Design effects of cycle infrastructure changes: An exploratory analysis of cycle levels

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ABSTRACT

Introduction: Cycling infrastructure policies yield health and environmental benefits. However, design variations may impact intervention effectiveness. This study explored relationships between infrastructure form (e.g., width, length) and function (e.g., access, safety) and cycling behavior.

Methods: We analysed data from a study evaluating 15 streets with new cycling infrastructure improvements in Paris and Lyon. Comparison streets were chosen based on having similar pre-intervention cycling trends and periods of data availability as intervention streets. The outcome was the difference in daily cycle counts between intervention and control streets. We conducted a virtual street audit with Google Street View to assess 14 street features and derived a function score based on 7 components. We used induced smoothed LASSO regression to identify relevant form or function variables associated with cycle count changes.

Results: The effects of new cycling infrastructure varied, with significant increases at half (7/15) of the sites and no change at the rest. For every 1 SD increase in cycle lane length, an increase of 83 cycle counts per day (95% CI 32, 134) was observed. Removing car parking and traffic lanes were associated with an increase of 197 counts (108, 285) and 154 counts (58, 249), respectively. Adding a public transport stop showed a negative association with a change of –83 counts (–158, –8). Functions positively associated with cycle count changes were improving safety (75, 95% CI 8, 141) and space (72, 95% CI 10, 135).

Conclusions: This study sheds light on cycling infrastructure design influences on cycling behavior. These insights can help guide future policies and infrastructure development to maximize cycling benefits for health and the environment.

Introduction

Cities face many challenges, including the adverse health, environmental, and social effects arising from car dependency. Motorised vehicle use contributes to sedentary lifestyles, congestion, air pollution, carbon emissions, and social inequalities (World Health Organization, 2022; United Nations Department of Economic and Social Affairs, 2019). Promoting active travel (e.g., walking or cycling for transport) can mitigate these negative impacts by creating opportunities to incorporate physical activity into daily routines while offering low or emission-free alternatives to driving. Studies have found that switching from passive to active transport supports population health, such as by...
increasing physical activity, lowering body mass index, reducing the risk of non-communicable disease, and improving mental health (Warburton et al., 2006; World Health Organization, 2018; Wanner et al., 2012).

Other studies have found that replacing motorised transport trips with active travel can lower mobility-related carbon emissions, and that these shifts can save up to a quarter of carbon emissions from passenger transport (Brand et al., 2021a; Brand et al., 2021b).

Previous research has extensively investigated the relationship between cycling and various built environment characteristics, predominantly through cross-sectional studies. These studies have consistently reported positive associations between cycling and factors such as street connectivity, proximity to cycling paths and facilities, and the presence of green spaces (Wang et al., 2016; Fraser and Lock, 2011; Wang and Wen, 2017).

In recent years, other studies have adopted longitudinal or natural experimental designs to explore how modifying the built environment can promote active travel behavior. A systematic review revealed that improving accessibility to different types of destinations, improving public transportation, and increasing land use diversity were generally linked to higher levels of transportation-related physical activity, including cycling (Kärnänen et al., 2018). Moreover, several reviews have examined the impact of introducing new cycling infrastructure or enhancing existing facilities on cycling behavior. While the overall findings have found positive associations between changing the built environment and changes to cycling behaviour, there have been some mixed results (Winters et al., 2017; Mölenberg et al., 2019; Stappers et al., 2018; Pant et al., 2019).

Few studies have examined the mechanisms or reasons as to why some results have been varied (Pant et al., 2019). Intervention effectiveness may be impacted by the quality of the built environment (Black and Street, 2014), or the variations in the form (e.g., specific features, components, or design elements) that cycling infrastructure can take. Also known as micro-environmental factors, these features can be defined as specific characteristics of the street environment that are more practical and less costly to modify on a local level, as opposed to macro-environmental factors such as street connectivity, residential density, or land-use diversity (Cain et al., 2014; Swinburn et al., 1999; Mertens et al., 2015) Previous literature, separately assessing preferences for various cycling infrastructural features among children and adults, identified that desirable features include coloured lanes, separation from traffic, routes with more greenery, even cycle path surfaces, and streets with speed restrictions (Ghekiere et al., 2018; Mertens et al., 2016; Rossetti et al., 2017; Rossetti et al., 2018; Skov-Petersen et al., 2018; Zimmermann et al., 2017; Winters et al., 2011).

There are, however, several limitations associated with previous study methods examining cycling micro-environmental features, which typically involved the use of stated preference surveys (Rossetti et al., 2017; Rossetti et al., 2018; Winters et al., 2011; Caulfield et al., 2012) and manipulated photographs (Mertens et al., 2015; Ghekiere et al., 2018; Mertens et al., 2016; Mertens et al., 2014; Verhoeven et al., 2017; Ghekiere et al., 2015a; Ghekiere et al., 2015b). Some issues with questionnaire-based evaluation tools include recall bias and lack of standard definitions (e.g., mismatch with actual environmental factors or misunderstanding of what neighbourhood means) (Mertens et al., 2016; Ghekiere et al., 2015a). For manipulated photographs, limitations include evaluating perceptions of routes under hypothetical controlled scenarios (dry weather conditions, no time constraints, limited view of the street). Furthermore, these studies often use a singular snapshot of the same street rather than the whole street length at one time point. As the same cycling lane features are unlikely to be present in the entire street length, this may be another constraint in terms of the generalizability of these studies’ findings. More fundamentally, while offering insights into which infrastructural qualities are more attractive than others, these findings cannot tell us how changing certain aspects of the built environment influences actual cycling behaviour (Mertens et al., 2015).

Using neighbourhood street audits to evaluate real-life changes to streets offers a potential solution to some of these issues surrounding the assessment of environmental features for health, transport, and urban planning research. One method of doing so includes on-site audits that are performed in-person. While in-person audits have been found to be reliable and valid (Pikora et al., 2002; Dunstan et al., 2005), they can be time-consuming, pose safety risks, be perceived as being intrusive, and incur substantial travel expenses (Rundle et al., 2011; Kelly et al., 2013). These factors may limit their application in large-scale data collection.

Virtual audits, such as those using Google Street View (GSV), provide an alternative to in-person audits. With coverage of more than 100 countries, GSV capitalises on Google’s vast collection of freely available images, providing a method to characterise street attributes across various locations and cities (Google, 2023; Rzotkiewicz et al., 2018). GSV offers panoramic views from a street-level perspective, enabling users to navigate along the streets in both directions, rotate the view 360 degrees horizontally and 290 degrees vertically, as well as zoom in and out for more detailed observations. The GSV timeline feature, available since 2014, offers historical street view imagery in select locations based on population density and weather conditions, facilitating longitudinal assessment of street feature changes (Google, 2023; Google, 2014).

Thus, using GSV imagery to perform audits can significantly decrease the resources required for conducting large-scale street-view audits. Furthermore, GSV allows better oversight and quality control by researchers from a central location, with screenshots that can be archived for future review (Rundle et al., 2011).

Virtual audits using GSV has been used previously to characterise the built environment across multiple settings, often achieving high levels of comparability with on-site audits (Rundle et al., 2011; Kelly et al., 2013; Rzotkiewicz et al., 2018; Steinmetz-Wood et al., 2019; Mooney et al., 2016; Gullón et al., 2015; Grew et al., 2013) Previous virtual street audits, however, have only been used to evaluate neighbourhood environments cross-sectionally rather than to assess longitudinal infrastructural changes. Therefore, a novel virtual street audit tool is needed to more accurately depict what cycling infrastructure interventions comprise of or changed in terms of their form, which is crucial for understanding intervention exposure (Humphreys et al., 2016).

With the variety of forms cycling infrastructure can take, difficulties can arise in generalising the findings from interventions with specific combinations of street features. Moreover, certain combinations of features may not be feasibly implemented across different contexts and settings. It may thus be important to identify the higher-order intervention functions (e.g., affecting access, convenience) based on the processes or mechanisms by which the interventions could be expected to change behaviour, which may help generalise findings (Hawe et al., 2004). That is, multiple different interventions can achieve a similar function, while the intervention form can (and should) vary to account for diverse intervention target populations and contexts (Hawe et al., 2009). For instance, introducing vehicle speed limits or a physically separated cycle lane (i.e., the intervention form) can improve both perceived and objective safety (i.e., the intervention function). Other common intervention functions that have been mentioned in the cycling literature include access, convenience, comfort, and aesthetics (Pant et al., 2019; Nawrath et al., 2019; Vallez-Borda et al., 2020; Berghofer and Vollrath, 2022; Xiao et al., 2022).

To fill these research gaps, we aimed to conduct an exploratory analysis using a novel virtual street audit tool. This allowed for a multi-site controlled longitudinal assessment of how changes to the forms of cycling lanes were associated with increased cycling levels over a one year period. We then derived overarching intervention functions from changes to each street form to better understand how these interventions brought about differential impacts to cycling levels. By doing so, we could jointly consider how the form and function of new cycling infrastructure can impact cycling behaviour.
Methods

Study sample

This longitudinal controlled intervention study describes secondary analyses of an evaluation of French cycling lane expansion interventions in Paris and Lyon. Methods of the previous study have been described in detail elsewhere (Xiao et al., 2022). A summary of the methods relevant to the current analysis is provided below.

Intervention

The cycling plans of both Paris and Lyon involved increasing the length of their cycle lanes and the number of traffic-calmed streets, availability of cycle parking, as well as subsidies for cargo or electric bikes (Mairie de Paris, 2020; Syndicat mixte des Transports pour le Rhône et l’Agglomération Lyonnaise, 2017; Grand Lyon, 2011). In addition, Paris also implemented annual and weekly car-free days (Journée Sans Voiture and Paris Respire) in specific neighbourhoods as well as low emission zones restricting older diesel vehicles from entering the city (Mairie de Paris, 2021; Paris sans voiture, 2021; Mairie de Paris, 2023). 18 intervention streets were identified as having received cycling infrastructure improvements with count data available both before and after the interventions were implemented. However, three streets with cycling infrastructure improvements had less than one month of pre-intervention data, so they were excluded from the primary analysis due to issues of comparability with the other intervention streets.

Control

Streets selected for intervention were matched with control streets according to three criteria: 1) both had data collected over the same one-year period, 2) they exhibited parallel pre-intervention trends upon visual examination, and 3) they possessed similar baseline built environment features, as determined by Google Street View (GSV) analysis. These characteristics included whether a similar type of infrastructure existed pre-intervention (e.g., painted cycle lane, shared bus lane, or no cycle lane infrastructure). Furthermore, control streets were chosen if they were more than 2 km from intervention street cycle counters to exist pre-intervention (e.g., painted cycle lane, shared lane markings or sharrows, and shared bus lanes), overall cycling infrastructure length, cycling direction relative to traffic, and lane width (quantified by the number of cycling lanes available on a particular side of the street) (Data Grand Lyon, 2023, Paris Data, 2020).

To ensure comparability between the street segments from which analyses are based and to minimise the number of images needed to characterise each street, we used a screen recording of each street captured on a date both before and after the intervention was introduced as well as from each side of the road (e.g., left to right, forward and backward) (e.g., Appendix Fig. 2). Two auditors assessed each street, with CX performing audits on all streets and JP and RP performing the audit on 50% of the streets. Discrepancies were discussed and agreed upon. Before-and-after changes were recorded, from which changes (e.g., increase, decrease, no change) were deduced. While GSV images are updated on a near-annual basis in both cities we could not gather images exactly six months before and after each intervention was introduced. However, the median difference between when the GSV image was captured and the study period was about 2 (QQR 1–4) months.

Outcome data was acquired using routinely collected cycling count data from approximately 110 cycling counters (40 in Paris and 74 in Lyon) between January 2014 and March 2020 from an open data repository for Paris (Ville de Paris, 2021) or by web-scraping Eco Counter (Grand Lyon, 2023), an online cycle count application for Lyon. The primary outcome was daily cycle counts collected using automatic cycle counters located throughout Paris and Lyon. These permanent automatic cycle counters (i.e., ZELT) use induction loop technology embedded in roads which count cyclists by detecting the metal in bicycle wheels (Personal communication, September 14, 2021). ZELT counters have been reported to have an accuracy rate of 94% to 98% in differentiating bikes from other forms of transport such as cars, motorcycles, and larger vehicles (EcoCounter, 2022; Tin Tin et al., 2012). Only data from before March 16, 2020 were included, as this was the date France entered confinement due to the coronavirus (République Française, 2020). Travel patterns after this time point may not represent typical transport behaviour.

Exposure

Exposure: Cycling lane features

We defined exposure as changes to the form of each overall street, which is comprised of individual micro-environmental cycling infrastructure features (further definitions can be found in Fig. 1), as characterised by a virtual street audit using GSV (Appendix Table 2). The selection of these features was informed by previous assessments conducted through GSV audits and what could be feasibly measured using these instruments. These features included the presence of designated cycle lanes and their surface condition, buffers, cycling infrastructure (e.g., crossings and cycle parking), cycling signage, availability of car parking, number of traffic lanes, presence of infrastructure for public transport (i.e., bus, metro), presence of traffic calming, physical disorder, and the presence of greenery in the surrounding area (Rundle et al., 2011; Kelly et al., 2013; Steinmetz-Wood et al., 2019; Mooney et al., 2016; Gullón et al., 2015). We also incorporated additional cycling infrastructure features, not assessed in prior virtual street audits, which we validated against descriptions from official public datasets from the cities Paris and Lyon. These additional features encompassed the type of cycling infrastructure (such as physically separated lanes, painted lanes, shared lane markings or sharrows, and shared bus lanes), overall cycling infrastructure length, cycling direction relative to traffic, and lane width (quantified by the number of cycling lanes available on a particular side of the street) (Data Grand Lyon, 2023, Paris Data, 2020).

To ensure comparability between the street segments from which analyses are based and to minimise the number of images needed to characterise each street, we used a screen recording of each street captured on a date both before and after the intervention was introduced as well as from each side of the road (e.g., left to right, forward and backward) (e.g., Appendix Fig. 2). Two auditors assessed each street, with CX performing audits on all streets and JP and RP performing the audit on 50% of the streets. Discrepancies were discussed and agreed upon. Before-and-after changes were recorded, from which changes (e.g., increase, decrease, no change) were deduced. While GSV images are updated on a near-annual basis in both cities we could not gather images exactly six months before and after each intervention was introduced. However, the median difference between when the GSV image was captured and the study period was about 2 (QQR 1–4) months.

Exposure: Cycling lane functions

In addition, each feature was categorised using a rubric (Appendix Table 3) as having one or more functions, including aesthetics, access, awareness, comfort, convenience, safety, and space (Table 1). For instance, an increase in cycling lane width would add one point each to the functions of space and convenience. The sum of each function was then calculated to arrive at a total score. Thus, greater scores denote larger increases in each function (e.g., more access or space). We based function categories on previous systematic reviews (Panter et al., 2019; Xiao et al., 2022). We considered functions that would apply only to increasing cycling behaviour, as the outcome under consideration was cycling counts.

Covariates

The models included variables that varied between streets: length of follow-up, to adjust for differences in the amount of data available for each street, and baseline number of cycling counts to adjust for major versus minor routes. We also included city (Paris or Lyon), to adjust for context, and whether the infrastructural changes occurred more centrally or peripherally from the city. This was performed to help adjust for convenient versus less convenient routes, as more centrally located routes may be accessed more often to reach places of interest (e.g., cultural sites, shops, workplaces).
All data analysis was performed using R. We estimated difference-in-differences (DiDs) representing the difference in the pre-post change in cycling counts between intervention and control streets. To estimate the DiD, an interaction term between time and an indicator variable for intervention/control was included in a linear regression model, as shown below:

\[ Y_i = \alpha + \beta T_i + \gamma t_i + \delta (T_i \cdot t_i) + \epsilon_i \]

- \( Y_i \): observed cycling count on day \( i \)
- \( T_i \): 0 (control), 1 (intervention)
- \( t_i \): 0 (pre-intervention implementation), 1 (post-intervention implementation)
- \( \epsilon_i \): a normally distributed random variable with mean 0 and constant variance
- \( \delta \): difference (post vs pre implementation) between intervention and control streets (i.e. DiD).

We then estimated Pearson correlation coefficients between each independent variable (feature or function) and the outcome measure (difference in change in cycling counts between intervention and control streets) along with covariates (follow-up period, baseline level of cycling counts, city, and location). Because we include a large number of independent variables, thus making the regression model prone to over-fitting and multicollinearity, we then performed least absolute shrinkage and selection operator (LASSO) regression, which is a variable selection method for estimating models such as generalised linear regression models. LASSO includes a penalty term which penalises or shrinks less relevant covariates towards 0 (Tibshirani, 1996). One limitation of LASSO regression, however, is that there is no commonly accepted procedure for the calculation of standard errors and therefore for inference. An induced-smoothing LASSO has been proposed, which shrinks coefficients to near-zero to be able to calculate confidence intervals (Cilluffo et al., 2020).

We performed the following steps on two models, both with the same outcome and covariates, but the first including intervention features and the second intervention functions. Prior to conducting the LASSO analysis, we centred and scaled continuous exposure variables to have a mean of zero and standard deviation of one. We then used a five-fold cross-validation approach to select the optimal tuning parameter to maximise the cross-validated likelihood function using the ‘glmnet’ package (Friedman et al., 2022). The selected tuning parameters were used to calculate estimates and confidence intervals using a smoothing LASSO method, where estimation is performed by penalising coefficients using a quasi-lasso penalty. We then used the ‘islasso’ package to test for linear hypotheses on combinations of our predictor (Sottile et al., 2023). The model parameters are interpreted in the same way as non-regularised regression parameters, with lower values indicating a smaller association.

### Results

During the study period, an average of 1864 cyclists were recorded per day across all intervention and control streets. Table 2 presents...
additional information on cycling counts before and after the interventions for each city and intervention group. Across each city and intervention group, mean daily counts of cyclists increased. This increase was most pronounced on intervention streets in Paris.

At the individual street level, there were significant increases in cycling counts for most intervention streets (relative to their matched controls) in Paris, with an increase of 181 daily cycle counts (95% CI 1,361) observed on Aubervilliers, 335 cycle counts (95% CI 190, 480) on Diderot, 1585 cycle counts (95% CI 934, 2236) on Rivoli, and 920 cycle counts (95% CI 395, 1444) on Voltaire (Fig. 2 and Appendix Table 4). Three streets in Lyon experienced an increase in daily cycle counts, including 118 counts (95% CI 36, 201) on Jayr, 96 counts (95% CI 39, 153) on Viabert, and 499 counts (95% CI 313, 686) on Victor Lagrange.

Following the virtual street audit on the 15 streets, street-level characteristics such as length and changes to cycling infrastructure features and function are summarised in Table 3. The mean length was 1.0 km (SD 1.1). The changes that were most commonly performed were changes in width (73%), adding bi-directionality (53%), improving pavement condition (73%), constructing cycling facilities (73%), and converting to a physically separated lane (33%). Most streets had no change in cycling signage (80%), amount of car parking (73%), number of traffic lanes (73%), or presence of traffic calming (93%). There was also little change made to access to public transport or the amount of disorder (73%) and greenery (87%).

Our analysis of the functions served by the interventions reported identified the greatest increase in the functions of aesthetics (mean 1.1; SD 1.0), access (mean 1.6, SD 1.0), convenience (mean 1.9; SD 1.4), and space (mean 1.0, SD 1.9). There were only small increases in awareness (mean 0.1, SD 0.5) and safety (mean 0.4, SD 1.1) for cyclists.

### Table 2

<table>
<thead>
<tr>
<th>City</th>
<th>Period</th>
<th>Intervention streets</th>
<th>Control Streets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Paris</td>
<td>Before</td>
<td>2009</td>
<td>1507</td>
</tr>
<tr>
<td></td>
<td>After</td>
<td>2703</td>
<td>2351</td>
</tr>
<tr>
<td>Lyon</td>
<td>Before</td>
<td>1336</td>
<td>1120</td>
</tr>
<tr>
<td></td>
<td>After</td>
<td>1663</td>
<td>1223</td>
</tr>
</tbody>
</table>

Fig. 2. Forest plot of difference-in-differences estimates for intervention streets in Paris and Lyon.
Several of the features and functions were moderately to highly correlated with each other (Appendix Figs. 3 and 4). For instance, reducing the amount of car parking and increasing greenery was found to correlate with improvements to environmental disorder (0.72 and 0.65, respectively). The most highly correlated function variables were safety and space (0.86).

Of the cycling lane features, only length was significantly associated with an increase in cycling count (Fig. 3 and Appendix Table 5) for every 1 SD increase in length, cycling count increased by 83 (95% CI 32, 134). For features related to motorised vehicles, removing car parking was associated with an increase of 197 cycling counts (95% CI 108, 285), while removing traffic lanes was associated with an increase of 154 cycling counts (95% CI 58, 249). Only one feature was associated with a decrease in cycling counts. For features related to public transport, adding a public transport stop was associated with a decrease of 83 counts (95% CI 8, 158).

Functions which were positively associated with a change in cycling counts were safety (75, 95% CI 8, 141) and space (72, 95% CI 10–135) (Fig. 4 and Appendix Table 6). The evidence of an association of any of the other functions with change in cycling counts was inconclusive.

**Discussion**

**Summary of findings**

This is the first controlled natural experimental study to assess the impact of changes to micro-environmental street-level forms and functions on cycling levels. There were variations in the changes to cycling levels after the introduction of new cycling infrastructure in Paris and Lyon. This may be due to differences in design between interventions, as we found that certain intervention forms may be more influential than others. These included those which remove space for traffic, either by reducing the number of traffic lanes or parking space when installing new cycling lanes. Furthermore, longer cycling lanes were positively associated with increased cycling levels. Adding a public transport stop, however, was negatively associated with cycling levels. We also found that changes to specific functions derived from the features, or safety and space, had positive associations with cycling levels.

**Interpretation of findings**

Although the methods used to identify the most influential cycling lane characteristics differ from those used in previous studies, which mainly used stated preference surveys, the findings from this study are generally consistent with those found in the literature. For instance, our results showing that stick-type strategies (e.g., with functions involving taking away space from traffic) had significant positive associations with cycling levels align with previous studies’ findings. Other studies found that cyclists prefer routes with lower motor traffic densities and no parking along cycle routes (Ghekiere et al., 2018; Mertens et al., 2016; Sener et al., 2009). We also found a positive association between the length of cycling lane infrastructure and cycling counts, which is consistent with cross-sectional findings from another study comparing
cycling infrastructure across more than 50 European cities (Bruhova Foltynova and Bruha, 2013). A greater length in cycling infrastructure may be potentially indicative of a more well-connected cycle network, as longer cycle paths would be more likely to link with other paths.

In addition, we found a negative association between new public transport stops and cycling levels, consistent with a study using a stated preference survey that reported respondents prefer cycling infrastructure not built next to bus routes (Rossetti et al., 2017). Another explanation may be that public transport use and some forms of cycling (e.g., electric bikes) can substitute each other (Bieliński et al., 2021; Bigazzi and Wong, 2020). There may also be potential conflict between cyclists and buses, particularly on shared bus lanes, as buses may interrupt the flow of cyclists when they stop for passengers to board. Another reason could be that there may not be sufficient integration between the two transport modes. Indeed, multi-modal transport with cycling and public transport (i.e., bus or metro) may not be well-integrated in these cities for a few reasons. Bicycles are generally not permitted on-board due to space constraints, save for on a few regional trains outside of rush hours. Moreover, other facilities to better integrate the two modes, such as bike parking or bike-share stations near public transport stations, may not be widely available.

Other important characteristics as reported in the manipulated photograph or stated preference literature were not found to be significantly associated with cycling levels in our study. Studies reporting on the type of separation from traffic used for cycling infrastructure have found that physically separated cycling paths were preferable compared to painted cycle lanes or shared cycle and bus lanes (Mertens et al., 2015; Mertens et al., 2016; Rossetti et al., 2018; Winters et al., 2011; Caulfield et al., 2012; Verhoeven et al., 2017; Ghekiere et al., 2015a; Ghekiere et al., 2015b). Although we found physically separated cycling lanes to have the largest positive association among the types of cycling infrastructure investigated (compared to painted cycle lanes, sharrows, and shared cycle and bus lanes), the confidence intervals were wide and inconclusive. Moreover, people generally prefer wider lanes (Rossetti et al., 2017; Rossetti et al., 2018), which we found also to have a potentially positive, but inconclusive, association with cycling levels. One study also reported the evenness of cycle path and a well-maintained environment (i.e., less disorder) to be among the most desirable of perceived environmental factors for invitingness to cycle for transport (Mertens et al., 2014), which we did not find in this study.

The functions we identified as being relatively important include safety and space, while other functions, such as aesthetics and comfort,
Continuous variables were centred and scaled to a mean of 0 and standard deviation of 1. Our use of LASSO regression allowed us to study combinations of forms and functions and select the most important features. This way, we could attempt to extrapolate the relative importance of specific forms and functions. We also included control streets with similar pre-intervention trends and baseline street environment characteristics, which allowed us to account for possible confounding from secular trends and other co-interventions and events that may have impacted cycling levels during the study period.

One benefit of identifying specific forms and functions of cycling infrastructure interventions is that it can help create a more unified terminology when describing the design of complex interventions, which can then be generalized and adapted to other local contexts (Hawe et al., 2004). Some issues of previous attempts of standardising cycle infrastructure, for instance by classifying them as a cycle track, path, boulevard, or lane, can represent various interventions in different contexts. Reporting on the effects of specific pieces of infrastructure (e.g., “bicycle boulevards”) without describing what it entails cannot help answer whether specific characteristics of the intervention contributed to its success (or lack thereof), or whether similar effects would be observed if the same infrastructure was constructed in other contexts (Aldred, 2019). To address this issue, this study identified and evaluated specific cycling infrastructure features as well as their associated functions, which can promote greater consistency when comparing intervention effectiveness.

Another key strength of this study is the development and use of a novel virtual street audit, which improves on previous virtual street audit tools by being able to measure longitudinal infrastructural changes across the whole length of the intervention. We were also able to examine more system-level changes to the street and how changes aimed at influencing one transport behaviour may influence others. In fact, it is these changes to other transport modes (e.g., reducing parking spaces, adding a public transport stops) which had some of the largest and most significant impacts on cycling level changes.

Strengths

By using a natural-experimental study design, we were able to assess how real-life changes to the built environment impacted actual cycling behaviour. We were able to examine street-level changes by comparing the form of the built environment before and after street improvements were made. Other studies evaluating differences within micro-environments did so using cross-sectional data and photo manipulation or survey questions (Ghekiere et al., 2018; Mertens et al., 2016; Rossetti et al., 2017; Winters et al., 2011; Caulfield et al., 2012; Mertens et al., 2014). However, these do not measure the impact of how individual street features influence cycling behaviour change in real-world settings.

Overall, our research findings align with the recommendations outlined in cycling infrastructure design guidelines developed by transportation authorities. For example, the Department for Transport in the United Kingdom recommends establishing safe and connected cycle routes by reducing motor traffic volumes and speeds, as well as reallocating street space (Department for Transport, 2020). European and North American guidelines, such as those developed by the National Association of City Transportation Officials, emphasise the importance of providing sufficient space for cyclists by introducing buffer zones or widening cycle lanes (e.g., 1.5–4.0 m widths for one-way cycle tracks) (National Association of City Transportation Officials, 2023; Gerike et al., 2019). Furthermore, guidelines discourage the sharing of bus lanes with cyclists due to safety concerns associated with mixing vehicles of varying sizes on the roadways (Woolsgrove and Armstrong, 2020).

Limitations

One limitation of this study is that it is exploratory rather than confirmatory, as we were only able to include a sample of 15 cycle lanes. Additional research using larger sample sizes and greater variety of cycling infrastructure features is needed to support or validate these findings. There are also several limitations regarding which street features were assessed and how they were measured using GSV. We could only examine changes to the street environment which occurred in Paris and Lyon, meaning we could not fully assess certain types of street features (e.g., changes to the colour of cycling surfaces, street lighting conditions). The conclusions we were able to make about cycling infrastructure features related to safety (e.g., physically separated paths, speed limits) were more important than those related to aesthetics (e.g., street trees, vegetation, disorder) and comfort (e.g., evenness of the cycle lane surface) (Wang et al., 2016; Mertens et al., 2016). Thus, our findings are consistent with the hypothesis that there may be a hierarchy of important characteristics which must first be addressed before others (e.g., safety and space before comfort). This is not to say that the other functions are not important, but they may not be the ones to prioritise given the financial or physical space constraints experienced in the majority of urban settings.

Overall, our research findings align with the recommendations outlined in cycling infrastructure design guidelines developed by transportation authorities. For example, the Department for Transport in the United Kingdom recommends establishing safe and connected cycle routes by reducing motor traffic volumes and speeds, as well as reallocating street space (Department for Transport, 2020). European and North American guidelines, such as those developed by the National Association of City Transportation Officials, emphasise the importance of providing sufficient space for cyclists by introducing buffer zones or widening cycle lanes (e.g., 1.5–4.0 m widths for one-way cycle tracks) (National Association of City Transportation Officials, 2023; Gerike et al., 2019). Furthermore, guidelines discourage the sharing of bus lanes with cyclists due to safety concerns associated with mixing vehicles of varying sizes on the roadways (Woolsgrove and Armstrong, 2020).
ascertained from the GSV audit. There may have been an element of subjectivity in the author’s method of performing the virtual street audit and calculating the subsequent function scores. Function categories were based upon the authors’ assessment of the potential benefits or alterations the infrastructure could feasibly offer. However, in future studies, additional metrics such as absolute traffic safety could be complemented by incorporating data on traffic-related injuries.

As we used routinely collected count data, we could not differentiate between the effects of individual street features on different groups of users (e.g., women, children, inexperienced cyclists, e-cyclists, recreational cyclists). However, studies have shown that women prefer cycling infrastructure that is separated from traffic to on-road cycling infrastructure that is integrated with traffic (Garrard et al., 2008; Aldred et al., 2017). Furthermore, a previous study using manipulated photographs found that the most important street features for parents to let their children cycle were traffic speed and degree of separation (Ghekiere et al., 2016; Verhoeven et al., 2017; Ghekiere et al., 2015a). These features are related to the function of safety, which we found was one of the functions that was positively associated with cycling levels in this study. Similar barriers have been reported for other types of cyclists, such as e-cyclists. These barriers include the quality and availability of cycle infrastructure, as well as the difficulty of integrating with public transport (Bourne et al., 2020). Recreational cyclists may have route preferences beyond safety and convenience, such as scenic views, interesting attractions, and access to facilities like restrooms and repair stations (Chen and Chen, 2013).

Paris is notable for the number and types of urban transport policies it has introduced over the past decade, which could have influenced cycling behaviour by reducing the volumes and speeds of motor vehicle traffic. Some noteworthy examples include 30 km/hour zones and city-wide speed restrictions that have been implemented in Paris. However, the 30 km/hour city-wide speed limit was introduced in August 2021 (Mairie de Paris, 2021), after the study period, and the 30 km/hour zones mostly did not cover the cycling lanes studied or were implemented outside the study period (Paris Data, 2019). Another concurrent policy that warrants consideration is the Paris Low Emission Zone, which was initiated in 2015, reinforced in 2017 and extended in July 2019 (Mairie de Paris, 2023). However, this policy, limited to the city centre within the ring road, would have had similar effects on both the intervention and control streets, since they are also situated within this zone. Nevertheless, we recognise that there may be other actions beyond these policy examples that this study may not be able to account for, as city transport systems are constantly evolving.

Suggestions for future research and policy implications

These findings can help support future studies by generating hypotheses about the impact of individual street forms and functions. Even when not comparing multiple intervention forms and functions within the same study, studies should provide a comprehensive description about what exactly the intervention changed (e.g., by using virtual or in-person street audits, official documentation about the interventions), as well as theoretical considerations as to how these changes in intervention form relate to how the interventions might work. Together with intervention forms, identifying changes to intervention functions can help illuminate what exposure to the intervention entails. This can influence how one conceptualises the theory of change and action (Humphreys et al., 2016), such as whether the intervention is meant to have a large impact or not and which groups are likely to benefit from such interventions.

To further develop measures for cycle infrastructure form and function, we recommend continual discussion with transport, health, and urban policymakers in defining, identifying, and using form and function in their design and evaluation of policies. Policymakers should also engage with cyclists, particularly under-represented cyclist groups, to consider their voices in designing cycling infrastructure. Additional suggestions include conducting qualitative studies to relate objective changes in the environment to perceived changes. Further insights into the relationship between different forms and functions. Having greater links between the two concepts can help strengthen our understanding of which elements of intervention design are integral for its effectiveness.

Future studies should also examine these concepts in relation to interventions in other contexts, as well as the interaction between micro- and macro-level route environments, such as by measuring changes to residential density (Mertens et al., 2015), cycling network connectivity, and access to places of interest (e.g., work, services, shops). Moreover, further work is needed to be able to assess how different forms and functions may benefit different population groups with low levels of cycling. We also recommend collecting more evidence about features that were not evaluated in this study, such as coloured lanes, other forms of traffic calming (e.g., speed humps, sidewalk widening), and speed limits.

The policy implications of this study include the notion that there may be specific cycle lane forms and functions that are more likely than others to increase cycling levels. This study also provides insights into how the quality of cycling lane infrastructure can affect intervention effectiveness rather than simply whether a cycle lane was built or not. Potential core functions can include safety and space, which may be adapted to other contexts by taking different forms (e.g., reallocating traffic lanes to create physically separated cycling lanes, traffic-free streets, streets with traffic calming). These intervention functions are being further explored in Paris, as interventions with the functions of safety (introduction of a city-wide 30 km/hour speed limit in 2021) and space (conversion of half of parking spaces into cycle paths and widening of sidewalks) are being implemented (Mairie de Paris, 2021; Mairie de Paris, 2021).

Conclusion

Using a novel application of both a virtual street audit of changes to the built environment attributes of cycle lanes and LASSO regression, we found that certain micro-environmental forms and functions were more relatively important than others. Cycling infrastructure forms which led to significant increases in cycling included those which were longer and those which removed space from traffic (i.e., traffic lanes and parking space). We also identified the intervention functions of safety and space to be positively associated with increases in cycling. Findings from this study could provide evidence as to which intervention forms and functions to prioritise when designing high-quality, cycling-friendly infrastructure.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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analysis, Investigation, Methodology, Writing – original draft. Richard Patterson: Investigation, Validation, Writing – review & editing. David Ogilvie: Conceptualization, Writing – review & editing. Esther M.F. van Suijs: Conceptualization, Supervision. Stephen J. Sharp: Methodology, Writing – review & editing. Jenna Pantzer: Conceptualization, Investigation, Validation, Supervision, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trip.2023.100949.

References


