Ryley and Davies, 1998; Bjørnskau et al., 2012). However, our findings that it can increase on converted two-way streets is new as we have not found any research on this street type. In particular, our discovery that with-flow cycling may increase suggests that cycling on these new one-way streets is more attractive than when they were two-way streets.

Looking at the literature it is unsurprising that we have found inconsistent associations between contraflow implementation and cycling volume and that local context and other factors seem to be important. Whilst individual studies have found that painted cycle lanes can increase cycling participation (e.g. Parker et al., 2013), systematic reviews have concluded that there is insufficient high quality evidence that cycle lanes or separated cycle tracks influence counts (Mulvaney et al., 2015; Stappers et al., 2018; Molenberg et al., 2019). However, when implemented in a wider cycling programme (e.g. Goodman et al., 2013) or cycle-friendly environment (e.g. Hull and O'Holleran, 2014; Aldred et al., 2019), they appear to have a positive effect on cycling volume. This could be explained by infrastructure delivering certain functions that increase cycling: improved accessibility and connectivity; traffic and personal safety; and cycling experience (Panter et al., 2019). Panter et al. (2019) found that even in unsupportive contexts, for example, car dominated areas, infrastructure that delivered such functions could be successful. This could also explain why car-dominated Roehampton High Street that had lower physical quality but good connectivity was successful whereas Harrowby Street, with good infrastructure but an unsupportive context due to no onward connectivity and busy roads, were less successful.

4.3. Strengths and limitations

Our study is the first large data analysis of changes in contraflow cycling trips and users after the introduction of contraflow cycling. We used 28 one-way streets and 14 former two-ways streets. Examining change on former two-way roads has not been performed before to the best of our knowledge. We examined twenty-four months of count data with a minimum of two months before and after

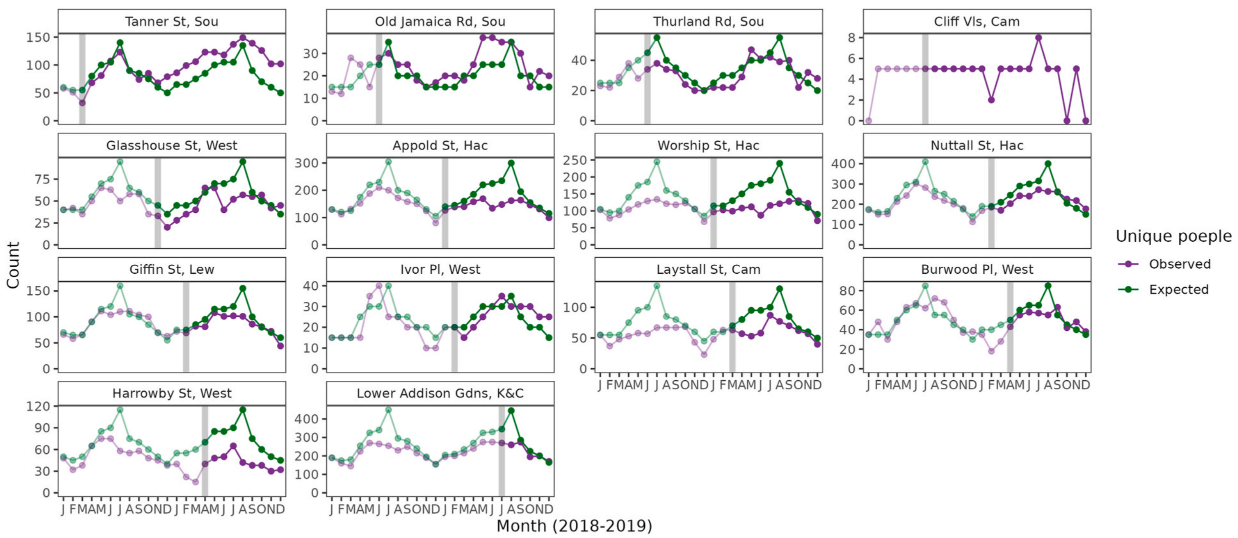

Fig. 8. Monthly variation in total observed and expected number of unique Strava users cycling contraflow on each former two-way road segment before (pale colours) and after (darker colours) contraflow introduction (month of transition shown as vertical grey line).

implementation. We generated expected counts to adjust for the number of Strava users, Strava trips, seasonality and time of year to examine whether changes in observed counts could be explained by these factors or whether such changes could be associated with contraflow implementation.

Our approach is not without limitations. The Strava Metro dataset makes it hard to generalise our findings to all cyclists as many groups are under-represented (Lee and Sener, 2021). Strava users may not behave in the same way as other cyclists. For example, Garber et al. (2019) found that fitness app users were more likely to illegally cycle contraflow than non-app users whilst Dunleavy (2015) found 95 percent of Strava users would cycle illegally contraflow rather than divert around a one-way street. Strava users motivations to cycle can be different, focussing on activity tracking, performance management and competition (Williams, 2013). We would have preferred to use more longitudinal data in the analysis but were limited by the availability of historical Strava Metro data and the impact of the COVID-19 pandemic. More longitudinal data may have helped unearth delayed adoption of contraflow cycling. For example, if there was delay in cyclists knowing that such infrastructure now existed or they were hesitant to start to use it.

We assumed the road segment dataset was accurate (limitations are discussed in Tait et al., 2023) . However, the contraflow had not been physically introduced on Meymott Street and there were delays in implementation on others. As we only qualitatively assessed 12 of the 42 intervention roads, there may be others affected by these factors and we may have erroneously concluded that there was no association between contraflow implementation and cycling volume.

Our methods have limitations. For example, our expected counts were generated using Strava counts on comparable inner London roads. However, they are unlikely to be fully comparable to our intervention roads but the large data volume may minimise any errors introduced by this approach. Our expected counts are not adjusted for other factors that can influence cycling volume such as motor vehicle volume or road speed nor did we examine wider improvements to routes or other interventions that can impact cycling participation.

Our qualitative assessment was subjective as there is no standard for contraflow implementation. It was also desktop based and limited by the data available. Data on road width, average road speeds and motor vehicle volumes coupled with an on-site visit would have improved the assessment process.

One limitation of descriptive studies is the difficulty in attributing change to specific factors but they can provide rich data and identify areas for future research.

4.4. Implications for policy and future research

Increasing contraflow cycling roads could increase cycling volumes and address key barriers to cycling participation. Safety and infrastructure are reported as the greatest barriers whilst quality infrastructure is the greatest enabler (Pearson et al., 2023). We have previously demonstrated that introducing contraflow cycling is safe and improves the safety on former two-way streets in particular (Tait et al., 2023). This, in combination with carefully designed contraflow infrastructure that delivers improved connectivity, accessibility and the cycling experience, preferably in supportive context should deliver greater cycling participation at lower cost than other types of cycling infrastructure (Steer Davies Gleave, 2016; Taylor and Hiblin, 2017). We echo our earlier call for UK highway authorities to review their one-way streets with a view to introducing contraflow cycling (Tait et al., 2023). In 2016, Lambeth Council did just that and identified only three unsuitable streets out of 67 (Steer Davies Gleave, 2016). We also call on UK highway authorities to consider two-way streets that could be reconfigured and encourage national governments to consider legislation making contraflow cycling mandatory on one-way streets unless exceptional circumstances exist (Tait et al., 2023).

This quantitative and qualitative research on cycling infrastructure can guide evidence-based decision making by policy-makers as to what type of infrastructure is effective in increasing cycling participation in what circumstances and thus maximise limited active travel resources. It also highlights the importance of the context in which such infrastructure is introduced as a factor influencing success. This research has demonstrated that highway authorities could use Strava Metro counts to identify one-way streets with high counts of illegal contraflow cycling that would benefit from contraflow implementation.

Research on cycling volume is important as such data is used to underpin questions that policy-makers are interested in such as how much cycling, who is cycling and where they are cycling (Handy et al., 2014). However, cycling volumes are also used as a measure of exposure and are vital for calculating crash rates involving cyclists (e.g. Vanparijs et al., 2015; Dozza, 2017), examining safety risk (Strauss et al., 2015; Ferster et al., 2021) and thus reducing risks to cyclists.

Future research could focus on detailed examination of the 42 roads to establish more clearly the factors for successful implementation of contraflows complemented with interviews with key stakeholders such as Transport for London, London Cycling Campaign and highway authorities. Such examination could include triangulation with other datasets such as public bike sharing scheme that have previously been used to assess bikeability (Beecham et al., 2023), gendered cycling behaviour (Beecham and Wood, 2014) and inclusivity (Lovelace et al., 2020). The method to generate the expected counts could be improved by using Bayesian techniques to generate more localised expected counts (Sahu, 2022). Such future research could reconfirm our findings using more comprehensive analysis techniques. For example, modelling that includes other aspects such as weather conditions and local factors.

5. Conclusion

This is the first large-scale analysis of the impact on cycling volumes of introducing contraflow cycling on one-way streets. We have demonstrated that it can be associated with increases in the number of contraflow trips and individuals measured using crowd-sourced data. Local context appears to be important in determining success of these implementations and connectivity, protective entrances, minimal on-road parking, clear vision and distance or separation from motor vehicles were positive influencing factors. Highway authorities should examine their one-way streets and consider converting these and two-way streets to one-way with contraflow cycling as such roads have previously been demonstrated to be safe (Tait et al., 2023), now shown to encourage cycling participation and represent a low-cost intervention compared to segregated cycle lanes or junction remodelling (Taylor and Hiblin, 2017). Legislative change to make one-way streets contraflow by default would facilitate faster implementation of such infrastructure. Further research could explore in more detail the aspects of contraflow implementation that are necessary for success, improve methods to use crowd-sourced data to generate cycling volume counts, examine the effect of such infrastructure on route choice and explore other potential influencing factors such as weather.

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CRediT authorship contribution statement

Caroline Tait: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Roger Beecham:** Supervision, Conceptualization. **Robin Lovelace:** Supervision, Conceptualization. **Stuart Barber:** Supervision.

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

The authors do not have permission to share Strava Metro data. The dataset of roads that had contraflow cycling introduced is available (see Methods for links)

Acknowledgments and Licenses

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Strava Metro data: This report includes aggregated and de-identified data from Strava Metro.

Appendix 1. Strava edge data dictionary (Strava Metro, 2023b)

Definitions:

- “Trip" counts indicate the number of bicycle or pedestrian trips on that edge during the given timeframe.
- “People" counts indicate the number of unique people who completed a bicycle trip on that edge during the given timeframe. For instance, 10 people may have completed 30 trips on an edge during the timeframe.
- “Forward" indicates trips travelling in the direction the street was digitized into OSM (from the first point of the line to the last point of the line).
- “Reverse" indicates trips travelling in the opposite direction the street was digitized into OSM (does not indicate wrong-way travel).

The exported Street (edge) level data contains the following columns:

- edge_UID – the identifier for the street block
- activity_type – the type of activity, e.g. (ride, walk)
- year-month-date-hour – one row per aggregated time frame in ISO8601 format (YYYY-MM-DD-HOUR). In this format an hour value of 5 represents data between 5:00 a.m. and 6:00 a.m. local time as the field is formatted to the local time zone of the data export.
- osm_reference_id – refers to the OpenStreetMap (OSM) Way ID associated with that particular edge. In OSM, a way normally represents a linear feature on the ground such as a road, trail, or bike path. Due to the way edges are created for Strava Metro, many edges can have the same osm_reference_id.

For each row, the following count columns are provided:
Trip counts:

- forward_trip_count, reverse_trip_count
- forward_commute_trip_count, reverse_commute_trip_count, forward_leisure_trip_count, reverse_leisure_trip_count
- total_trip_count, ride_count (meaning traditional bikes), ebike_ride_count (from Strava activities listed as ebike rides)

People counts:

- forward_people_count, reverse_people_count

People counts by Gender:

- forward_male_people_count, reverse_male_people_count, forward_female_people_count, reverse_female_people_count,forward_unspecified_people_count, reverse_unspecified_people_count

People counts by Age:

- forward_18_34_people_count, reverse_18_34_people_count
- forward_35_54_people_count, reverse_35_54_people_count
- forward_55_64_people_count, reverse_55_64_people_count
- forward_65_plus_people_count, reverse_65_plus_people_count

Average Speed:

- forward_average_speed, reverse_average_speed (metres per second)

Appendix 2. 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

We also removed any highways that went through parks as these are not comparable to our intervention roads.

Appendix 3. Roads with contraflow cycling introduced April 2018 to October 2019

The below tables list the one-way and two-streets that introduced contraflow cycling. The contraflow start date and notice ID come from the Traffic Regulation Orders (TRO) that legally allowed the contraflow cycling. The actual orders can be accessed by appending the notice ID to https://www.thegazette.co.uk/notice/, for example, https://www.thegazette.co.uk/notice/2999427 is the TRO for Trinity Crescent, Candahar Road, Furmage Street, Twilley Street and Temperley Road. More details such as the description of the contraflow spatial extent and actual spatial data can be accessed via the full dataset available from Tait (2022)

Saltram Crescent only appears once in Table A1 as both sections had the same contraflow start date.

Table A1
Existing one-way roads with contraflow cycling introduced

Road name	London Borough	TRO contraflow start date	TRO notice ID
Trinity Crescent	Wandsworth	06 April 2018	2999427
Candahar Road	Wandsworth	06 April 2018	2999427
Furmage Street	Wandsworth	06 April 2018	2999427
Twilley Street	Wandsworth	06 April 2018	2999427
Temperley Road	Wandsworth	06 April 2018	2999427
Upper Marsh	Lambeth	29 May 2018	2824241
Hammersmith Grove	Hammersmith and Fulham	11 June 2018	3035229
St John's Park	Greenwich	06 August 2018	3080077
Cumberland Road	Newham	16 August 2018	2846585
Saltram Crescent	Westminster	11 September 2018	3048578
Norfolk Crescent	Westminster	19 November 2018	2745411
Clarence Terrace	Westminster	10 December 2018	2659170
Centaur Street	Lambeth	11 February 2019	3104035
Cosser Street	Lambeth	11 February 2019	3104035
Cubitt Terrace	Lambeth	11 February 2019	3104035
Hayter Road	Lambeth	11 February 2019	3104035
Sudbourne Road	Lambeth	11 February 2019	3104035
Hopton Road	Lambeth	11 February 2019	3104035
Magee Street	Lambeth	11 February 2019	3104035
Venn Street	Lambeth	11 February 2019	3104035
Ivor Place	Westminster	24 February 2019	2648991
Dorset Square	Westminster	24 February 2019	2648991
Melcombe Street	Westminster	24 February 2019	2648991
Aldworth Road	Newham	25 March 2019	2846585
Roehampton High Street	Wandsworth	13 April 2019	2918580
Drummond Street	Camden	01 July 2019	3268444
Meymott Street	Southwark	16 September 2019	3260316

Table A2
Former two-way roads converted to one-way with contraflow cycling

Road name	London Borough	TRO contraflow start date	TRO notice ID
Tanner Street	Southwark	05 March 2018	2918355
Old Jamaica Road	Southwark	01 June 2018	3034235
Thurland Road	Southwark	01 June 2018	3034235
Cliff Villas	Camden	30 July 2018	2984851
Glasshouse Street	Westminster	12 November 2018	3148658
Appold Street	Hackney	21 January 2019	3153817
Worship Street	Hackney	21 January 2019	3153817
Nuttall Street	Hackney	11 February 2019	3206808
Giffin Street	Lewisham	18 February 2019	3186754
Ivor Place	Westminster	24 February 2019	2648991
Laystall Street	Camden	11 March 2019	3139336
Burwood Place	Westminster	01 April 2019	3085582
Harrowby Street	Westminster	01 April 2019	3085582
Lower Addison Gardens	Kensington and Chelsea	15 July 2019	3153789

Appendix 4. Additional figures

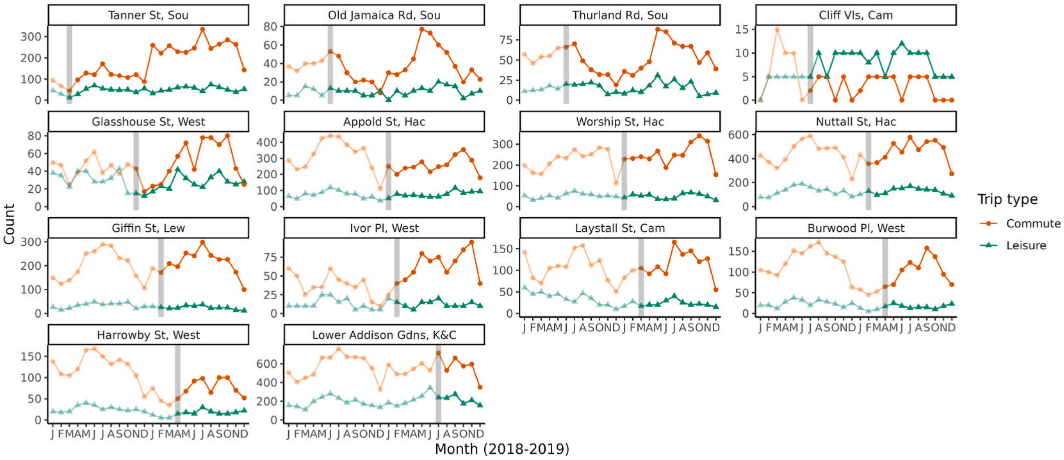

Fig. A1. Monthly variation in observed commute and leisure contraflow Strava trip counts on each former two-way road segments before (pale colours)and after (darker colours) contraflow introduction (month of transition shown as vertical grey line).

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