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Impacts of active travel interventions on travel behaviour and health: Results from a five-year longitudinal travel survey in Outer London

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ABSTRACT

Introduction: This paper analyses six years' data from the People and Places longitudinal study. The study examines travel behaviour impacts of major investments in active travel infrastructure in three Outer London boroughs (the 'mini-Hollands programme').

Methods: A controlled longitudinal analysis was used to compare changes in active travel in intervention and control groups, with three levels of intervention group (mini-Holland borough but no local intervention; active travel infrastructure but no low traffic neighbourhood; low traffic neighbourhood, usually also with proximity to active travel infrastructure). Finally, the article estimates the 20-year health economic benefit from uptake of active travel, using the average point estimates across all waves for both the mini-Holland programme as a whole and in the most intensively treated areas.

Results: At all waves, living in an area with mini-Holland interventions was consistently associated with increased duration of past-week active travel, compared with the control group. Changes in active travel behaviour were largest and had the strongest evidence for those living in low traffic neighbourhoods. Most of the increase was in time spent walking, although the strongest evidence of increased participation was for cycling. There was also evidence of decline in car ownership and/or use, although this was weaker and seen convincingly only in the low traffic neighbourhood areas. The 20-year health economic benefit from the mini-Holland areas was calculated at £1,056 m, from a programme cost of around £100 m. The most effective interventions (low traffic neighbourhoods) provide a twenty-year per-person physical-activity related benefit of £4800 compared to a per-person cost of £28–35 (LTNs implemented during 2020 as Covid-19 emergency interventions) or £112 (higher-cost LTNs with more features like greening and crossing improvements).

Conclusions: Active travel interventions provided high value for money when comparing health economic benefits from physical activity to costs of scheme implementation, particularly low traffic neighbourhoods.

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1. Introduction

1.1. Active travel interventions and uptake

Active travel interventions typically seek to increase the amount of people using active modes (e.g. walking and/or cycling). However, limitations in commonly used methods mean that identifying such changes and attributing them to a scheme is frequently problematic, both within routine local monitoring and academic research. For example, UK transport authorities often use cycle counters as a low-cost method of measuring changes in cycling following scheme introduction; with walking usually not measured. Without additional data collection (control counters and/or intercept surveys – see Sloman et al., 2019 for a programme-level study incorporating both) this cannot distinguish between additional users and existing users who change route, nor identify mode shift from the car. Similarly, Mölenberg et al.'s (2019) international review found greater evidence that cycling schemes led to an increase in cyclists using those schemes than of evidence that they led to a wider increase in cycling. Many of the studies Mölenberg et al. reviewed were uncontrolled, often involving only one before-and-after data point.

Academic evidence is growing but remains incomplete. A physical-activity focused review by Kärmeniemi et al. (2018) found that in nine of sixteen natural experiment studies, new infrastructure for walking, cycling and public transportation were associated with increased overall and transportation-related physical activity.[1] However, while a review by Winters et al. (2017) agreed that active travel can result in substantial health benefits, it highlighted uncertainty about the effects of specific policies on walking or cycling rates. Javaid et al.'s review of reviews (Javaid et al., 2020) identified 'a consensus in the literature that separated bicycle infrastructure, especially bike lanes and bike paths, increase bicycle usage'. Aldred's (2019) review concurred and commented that evidence remained limited for walking and some literature was methodologically weak.

The academic evidence that active travel infrastructure leads to reduced car use also remains relatively weak. Brand et al. (2014) found that even well-used new active travel infrastructure was not associated with reduced transport CO_2 emissions. This is perhaps not surprising. Firstly, Brand et al. were studying schemes that increased space for walking and cycling without taking this from cars, i.e. a 'carrot' without an accompanying 'stick' (c.f. Xiao et al., 2022; Piatkowski et al., 2017).[2] Secondly, any increased active travel would come from a mix of re-routed trips, new trips, and mode shift. Studies sufficiently powered to detect increased walking and cycling may not be large enough to detect any one element, particularly if change is modest.

Additionally, reductions in car use may take longer to manifest than active travel uptake (Goodman et al., 2020), and longitudinal studies typically only run for two years or even less. By contrast, the People and Places study reported here had five years of follow-up. Specifically, between 2016 and 2021, it asked the same group of Outer Londoners about travel behaviour and attitudes to transport and the local environment. Between 1354 and 1712 people participated in each follow-up wave. The end of the study provides the opportunity to analyse six survey waves to draw conclusions about the more medium-term impacts of schemes over time.

1.2. Pandemic-era active travel interventions in London

With the Covid-19 pandemic, active travel took on renewed importance. Initially, this related to direct pandemic response – such as providing safe outdoor recreational space, or key worker commuting alternatives to public transport and the car. Cities from Paris to Bogotá created temporary cycle tracks along main arteries, while 'Open Streets', 'Slow Streets', and 'Streateries' appeared in North America.

As pandemic restrictions loosened, continued reluctance to use public transport alongside some evidence of the impact of these measures (e.g. Kraus and Koch 2021) gave them renewed significance. In London, 'low traffic neighbourhoods' (LTNs) played an important role in early and later pandemic response. LTNs use physical and/or virtual barriers to restrict through motor traffic in a contiguous set of local streets, similar to Superblocks/Superillas in Spain and Kiezblocks in Germany.[3]

LTNs have been particularly contentious, partly because they are perceived as containing large amounts of 'stick' in making driving more difficult (Transport for All, 2021). Their retrofit introduction during 2020 in London was unprecedented, covering 4% of the population within six months, around 300,000 people (Aldred et al., 2021). Transport for London estimated that the capital still has around a hundred LTNs introduced since March 2020, although around a further thirty had been removed.[4]

As the pandemic continued, London's Covid-era LTNs were increasingly framed within a wider shift in sustainable transport policy from foregrounding routes (e.g. Cycle Superhighways) to more local schemes (known as Healthy Streets).[5] While attractive in the pandemic context (as measures that could be low-cost and/or temporary), LTNs had been gaining ground before then, particularly in North and North-East London. Some existing active travel programmes already included LTN-type schemes, although not originally under that name.

[1] One study found a decrease, and six found no statistically significant impacts.

[2] More frequently, schemes in urban areas to improve sustainable travel conditions necessarily make driving somewhat harder; for instance, bus priority or cycle tracks reducing space allocated to general motor traffic.

[3] See 'Kiezblocks für Berlin: Mehr als nur Poller!' [Kiezblocks in Berlin: more than just bollards!] which draws heavily on the Barcelona example: https://difu.de/nachrichten/kiezblocks-fuer-berlin-mehr-als-nur-poller.

[4] Personal communication.

[5] https://tfl.gov.uk/corporate/about-tfl/how-we-work/planning-for-the-future/healthy-streets.

1.3. The mini-Holland programme

The People and Places survey began with the aim of studying the impacts of 'mini-Holland' interventions in three Outer London boroughs (Enfield, Kingston, and Waltham Forest: see Fig. 1). These interventions comprised an ambitious package of measures, with a budget of around £100 m. The programme was announced in 2013 as part of then Mayor Boris Johnson's Vision for Cycling.[6] Outer London boroughs were invited to bid, with winners announced in 2014. Many individual schemes then had extensive consultation. Waltham Forest implemented a trial LTN-type scheme in 2015 made permanent in 2016, but construction only started in earnest in all three boroughs from 2016/7. By June 2019, 46 of 59 proposed infrastructure schemes were complete or under construction,[7] with the programme formally ending in March 2021.

Enfield concentrated on building new cycle routes, often taking some years to complete and being finished in the final half of the five-year programme. Kingston similarly focused on routes, including cycle schemes and a new waterside pedestrian route, plus one pedestrian-focused town centre scheme. Waltham Forest, by contrast, planned from the start route- and area-level schemes; rebranding its programme as wider than cycling ('Enjoy Waltham Forest', compared to 'Cycle Enfield' or 'GoCycle' in Kingston). Much of the South of the borough saw LTN-type schemes aiming to reduce motor traffic in local neighbourhoods.[8] This went alongside slower to implement cycle routes on main roads.

Towards the end of the mini-Holland programme, Enfield and Kingston began to implement some low traffic neighbourhood type measures. During 2020 and 2021, other Outer London boroughs implemented similar schemes, and are included in the analysis for those years (see below). With the benefit of multi-year follow-up, this analysis can both evaluate the overall achievements of the mini-Holland programme, and explore the impact specifically of LTNs, in most cases introduced alongside other active travel interventions. This builds on earlier research (Rachel Aldred et al., 2021) which only included the former type of analysis.

2. Methods

Funded by Transport for London (for five of six waves[9]), Westminster University ran the longitudinal People and Places survey, following a cohort of Outer Londoners over time as interventions were introduced. The study was designed as a natural experiment evaluation, with interventions implemented under the mini-Holland programme as our 'natural experiment'. The general sample population was defined as adults aged 16+ living in Outer London[10], due to substantial differences between Inner and Outer London in demographics, density, and other indicators.

The control group was defined as Outer Londoners living in boroughs other than Enfield, Kingston, and Waltham Forest. Intervention groups were initially defined in the following ways:

- A 'low-dose' group of residents who lived in a mini-Holland borough but not within an area directly affected by mini-Holland schemes.
- A 'high-dose' group of residents who lived within a mini-Holland borough **and** in an area of the borough where one might expect residents' travel behaviour to be affected by mini-Holland schemes, if these were successful. This was measured prospectively each year, usually in October, when officers from each borough were asked to mark on a map the areas that based on their knowledge, would, by the following survey wave, be covered by interventions likely to affect travel behaviour.[11]

Fig. 1 shows high- and low-dose areas at Wave 1: with the larger high-dose area in Waltham Forest due to early implementation of area-based schemes, compared to the other two boroughs (Enfield, adjoining Waltham Forest, and Kingston).

At Wave 2, there was growing interest in low traffic neighbourhoods (LTNs), which constituted much of the Waltham Forest 'high-dose' area. People living in these LTN areas generally had access to mini-Holland cycle routes but additionally lived within an area from which most or all through motor traffic had been removed; hence forming a sub-group of the high-dose area with particularly intensive interventions. Other high-dose area residents lived in proximity to other interventions that local authority officers thought likely to influence travel behaviour – for instance, close to a new cycle route – but not also within an LTN.

From Wave 2 onwards, additional analysis was conducted looking at route-based distance from new cycle routes, as an alternative measure of proximity to interventions. This generally found similar trends which were less likely to be statistically significant than

[6] https://www.london.gov.uk/sites/default/files/cycling_vision_gla_template_final.pdf.

[7] https://www.gov.uk/government/case-studies/london-mini-hollands.

[8] We use the term 'LTN' to refer to removal or substantial reduction (e.g. exemptions for buses or disabled car users) of through motor traffic from a contiguous set of residential streets. Some schemes/authorities do not use the term as it is perceived to be controversial; however, for our purposes it has the advantage of specifically referring to removal of traffic, compared to 'brand' names like Active Neighbourhoods.

[9] At Wave 4 (2020) funding was not available due to TfL's financial crisis. The team decided to run the study anyway to avoid data loss/attrition in a future possible year; however, this meant the timing was later than usual, September–October rather than May–June.

[10] This used the Office of National Statistics (ONS) classification of Outer London as comprising the following boroughs: Barking and Dagenham, Barnet, Bexley, Brent, Bromley, Croydon, Ealing, Enfield, Greenwich, Harrow, Havering, Hillingdon, Hounslow, Kingston, Merton, Redbridge, Richmond, Sutton, Waltham Forest.

[11] This allowed the team to benefit from expert knowledge of where more substantial schemes were being introduced. For instance, officers would include in their 'high-dose' area a planned 'town centre' scheme that they knew would involve substantial motor traffic restriction, but not one that entailed small cosmetic changes that they judged unlikely to increase active travel (even if these changes might be desirable for other reasons).

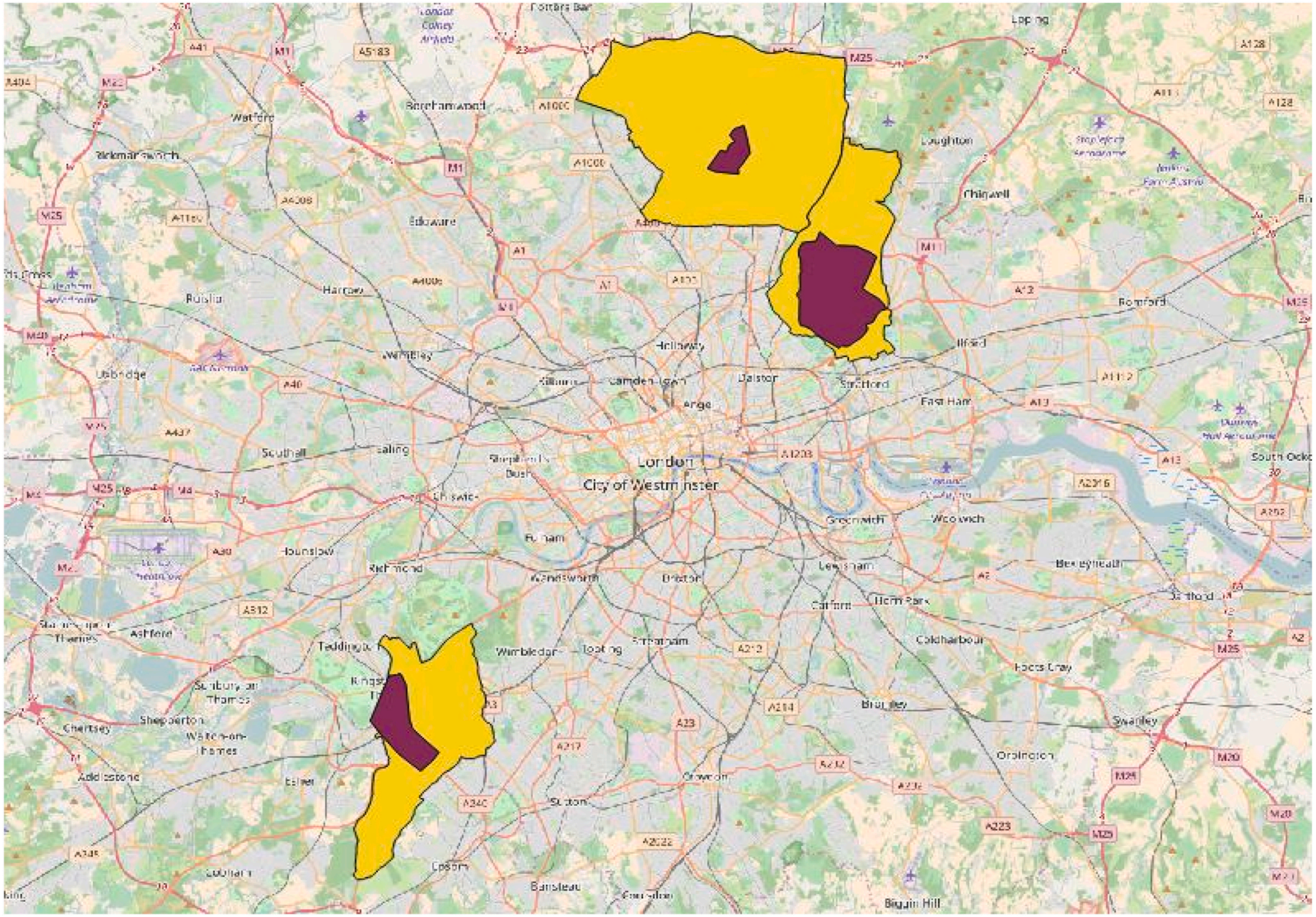

Fig. 1. Low (yellow) and high (purple) dose areas at Wave 1, as defined by stakeholders in advance of that year's survey wave.

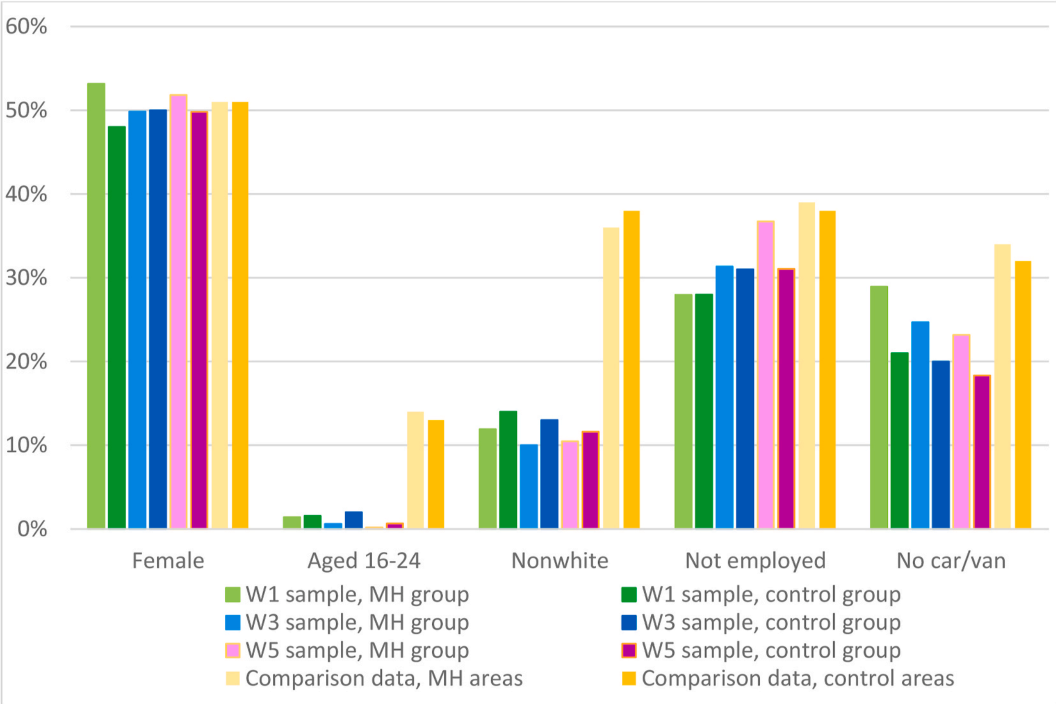

Fig. 2. Comparing the Wave 1 (N = 1712), Wave 3 (N = 1498) and Wave 5 (N = 1354) samples with other data.
Sources for comparison data: ONS midyear population data mid-2015, for age and gender. Census 2011 for ethnicity, employment status and car ownership. The pattern for Waves 2 and 4 was very similar to the three Waves presented.

area-based measures (see Table 10, Appendix, presenting active travel outcomes; car-based outcomes were generally not statistically significant).

As context, the primary area-based measure was associated with distance to new mini-Holland cycle routes as follows:

- Control group: Residents lived a median of 13.5 km from a new mini-Holland cycle route in Wave 2; 11.6 km in Wave 3; 12.6 km in Wave 4; and 11.9 km in Wave 5.
- Low-dose group: Residents lived a median of 3.1 km from a new mini-Holland cycle route in Wave 2; 2.0 km in Wave 3; 1.7 km in Wave 4; and 1.7 km in Wave 5.
- High-dose, non-LTN: Residents lived a median of 1.0 km from a new mini-Holland cycle route in Wave 2; 0.5 km in Wave 3; 0.5 km in Wave 4; and 0.5 km in Wave 5.
- High-dose, LTN: Residents lived a median of 0.7 km from a new mini-Holland cycle route in Wave 2; 0.5 km in Wave 3; 0.5 km in Wave 4; and 0.5 km in Wave 5.

Hence, the distance to new mini-Holland routes for the high-dose non-LTN and high-dose LTN groups were similar, with both groups generally having new routes relatively close by from Wave 3 (in Waves 3–5, both groups were a median route distance of 0.5 km from a new route).

This picture became more complicated with the pandemic and the growth of LTN schemes in other Outer London boroughs, during 2020–21.[12] As these covered a substantial proportion of the population (around 300,000 people lived in LTNs built in six months of 2020 alone) and mini-Holland LTNs had been found to have a particularly strong impact on travel behaviour, analysis was adapted to include these schemes. Accordingly, in the final two years of the survey (2020 and 2021), the high-dose LTN group included around 20–25 people who lived outside the mini-Holland boroughs, but in a new LTN.

2.1. The survey

The People and Places survey remained almost identical for six survey waves, such that results would be comparable year-on-year. It contained, in addition to standard demographic questions, travel behaviour questions, measured through a simplified past-week

[12] See https://www.sciencedirect.com/science/article/pii/S0966692321002477.

travel diary with additional questions about daily time spent using key modes of interest (car use, walking, cycling).[13]

Here, four primary hypotheses are discussed, these being:

H1a: Living in an intervention area is associated with an increased amount of walking and/or cycling.
H2a: Living in an intervention area is associated with decreased amount of time spent travelling by car or van.
H2b: Living in an intervention area is associated with a decreased likelihood of travelling by car or van.
H2c: Living in an intervention area is associated with a decreased likelihood of car or van ownership.

The baseline survey was open between May 6th and June 12th, 2016, for completion online, while the telephone option was available during the same dates. As only a small number (<50) chose the telephone option, and these agreed to complete online in future, the telephone option was discontinued. Subsequent online waves ran during similar dates, except for 2020, when following a Covid-related delay, it ran in September–October and in 2021, when it ran slightly later (June–July, before the school holidays). At each wave, participants were asked if they would be happy to be contacted about participating in the following year's wave.

The online survey was administered each year using Qualtrics survey software, with only the lead researcher having access to the data collected. This was separated into different files to ensure confidentiality and maintain secure storage of personal data, with a cut-down fully anonymised dataset created for longitudinal analysis. Ethical approval for the study was granted by Westminster University.

2.2. Recruitment approach

Recruitment took place prior to the baseline survey wave of May–June 2016. Initially random household sampling was used via leaflets ('household leaflet' sample), cluster sampling Lower-Level Super Output Areas in intervention and control boroughs, within a sampling frame including the same numbers of households in both groups. However, response rate was around 1%. Therefore, TfL customer databases (Oyster and Cyclist – i.e., people who had an Oyster public transport card, or had signed up to receive information about cycling) were used, where those people had agreed to be re-contacted.

The final baseline sample included 1519 participants in mini-Holland boroughs (615 in Waltham Forest, 490 in Kingston, 414 in Enfield) and 1916 in the rest of outer London. 38% came from the household leaflet sample, 32% from the Oyster database and 20% from the Cyclist database. The remaining 10% came from one of the two databases but it was not possible to identify which one.[14]

2.3. Statistical analysis

At baseline, a weight was constructed to adjust for the fact that the mini-Holland and non-mini-Holland groups differed somewhat in the profile of sources for their participants (e.g. a higher proportion of the mini-Holland group came from the household leaflet sample, and a lower proportion from the Cyclist database). This weight was updated for use in the Waves 1 to 5 analyses to take account of differences in follow-up rates across these different sources, as follows:

$$\text{Wave 1 weight} = \text{Baseline weight} * \frac{\text{Overall Wave 1 follow} - \text{up rate}}{\text{Wave 1 follow} - \text{up rate for source in question}}$$

Equivalent formulae were used for Waves 2 to 5. These formulae plus further details on the construction of weights can be found in the Appendix.

In analysing travel behaviour at each Wave, we used linear regression for continuous variables. We used Poisson regression with robust standard errors for binary outcomes because many of our binary outcomes are common (Zou, 2004).

In our main analyses, our primary exposure of interest in each model was 'intervention status', i.e. our area-based definition of exposure to MH infrastructure (i.e. Non-mini-Holland control/Low dose/High dose, non-LTN/High dose, LTN). All regression analyses adjust for the corresponding measure at baseline, e.g. when the outcome is whether the participant did any past-week cycling at Wave 3, the regression model is adjusted for whether that participant did any past-week cycling at baseline. We entered continuous baseline measures of past-week travel as linear terms, alongside quadratic terms if these were statistically significant. We included these quadratic terms to improve model fit, and therefore increase precision; our study findings are similar in analyses excluding these quadratic terms. This approach allowed us to look at the association between intervention status and follow-up behaviour adjusted for baseline behaviour.

After conducting minimally-adjusted analyses, we adjusted for the following demographic and socio-economic characteristics: gender, age, ethnicity, disability status, household type and employment status as measured during the Wave in question; and for the presence of household cars or vans at baseline. The response categories to these demographic and socio-economic characteristics are shown in Table 8 of Appendix 1.

Our main analyses used our area-based definition of exposure to MH infrastructure as the exposure. A further set of analyses sought

[13] A range of attitudinal questions are not discussed in this paper.

[14] The aim was to sample equal proportions of Oyster and Cyclist customers in the control and intervention area; however, as this was not possible, we needed to identify the databases from which customers came. In most but not all cases this was possible. A weighting strategy has been applied to redress this as described in the Appendix.

to investigate whether the impact of new infrastructure increased across time. To simplify interpretation of these effects over time, these analyses were restricted *a priori* to Waves 1 to 3, in order to predate the Covid-19 pandemic (a period when travel was substantially disrupted and also when many new LTNs were introduced). For these analyses, we subdivided the two high dose exposure categories according to the duration of time that the MH infrastructure had been in place (LTN, <1 year/LTN, 1 year/LTN, 2+ years/High dose non-LTN, <1 year/High dose non-LTN, 1 year/High dose non-LTN 2+ years[15]).

2.4. Estimating health economic benefits

The analysis of monetised benefits due to increased physical activity used the DfT's TAG Active Mode Appraisal spreadsheet, which was used to calculate the benefits from reduced premature mortality via the value of a statistical life year (VSLY) approach, and the benefits to employers from reduced sickness absence of employees. For more details see https://www.gov.uk/government/publications/tag-unit-a5-1-active-mode-appraisal. In part developed by JW the approach extends transport appraisal's traditional focus on car journey times and focuses on monetising benefits from impacts of increasing active travel. The approach uses dose response relationships between physical activity energy expenditure from walking or cycling (both were used here) and risk of premature death and numbers of days of sickness absence. Physical activity energy expenditure was calculated as MET (Metabolically Equivalent Task hours per week). Premature deaths averted are converted into years of life lost averted using Global Burden of Disease age and gender specific relationships.

In calculating the population affected by the interventions, data from the Office for National Statistics[16] was used to estimate the adult population aged 20–80 in mid-2020 (i) living in high-dose areas and (ii) living in low-traffic neighbourhoods, either in mini-Holland boroughs or in other Outer London Covid-era LTNs. The latter was done both to provide an estimate of benefit where it was likely to be most concentrated, and benefit for those living outside the mini-Holland areas where interventions remained (unlike in mini-Holland boroughs and Inner London, many Outer London Covid-era LTNs were later removed).

This provided estimates of adults exposed to the intervention at Wave 5 (272,104) and those exposed to the most effective 'dose' both in mini-Holland boroughs (71,533) and in the rest of Outer London (71,738). No benefit was assumed in the over 80s. In calculating sickness absence impacts were only included for the age group 20 to 64, using gender, age, and region-specific rates. Uptake was assumed to be immediate, given broadly similar higher rates of walking and cycling related physical activity across the waves (albeit with more variability in Waves 4 and 5, affected by Covid). The infrastructure was assumed to last for 20 years from 2021. We used a discount rate of 1.5%.

The calculation is available in a spreadsheet (Appendix 2) for download.

3. Results

3.1. About the sample

3.1.1. Follow-up rate

At baseline there were 3435 participants. In Waves 1 to 5, analysis was restricted to individuals who participated in the Wave in question and did not in the interim move into or out of one of the three mini-Holland boroughs. Participants were not excluded who had moved house but (a) remained in the same mini-Holland borough or (b) remained outside the mini-Holland boroughs. This gave a study population of 1712 participants at Wave 1 (follow-up rate 50%); 1610 participants at Wave 2 (follow-up rate 47%); 1498 participants at Wave 3 (follow-up rate 44%); 1496 participants at Wave 4 (follow-up rate 44%); and 1354 participants at Wave 5 (follow-up rate 39%). This follow-up rate was very similar across the three MH boroughs, and across the MH boroughs versus the control group. The result was that the composition of participants across boroughs was very similar in the five waves compared to baseline.

3.1.2. Proportion of sample living in intervention areas

Among those living in mini-Holland boroughs, the proportion of people living in a 'high dose, non-LTN area' increased across Waves 1 to 3, and the proportion living in a 'high dose, LTN' area increased across Waves 1 to 5 (see Table 1). For instance, the percentage of those in mini-Holland boroughs also living in a high-dose, non-LTN area grew from 32% at Wave 1, to 37% at Wave 3, falling back to 32% at Wave 5. By contrast, the percentage of those in mini-Holland boroughs also living in a high-dose, LTN area grew from 7% at Wave 1, to 11% at Wave 3, to 16% at Wave.

3.1.3. Sample characteristics and representativeness

Demographic characteristics of the mini-Holland and non-mini-Holland groups were very similar in all waves, with selected Wave 1 results presented in Fig. 2. There were more marked demographic and socio-economic differences comparing the stakeholder-identified 'high-dose' areas with 'low-dose' mini-Holland areas. People living in 'high-dose' areas were far more likely to be from

[15] A small number of people lived in areas that were classified as high dose non-LTN in Waves 1 or 2 and subsequently became LTNs. In these cases we assigned their status based on how long they had been in an LTN.

[16] https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/datasets/censusoutputareaestimatesinthelondonregionofengland.

Waltham Forest and far less likely to be from Enfield. In addition, they were more likely than those in the low-dose areas to be: female (e.g. 58% versus 49% in the low-dose areas in Wave 1); younger (42% aged under 45 versus 30% in Wave 1); single adults (44% versus 31% in Wave 1); in full-time employment (65% versus 53% in Wave 1); and without any household car or van (43% versus 20% in Wave 1). There were no differences by sampling source, ethnicity, or disability status. Similar trends were seen when restricting the analyses to Waltham Forest, suggesting that these differences did not reflect differences between the boroughs per se, but rather

Table 1
Sample sizes by intervention status in each wave.

	Sample size for analyses of % with a car and doing any past week travel of a given mode	Sample size for analyses of average minutes of past week travel	Comments
Wave 1 (June-July 2017)			
Non-mini-Holland	962 (56.2%)	914 (55.9%)	Most interventions are in Waltham Forest, including LTNs. Very little route-based infrastructure built.
Low dose	460 (26.9%)	440 (26.9%)	
High dose, non-LTN	241 (14.1%)	234 (14.3%)	
High dose, LTN	49 (2.9%)	46 (2.8%)	
Total	1712	1634	
Wave 2 (June-July 2018)			
Non-mini-Holland	902 (56.0%)	811 (56.2%)	Relatively slow progress this year in all boroughs.
Low dose	413 (25.7%)	366 (25.3%)	
High dose, non-LTN	232 (14.4%)	209 (14.5%)	
High dose, LTN	63 (3.9%)	58 (4.0%)	
Total	1610	1444	
Wave 3 (June-July 2019)			
Non-mini-Holland	830 (55.4%)	830 (55.4%)	Some additional interventions (including routes) introduced in all three boroughs.
Low dose	346 (23.1%)	346 (23.1%)	
High dose, non-LTN	248 (16.6%)	248 (16.6%)	
High dose, LTN	74 (4.9%)	74 (4.9%)	
Total	1498	1498	
Wave 4 (September-October 2020)			
Non-mini-Holland	806 (53.9%)	789 (53.7%)	LTNs begin to be introduced in more boroughs, and in Waltham Forest, but in some cases have only been in a few months.
Low dose	353 (23.6%)	347 (23.6%)	
High dose, non-LTN	203 (13.6%)	201 (13.7%)	
High dose, LTN	134 (9.0%)	133 (9.0%)	
Total	1496	1470	
Wave 5 (June-July 2021)			
Non-mini-Holland	715 (52.8%)	699 (52.7%)	Relatively little new infrastructure compared to Wave 4.
Low dose	319 (23.6%)	312 (23.5%)	
High dose, non-LTN	198 (14.6%)	194 (14.6%)	
High dose, LTN	122 (9.0%)	121 (9.1%)	
Total	1354	1326	

In Waves 4 and 5, the ‘LTN’ group included a small number of people from non-Mini-Holland boroughs who lived in LTNs introduced in 2020 under emergency legislation. Hence in those waves, ‘non-MH’ means non-MH as well as non-LTN, as some people who would otherwise have been in the control group are included within the main intervention group due to living in an LTN. This related to 26 individuals at wave 4 and 21 at wave 5. Findings were always similar after excluding these individuals. See the Appendix, Table 8, for the demographic and socio-economic characteristics of the Wave 5 sample.

Table 2
Past week travel behaviour: raw changes baseline to Waves 1-5.

	Base (1354)	% point change W1 (1712)	% point change W2 (1610)	% point change W3 (1498)	% point change W4 (1406)	% point change W5 (1354)
Past-week car travel						
% with any car travel in past week	76%	2%	−1%	−3%	−7%	−4%
Minutes of car travel in past week	157	−6	−4	−11	−20	−4
Past-week cycling						
% Doing any cycling in past week	19%	−2%	−1%	−3%	1%	−1%
Minutes of cycling in past week	38	−6	−6	−8	−4	−1
Past-week walking						
% Doing any walking in past week	87%	−2%	−0%	0%	−6%	−3%
Minutes of walking in past week	223	4	18	21	−11	24
Past-week active travel						
% Doing any active travel in past week	89%	−2%	0%	−1%	−7%	−4%
% Doing 140+ minutes active travel in past week	66%	−2%	1%	1%	−6%	−2%
Minutes of active travel in past week	261	−1	12	13	−18	20
Past-week public transport						
% with any public transport use in past week	89%	−5%	−3%	−5%	−46%	−40%

Base = baseline (using the W5 sample), Percentage point change W1–W5 are the differences Waves 1 to 5 (Wave in question minus baseline), using the available sample each time.

characteristics of the high-dose areas in each borough (e.g. housing type). These differences indicate the importance of adjusting for these participant demographic and socio-economic characteristics when seeking to make comparisons between the high-dose and low-dose mini-Holland areas.

Characteristics of participants were compared with those of the background population, where comparison data were available. This comparison is summarised below for Wave 1, 3 and 5. Within both mini-Holland and non-mini-Holland areas, the sample was fairly representative with respect to gender, but there was a marked underrepresentation of 16–24-year-olds and non-White individuals. In addition, there was some underrepresentation of individuals not in employment and households with no car or van.

The underrepresentation of individuals not in employment seems partly due to the Oyster and Cyclist databases: the underrepresentation of non-employed people was smaller in the household leaflet sample. Otherwise, these effects appeared to reflect differential response rates in the baseline survey compounded by lower follow-up rates among young adults and non-White individuals.

3.2. *Impacts of interventions on travel behaviour*

Before presenting impacts of interventions on travel behaviour, Table 2 provides raw figures at baseline and comparing the baseline to Waves 1–5. At baseline, around three-quarters of respondents had done any past-week car travel, nearly nine in ten had done any past-week walking and similar numbers reported and past-week public transport use, but (despite a minority of respondents coming from TfL's Cyclist database) only one in five had done any past-week cycling. The impacts of Covid-19 can be seen in Waves 4 and 5 in the substantial decline in public transport use, but not in the use of other modes.

3.2.1. *Impacts on cycling, walking and active travel*

Fig. 3 and Table 3 provide active travel outcomes by wave adjusted for demographic factors, comparing changes in all cases to changes in the non-mini-Holland control group. There was a consistent trend towards increased minutes of walking and cycling in the LTN areas, translating into increases in total minutes of active travel. These increases were substantial, with point estimates ranging from 65 to 114 min per week across the waves, albeit with wide confidence intervals.

In the high-dose non-LTN areas the trend was for some increase in past week minutes of active travel, but in most waves this increase was smaller than the increase within the LTN and not statistically significant, except in Wave 5 where the two groups are similar.

There was evidence of increased participation in 'any past week cycling' in the LTN areas (Waves 1 to 5), and to a lesser extent in the high-dose-non-LTN areas (Waves 3 to 5). There was little or no evidence of a change in participation in, or amount of, walking and cycling in the low-dose mini-Holland areas.

See Table 3 for a tabulation of the data presented in this graph.

3.2.2. *Impacts on car ownership and car use*

As shown in Table 4, there was some evidence of decreased car ownership in the LTN areas in Waves 2 to 4, although not in Wave 5. There was a statistically significant (or borderline significant) decrease in past week car use in the LTN areas in Waves 2 to 5. There

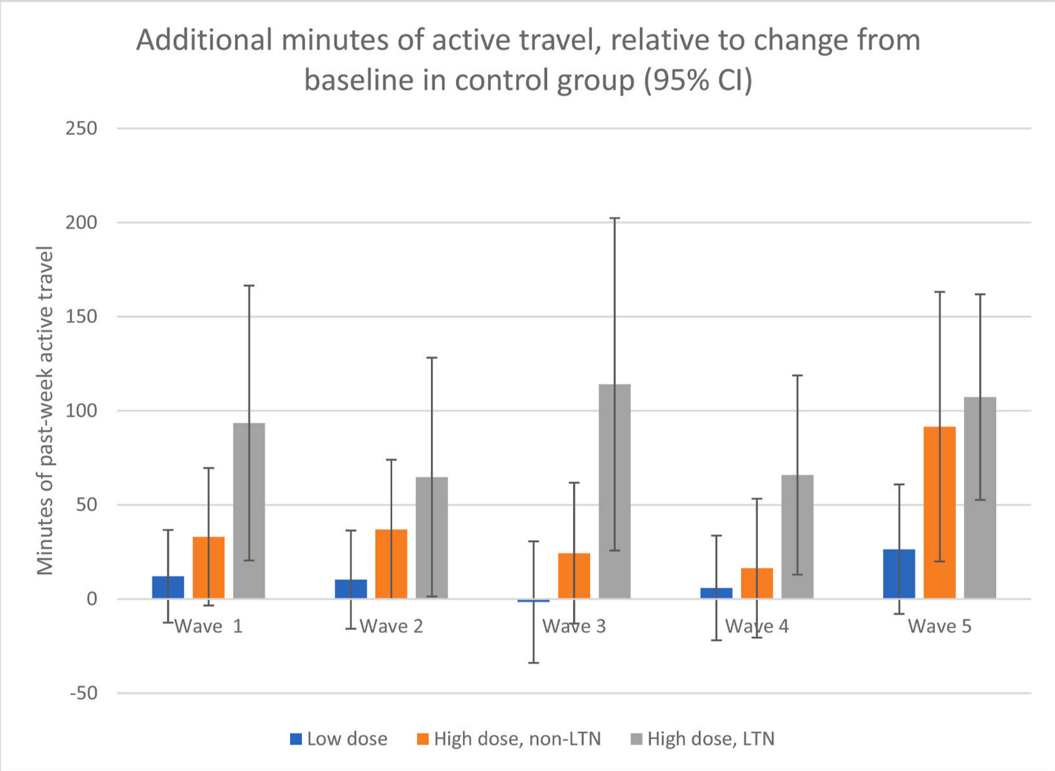

Fig. 3. Change in past-week active travel minutes, by wave, intervention groups.

were consistent corresponding trends towards decreased past-week minutes of car driving although this effect was only statistically significant in Wave 2. For the high-dose non-LTNs sample there was never statistically significant evidence of a change in car use, although the non-significant trends tended to be towards a reduction in use.

3.2.3. How impacts on travel behaviour change across time, as schemes become established

Table 9 presents analyses restricted to Waves 1–3, to examine the impact of the duration of LTN implementation on the magnitude of behaviour change. These results suggest that positive effects on walking and cycling tend to increase after 1 and 2 years compared to after less than 1 year. A similar trend appears for the car travel time point estimates, although this is never statistically significant. There was likewise a tendency for an increase across Waves in several other outcomes, including the proportion of people doing any past-week cycling, the proportion of people doing 140 min/week of active travel, and the proportion of households without a car.[17] Although the confidence intervals overlap, the trends shown in Fig. 4 suggest that active travel may increase, and traffic evaporation effects grow over time after an LTN has been implemented, as effects may somewhat lag intervention implementation. However, in calculating health economic benefits this has been assumed as stable, likely to be a conservative assumption.

See Appendix Table 9 for a tabulation of these results.

3.3. Health and health economic benefits

At Wave 5, a total of 272,104 adults aged 20–80 were living in a high-dose area in one of the three mini-Holland boroughs. Of these, 71,533 were living in an LTN. Health and health economic benefits for the programme as a whole and its LTNs were calculated separately using the mean average of point estimates for both. Additionally, at June 2021 (Wave 5) there were 71,738 people aged 20–80 living in Covid-era LTNs introduced in the rest of Outer London, in the boroughs of Brent, Croydon, Ealing, Greenwich, Harrow,

[17] With respect to car ownership, this corroborates findings we have published using Driver and Vehicle Licensing Agency data on car ownership at the small area level, up to end 2019. Specifically, we found that the total number of cars fell progressively with increasing duration since scheme implementation. This was true in both the high dose non-LTN areas (change −2% by 2 years post scheme implementation) and high dose LTN areas (change −6% by 2 years post scheme implementation). Published at https://findingspress.org/article/18200-the-impact-of-low-traffic-neighbourhoods-and-other-active-travel-interventions-on-vehicle-ownership-findings-from-the-outer-london-mini-holland-progr.

Table 3
Active travel outcomes: adjusted rate ratios/regression coefficients (95% confidence interval).

		% doing any walking in the past week (adjusted rate ratios)	Minutes of walking in the past week (adjusted regression coefficients)	% doing any cycling in the past week (adjusted rate ratios)	Minutes of cycling in the past week (adjusted regression coefficients)	% doing any active travel in the past week (adjusted rate ratios)	Minutes of active travel in the past week (adjusted regression coefficients)
Wave 1	Non-mini-Holland (control)	1	0	1	0	1	0
	Low dose	1.03 (0.98, 1.08)	10.8 (−12.1, 33.8)	1.11 (0.91, 1.35)	1.6 (−8.3, 11.4)	1.03 (0.98, 1.07)	12.1 (−12.5, 36.7)
	High dose, non-LTN	1.00 (0.94, 1.06)	26.4 (−8.0, 60.9)	1.20 (0.95, 1.51)	6.7 (−6.4, 19.8)	1.02 (0.97, 1.07)	33.1 (−3.5, 69.6)†
	High dose, LTN	1.14 (1.07, 1.21)***	76.4 (8.4, 144.4)*	1.46 (1.12, 1.91)**	14.5 (−6.2, 35.3)	1.11 (1.05, 1.18)***	93.5 (20.4, 166.5)*
Wave 2	Non-mini-Holland (control)	1	0	1	0	1	0
	Low dose	1.01 (0.96, 1.06)	12.8 (−12.4, 37.9)	0.99 (0.80, 1.23)	−1.5 (−10.9, 8.0)	1.00 (0.96, 1.05)	10.3 (−15.9, 36.4)
	High dose, non-LTN	1.03 (0.97, 1.09)	43.8 (8.6, 78.9)*	1.00 (0.76, 1.32)	−7.7 (−18.1, 2.8)	1.03 (0.99, 1.08)	37.0 (−0.1, 74.0)†
	High dose, LTN	1.02 (0.94, 1.11)	47.9 (−10.0, 105.8)	1.36 (1.00, 1.84)*	16.6 (−10.4, 43.5)	1.01 (0.94, 1.10)	64.8 (1.4, 128.2)*
Wave 3	Non-mini-Holland (control)	1	0	1	0	1	0
	Low dose	1.00 (0.95, 1.05)	−1.0 (−32.3, 30.2)	1.00 (0.78, 1.29)	−1.6 (−11.1, 8.0)	0.99 (0.94, 1.04)	−1.6 (−33.9, 30.7)
	High dose, non-LTN	1.02 (0.97, 1.08)	12.6 (−22.9, 48.1)	1.28 (1.01, 1.61)*	12.1 (−2.2, 26.4)†	1.03 (0.98, 1.08)	24.4 (−13.0, 61.8)
	High dose, LTN	1.11 (1.06, 1.17)***	95.7 (9.3, 182.0)*	1.64 (1.20, 2.23)**	19.6 (0.1, 39.1)*	1.10 (1.04, 1.15)**	114.1 (25.8, 202.4)*
Wave 4	Non-mini-Holland (control)	1	0	1	0	1	0
	Low dose	1.00 (0.94, 1.06)	7.6 (−18.6, 33.7)	1.23 (0.98, 1.55)†	−1.8 (−13.7, 10.1)	1.02 (0.96, 1.08)	5.9 (−22.0, 33.7)
	High dose, non-LTN	1.01 (0.94, 1.09)	10.0 (−24.4, 44.5)	1.28 (0.96, 1.69)†	7.4 (−7.9, 22.6)	1.07 (1.00, 1.14)*	16.4 (−20.5, 53.3)
	High dose, LTN	1.04 (0.96, 1.12)	51.1 (0.8, 101.3)*	1.58 (1.23, 2.03)***	13.6 (−8.7, 36.0)	1.06 (0.98, 1.15)	65.9 (13.0, 118.8)*
Wave 5	Non-mini-Holland (control)	1	0	1	0	1	0
	Low dose	1.00 (0.94, 1.06)	19.6 (−13.2, 52.4)	1.13 (0.86, 1.48)	6.4 (−6.5, 19.3)	1.01 (0.95, 1.07)	26.5 (−7.9, 60.9)
	High dose, non-LTN	1.05 (0.99, 1.12)	60.7 (19.7, 101.7)**	1.33 (1.00, 1.78)*	30.9 (−25.0, 86.8)	1.06 (1.00, 1.13)*	91.6 (20.0, 163.2)*
	High dose, LTN	1.07 (0.99, 1.15)†	61.7 (14.7, 108.7)*	1.38 (1.06, 1.79)*	43.1 (10.6, 75.7)**	1.09 (1.02, 1.16)*	107.3 (52.7, 161.9)***

†$p < 0.10$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, for difference from the non-mini-Holland group. Analyses adjust for the baseline measure of the outcome in question and the baseline number of cars in the household, plus gender, age, ethnicity, disability, household type and employment type at follow-up.

Hounslow, Merton, and Sutton. Some of those boroughs have since removed some or all of their Covid-era LTNs.[18] The calculation here therefore estimates the benefits that those LTNs would have generated, had they remained in place.

Using the mean average of the point estimates, the high-dose area as a whole (combining LTN and non-LTN areas within the mini-Holland boroughs) was assumed to generate an average increase of 13.0 min of cycling and 39.9 min of walking. Repeating the analysis with point estimates for the LTN areas (including in 2020 and 2021 Covid-era LTNs in Waves 4 and 5) led to using an average increase

[18] Specifically, Brent removed some, Croydon some, Ealing all but one, Greenwich one of its two, Harrow all, and Sutton all of its LTNs. Only Hounslow and Merton kept all of theirs.

Table 4
Car-related outcomes: Adjusted rate ratios/regression coefficients (95% confidence interval).

		% with a household car (adjusted rate ratios)	% with any car use in the past week (adjusted rate ratios)	Minutes of car use in the past week (adjusted regression coefficients)
Wave 1	Non-mini-Holland	1	1	0
	Low dose	1.01 (0.99, 1.03)	0.98 (0.93, 1.02)	4.6 (−14.5, 23.6)
	High dose, non-LTN	0.98 (0.93, 1.03)	0.93 (0.84, 1.02)	−2.7 (−25.8, 20.3)
	High dose, LTN	0.92 (0.82, 1.03)	0.91 (0.77, 1.09)	−9.9 (−51.2, 31.5)
Wave 2	Non-mini-Holland	1	1	0
	Low dose	1.02 (0.99, 1.06)	1.02 (0.97, 1.07)	−6.7 (−34.6, 21.3)
	High dose, non-LTN	0.98 (0.93, 1.03)	0.96 (0.88, 1.05)	−3.1 (−37.2, 30.9)
	High dose, LTN	0.89 (0.77, 1.02)†	0.78 (0.63, 0.96)*	−43.3 (−74.8, −11.9)**
Wave 3	Non-mini-Holland	1	1	0
	Low dose	1.02 (0.98, 1.05)	1.05 (0.99, 1.10)	15.3 (−12.5, 43.1)
	High dose, non-LTN	0.96 (0.91, 1.02)	0.94 (0.86, 1.02)	−2.4 (−33.0 28.1)
	High dose, LTN	0.80 (0.68, 0.94)*	0.82 (0.66, 1.02)†	−7.9 (−52.1, 36.4)
Wave 4	Non-mini-Holland	1	1	0
	Low dose	1.03 (0.99, 1.07)	1.04 (0.97, 1.10)	5.5 (−21.9, 32.9)
	High dose, non-LTN	0.99 (0.92, 1.06)	1.06 (0.97, 1.17)	−18.3 (−46.0, 9.4)
	High dose, LTN	0.91 (0.82, 1.01)†	0.86 (0.73, 1.00)*	−15.4 (−63.6, 32.9)
Wave 5	Non-mini-Holland	1	1	0
	Low dose	1.03 (0.98, 1.07)	1.01 (0.95, 1.08)	2.9 (−24.8, 30.6)
	High dose, non-LTN	0.98 (0.91, 1.05)	0.97 (0.88, 1.06)	−20.3 (−47.4, 6.9)
	High dose, LTN	0.97 (0.87, 1.10)	0.81 (0.68, 0.97)*	−17.6 (−50.9, 15.6)

†$p < 0.10$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, for difference from the non-mini-Holland group. Analyses adjust for the baseline measure of the outcome in question and the baseline number of cars in the household, plus gender, age, ethnicity, disability, household type and employment type at follow-up.

of 21.5 min of cycling and 66.6 min of walking in the LTN areas. Note that these averages in each Wave capture impacts of infrastructure that has been in place for between 1 and 5 years. Given evidence that the impacts of LTNs may rise over time (Fig. 4) this is likely a conservative estimate.

The high-dose area generated over 20 years a health economic benefit of £1,056 m, of which £821 m came from reduced mortality due to additional physical activity. The total health economic benefit is around ten times the programme cost. Each year, there are 37 deaths avoided and 753 years of life lost (YLL) avoided, with 535,421 sick days avoided. This benefit is likely to have been concentrated within the LTN areas that saw the greatest rise in walking and cycling. For the LTN areas within the mini-Holland boroughs, the health economic benefit is £443 m, around 40% of the whole programme benefit, of which £344 m comes from physical activity benefits.

The health economic benefits of the LTN areas outside the mini-Holland boroughs was also calculated. Uncertainty is greater here as the survey sample size was small and the interventions were only in place in Covid times; however, the results seemed similar to the main LTN group and the same point estimates have been used as providing a better likely estimate of longer-term effects for interventions left in beyond the immediate pandemic period. Making these assumptions, the benefits are very similar to the MH LTN benefits as the population sizes are very similar: an economic benefit of £406 m from physical activity which rises to £507 m when absence benefits are incorporated. As noted above, unlike in Inner London, many have been removed hence this represents the benefit that could have been gained from the programme.

LTNs alone have been estimated by one of the authors as costing around £20-£25 per resident where implemented as low-cost emergency schemes; and £80 per resident where implemented to a higher-quality threshold (see Appendix 1 for details). Converting this to benefit per adult aged 20–80 (as these are the residents for whom the health benefit can be calculated) this becomes £28–35 per person, per low-cost LTN and £112 per person, per higher-quality LTN. This can then be compared to the estimated average benefit

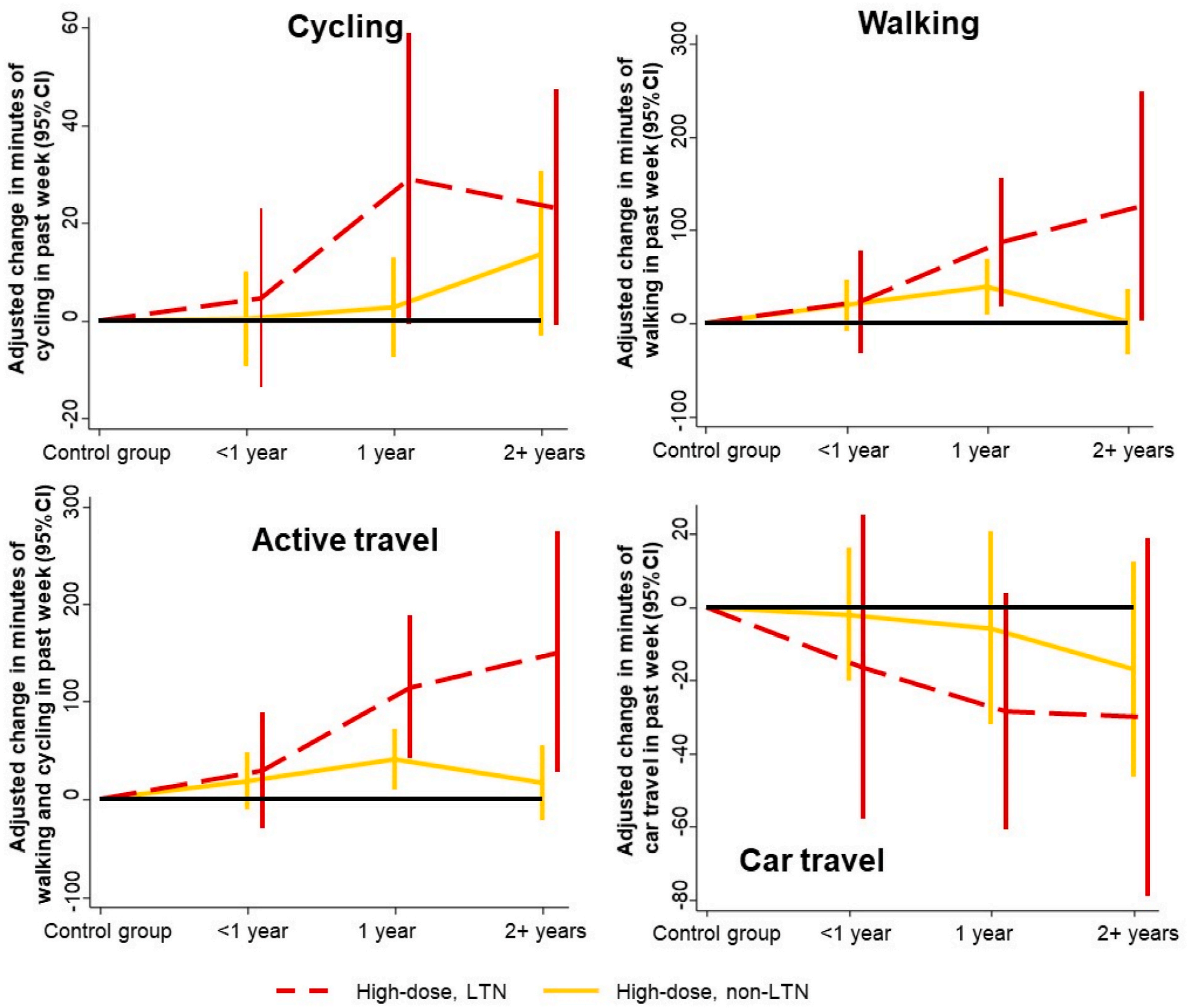

Fig. 4. Association between duration of living in an intervention area and impacts on duration of travelling by different modes in the past-week, Waves 1-3.

Table 5
Findings in relation to key hypotheses.

H1a: Living in an intervention area is associated with an increased amount of walking and/or cycling.

Consistent evidence of a substantial amount of active travel especially in high-dose LTN areas, and some evidence of increases in high-dose non-LTN areas. Little or no evidence of change in low-dose areas.

H1b: Living in an intervention area is associated with an increased likelihood of walking and/or cycling.

Consistent evidence of increased participation in cycling in high-dose LTN areas (Waves 1–5), and to a lesser extent in high-dose non-LTN areas (Waves 3–5). Little or no evidence of change in low-dose areas.

H2a: Living in an intervention area is associated with decreased amount of time spent travelling by car or van.

Limited evidence of decreased amount of *time spent travelling* by car or van in high-dose LTN areas. Weak, non-significant trends to reductions in high-dose non-LTN areas. No evidence of any change in low-dose areas.

H2b: Living in an intervention area is associated with a decreased likelihood of travelling by car or van.

Some evidence of decreased *likelihood of travelling* by car or van in high-dose LTN areas. Weak, non-significant trends to reductions in high-dose non-LTN areas. No evidence of any change in low-dose areas.

H2c: Living in an intervention area is associated with a decreased likelihood of car or van ownership.

Some evidence of decreased car ownership in high-dose LTN areas in Waves 2–4. Weak, non-significant trends to reductions in high-dose non-LTN areas. No evidence of any change in low-dose areas.

of just over £4800 per adult aged 20–80 due to increased physical activity.

4. Discussion

4.1. Summary of findings: active travel and car use

Table 5 summarises the direction, strength, and consistency of findings for all hypotheses reported here. Mini-Holland interventions have been associated with changes in travel behaviour. This is most strongly evidenced for the areas with the most interventions (i.e., in LTNs within high-dose areas, compared to high-dose areas without LTNs). There is no clear evidence of a change in travel behaviour for those living within a mini-Holland borough but not close to an intervention ('low-dose areas'). The strongest evidence is for a change in walking and cycling, with the largest additional amount of active travel in absolute terms generally coming from walking, but with the strongest evidence of additional participation (i.e., new active travellers) for cycling, which had much lower participation rates at baseline. There is less strong but generally consistent evidence of less car ownership and/or use, particularly in the high-dose LTN areas.

4.2. Summary of results: health impacts

Compared to the programme cost of £100 m, the health economic benefits are ten-fold higher, at £1,056 m. Benefits are concentrated within LTN areas where the physical activity benefit reaches £4800 per person over the twenty-year appraisal period, as opposed to an average of £3000 across the wider 'high-dose' area. The LTN area benefits could be compared to estimated per-beneficiary costs of around £112 for higher-quality LTNs or £27–35 in low-cost LTNs such as those implemented in some other Outer London boroughs during the Covid period.

4.3. Strengths and limitations

A strength of the method is its use over multiple, repeated waves, reducing the likelihood of findings being due to chance (where they are replicated). The pre-post controlled design provides greater confidence than commonly used monitoring designs (such as counts combined with intercept surveys) that travel behaviour change is measured accurately. However, the measure of travel behaviour is self-report rather than objective, although this may be more likely to appear as noise than as bias, given individuals are unlikely to remember the minutes they reported in previous waves, even if they know their intervention status.

The sample composition and size represent another limitation. In terms of size, while the sample would have been sufficient to detect even small changes in travel behaviour in mini-Holland boroughs, study power became much lower to detect changes in behaviour in specific intervention areas (where, as it turned out, changes were concentrated). Sample composition would ideally have been entirely from the household leaflet sample, which was more representative. However, funding was insufficient to conduct the kind of recruitment approach that would have obtained a larger sample from this method. Using the TfL customer databases was a compromise but adequate in the authors' opinion, considering that travel behaviour of the subsequent sample was akin to that of Outer Londoners more generally despite some demographic bias.

4.4. Findings in the context of wider literature

Xiao et al. (2022) found that "interventions that combine both positive and negative strategies might be more effective at encouraging alternatives to driving at the population level" than those comprising only positive or only negative strategies. The interventions researched here tended to be combinations of 'carrots' and 'sticks' – in the case of low traffic neighbourhoods, seeking to discourage driving while making walking and cycling more pleasant (due to fewer motor vehicles, and in some cases, greening of the local environments permitted due to a freeing up of space). However, even most route-based infrastructure could be seen in these terms, because in what are crowded urban settings, the creation of cycle routes tended to involve space reallocation away from general traffic and/or car parking.

This research therefore advances the wider literature in responding to the call in Xiao et al. (2022) for additional research on such combined interventions. It complements other research already published using less complete versions of this dataset; finding for instance that interventions tended to be perceived as improving the cycling but not walking environment, despite their generally stronger impact on walking (Aldred et al., 2019; also found in subsequent waves). A final report for TfL (Aldred et al., 2022) concluded that controversy over schemes was high early on even well before implementation of many interventions, but in some cases at least, this seemed to decline over time. Other research using secondary data has found positive impacts of LTNs on injuries, crime, car ownership and/or use, without negative impacts on emergency service response times (Aldred et al., 2022). More research into such controversial but potentially high impact interventions is crucial.

5. Conclusion

With five years of consistent follow-up results, the study supports building active travel infrastructure to help meet policy goals of increasing active travel and reducing car use (which should continue to be studied in future research). The strongest support is for a policy combining low traffic neighbourhoods with providing proximity to main road cycle tracks, as was done most consistently during this time in the South of Waltham Forest. The findings suggest that this leads to substantially increased walking, increased participation in cycling, and reductions in car ownership and/or use, and that the benefits of increased walking and cycling substantially outweigh scheme costs. Future research should examine impacts of such measures in a wider range of contexts, e.g. in the UK outside London and/or in other London boroughs, including Inner London.

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CRediT authorship contribution statement

Rachel Aldred: Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing, Formal analysis. **Anna Goodman:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **James Woodcock:** Conceptualization, Formal analysis, Investigation, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jth.2024.101771.

Appendix 1

Weighting

The mini-Holland and non-mini-Holland groups differed in terms of the proportion of participants coming from different sampling sources (Household leaflet sample, Oyster database, Cyclist database, and Unknown database). The disproportionality of the sampling sources was adjusted in two stages – via group weighting and individual-level weighting. Group level weights were applied to the non-mini-Holland group to equalise the relative contribution of different sources. The Unknown sample was a mixture of individuals from the Oyster and Cyclist databases, and the balance between the two groups was likely to be different in the mini-Holland group and in the non-mini-Holland group, as we knew that there were proportionally more from the Cyclist database in the non-mini-Holland group, and proportionally more from the Oyster database in the mini-Holland group. To take account of this, we further assigned individual weights for the unknown group, separately for cyclists and non-cyclists.

At Waves 1 to 5, these four sources differed in their follow-up rate, and we therefore updated our Baseline weight to take account of that. We did this as follows:

$$\text{Wave 1 weight} = \text{Baseline weight} * \frac{\text{Overall Wave 1 follow} - \text{up rate}}{\text{Wave 1 follow} - \text{up rate for source in question}}$$

$$\text{Wave 2 weight} = \text{Baseline weight} * \frac{\text{Overall Wave 2 follow} - \text{up rate}}{\text{Wave 2 follow} - \text{up rate for source in question}}$$

$$\text{Wave 3 weight} = \text{Baseline weight} * \frac{\text{Overall Wave 3 follow} - \text{up rate}}{\text{Wave 3 follow} - \text{up rate for source in question}}$$

$$\text{Wave 4 weight} = \text{Baseline weight} * \frac{\text{Overall Wave 4 follow} - \text{up rate}}{\text{Wave 4 follow} - \text{up rate for source in question}}$$

$$\text{Wave 5 weight} = \text{Baseline weight} * \frac{\text{Overall Wave 5 follow} - \text{up rate}}{\text{Wave 5 follow} - \text{up rate for source in question}}$$

For example, in the household leaflet sample the Wave 1 follow-up rate was 42%, as opposed to 50% for the sample as a whole. We therefore multiplied the Baseline weight by 50%/42% = 1.19 (Table 6, row C).

The Baseline group-level weight, Baseline individual-level weight and Wave 1 wt were then multiplied together to create a final weight, as summarised in Table 6. An analogous process was used to calculate the Waves 2 to 5 wt

Table 6
Summary of calculation of weights

		Household leaflet	Oyster database	Cyclist database	Unknown (Oyster or Cyclist database)
Column % of participants at Baseline	**non-MH**	31.1%	19.9%	36.4%	12.6%
	MH	37.6%	32.5%	19.6%	10.3%
% followed-up at Wave 1	**Whole sample**	41.9%	52.3%	62.1%	36.8%
% followed-up at Wave 2	**Whole sample**	38.5%	48.2%	58.7%	38.9%
% followed-up at Wave 3	**Whole sample**	36.6%	45.6%	53.9%	34.1%
% followed-up at Wave 4	**Whole sample**	35.6%	44.9%	55.1%	35.1%
% followed-up at Wave 5	**Whole sample**	33.4%	40.6%	48.3%	32.3/%
Group-level Baseline weight (A)	**non-MH**	1.21	1.63	0.54	0.82
	MH	1.00	1.00	1.00	1.00
Individual-level weight (B)	**non-MH**	1.00	1.00	1.00	0.76 cyclists 1.05 non-cyclists
	MH	1.00	1.00	1.00	1.00
Wave 1 wt multiplier (C)	**Whole sample**	1.19	0.95	0.80	1.35
Wave 2 wt multiplier (D)	**Whole sample**	1.21	0.97	0.80	1.21
Wave 3 wt multiplier (E)	**Whole sample**	1.19	0.96	0.81	1.28
Wave 4 wt multiplier (F)	**Whole sample**	1.22	0.97	0.79	1.24
Wave 5 wt multiplier (G)	**Whole sample**	1.18	0.97	0.82	1.22
Wave 1 final weight (A × B*C)	**non-MH**	1.44	1.55	0.43	0.84 cyclists 1.18 non-cyclists
	MH	1.19	0.95	0.80	1.35
Wave 2 final weight (A × B*D)	**non-MH**	1.47	1.58	0.43	0.75 cyclists 1.05 non-cyclists
	MH	1.21	0.97	0.80	1.21
Wave 3 final weight (A × B*E)	**non-MH**	1.44	1.56	0.44	0.80 cyclists 1.10 non-cyclists
	MH	1.19	0.96	0.81	1.28
Wave 4 final weight (A × B*F)	**non-MH**	1.48	1.58	0.43	0.77 cyclists 1.07 non-cyclists
	MH	1.22	0.97	0.79	1.24
Wave 5 final weight (A × B*G)	**non-MH**	1.43	1.58	0.44	0.76 cyclists 1.05 non-cyclists
	MH	1.18	0.97	0.82	1.22

MH = mini-Holland.

Comparability of intervention and control groups, sample representativeness

Table 7
Demographic and socio-economic characteristics of participants in Wave 1 follow-up, comparing the mini-Holland and non-mini-Holland groups (N = 1712)

	Mini-Holland group (N = 750)		Non-mini-Holland group (N = 962)		p-value for difference†
	N	Weighted %	N	Weighted %	
Source of participants					
Household Leaflet	243	37.7%	246	37.5%	n/a
Oyster database	260	32.3%	198	32.3%	
Cyclist database	189	19.8%	429	19.7%	
Unknown (Oyster or Cyclist database)	58	10.2%	89	10.2%	
Borough					
Waltham Forest	314	42.0%	0	0%	n/a
Kingston	237	31.2%	0	0%	
Enfield	199	27.8%	0	0%	
Non-mini-Holland	0	0%	962	100%	
Gender					
Male	358	47.5%	533	52.5%	0.002
Female	385	52.5%	426	47.5%	
Age (years)					

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Table 7 (*continued*)

	Mini-Holland group (N = 750)		Non-mini-Holland group (N = 962)		p-value for difference†
	N	Weighted %	N	Weighted %	
16–24	10	1.4%	12	1.6%	0.89/
25–34	80	10.8%	117	12.1%	0.73
35–44	168	22.3%	206	19.2%	
45–54	186	25.0%	239	23.1%	
55–64	201	26.7%	271	30.2%	
65+	95	13.8%	112	13.8%	
Ethnicity					
White	639	88.2%	816	86.3%	0.48
Non-White	83	11.8%	118	13.8%	
Disability					
No	660	88.7%	846	86.6%	0.68
Yes	82	11.3%	112	13.4%	
Household type					
A couple without children	241	31.9%	307	31.6%	0.03
Single adult living alone	179	23.9%	196	21.6%	
Single adult living with other adults	69	9.0%	87	9.7%	
A couple with children	230	31.0%	309	30.4%	
Single adult living with children	19	2.6%	22	2.5%	
Other	12	1.6%	41	4.2%	
Employment status					
Full-time employed	440	57.4%	587	58.2%	0.35
Part-time employed	111	15.0%	125	14.2%	
Not in paid employment: retired	135	19.0%	154	17.8%	
Not in paid employment: other	64	8.6%	96	9.9%	
Number of cars or vans in household					
0	217	28.7%	196	20.8%	<0.001/
1	366	48.8%	498	49.3%	<0.001
2+	167	22.5%	277	30.0%	

†p-values calculated using Chi-squared tests for association, with Chi-squared tests for trend additionally reported for ordered categorical variables.

Demographic and socio-economic characteristics of Wave 5 participants

Table 8
Demographic and socio-economic characteristics of Wave 5 participants

		N	%
Full sample		1354	100
Borough	Enfield	736	54%
	Kingston	150	11%
	Waltham Forest	233	17%
	Other outer London	235	17%
Gender	Male	712	53%
	Female	637	47%
Age (years)	16–24	3	0%
	25–44	277	20%
	45–64	760	56%
	65+	314	23%
Ethnicity	White	1158	86%
	Non-White	147	11%
	Prefer not to say	49	4%
Disability	No	1257	96%
	Yes	56	4%
Household type	A couple without children	451	33%
	Single adult living alone	300	22%
	Single adult living with other adults	89	7%
	A couple with children	427	32%
	Single adult living with children	39	3%
	Other	47	3%
Employment status	Full-time employed	678	50%
	Part-time employed	195	14%
	Not in paid employment: retired	375	28%
	Not in paid employment: other	106	8%
Number of cars or vans in household	0	309	23%
	1	685	51%

(*continued on next page*)

Table 8 (*continued*)

		N	%
at baseline	2	360	27%
Working from home more than usual†	No	1086	80%
	Yes	268	20%
Covid-19 impact on travel behaviour†	Travelling less than 1 year ago	1123	83%
	'No effect'	200	15%
	Travelling more than 1 year ago	26	2%

† These variables were measured and adjusted for only in the Wave 4 and 5 analyses, not analyses of Waves 1–3.

Table 9
Car ownership and past week travel behaviour in relation to intervention type and duration of follow-up living in the area, Waves 1–3: adjusted rate ratios/regression coefficients (95% confidence interval)

Domain	Outcome	Control group	LTN, <1 year	LTN, 1 year	LTN, 2+ years	High dose non-LTN, <1 year	High dose non-LTN, 1 year	High dose non-LTN 2+ years
Number of observations		3856	70	54	44	349	272	175
Past-week cycling								
	% Doing any cycling in past week	1	1.38 (1.07, 1.79)*	1.40 (1.04, 1.88)*	1.95 (1.45, 2.62)***	1.07 (0.89, 1.30)	1.11 (0.87, 1.40)	1.32 (1.05, 1.67)*
	Minutes of cycling in past week	0	4.6 (−13.7, 22.8)	29.0 (−0.8, 58.9)†	23.1 (−1.2, 47.3)†	0.4 (−9.4, 10.2)	2.7 (−7.4, 12.9)	13.7 (−3.1, 30.5)
Past-week walking								
	% Doing any walking in past week	1	1.08 (1.02, 1.15)**	1.09 (1.03, 1.15)**	1.11 (1.05, 1.17)***	0.98 (0.93, 1.03)	1.03 (0.99, 1.08)	1.03 (0.97, 1.09)
	Minutes of walking in past week	0	22.9 (−32.3, 78.2)	86.7 (18.1, 155.3)*	125.7 (3.0, 248.5)*	19.5 (−8.3, 47.2)	38.9 (9.2, 68.7)*	1.7 (−33.7, 37.2)
Past-week active travel								
	% Doing any AT in past week	1	1.06 (1.00, 1.12)*	1.09 (1.04, 1.14)***	1.10 (1.04, 1.16)**	1.00 (0.96, 1.05)	1.04 (1.00, 1.08)*	1.03 (0.97, 1.08)
	% Doing 140+ minutes AT in past week	1	1.08 (0.93, 1.25)	1.12 (1.00, 1.27)†	1.18 (1.03, 1.35)*	1.08 (1.01, 1.16)*	1.11 (1.03, 1.20)**	1.10 (1.01, 1.21)*
	Minutes of AT in past week	0	29.1 (−30.3, 88.4)	114.6 (41.2, 188.0)**	150.3 (26.9, 273.8)*	18.5 (−10.6, 47.5)	41.0 (9.9, 72.1)*	17.0 (−21.5, 55.6)
Car ownership and past-week car travel								
	% with a household car	1	0.93 (0.80, 1.09)	0.91 (0.76, 1.08)	0.80 (0.64, 1.01)†	0.96 (0.90, 1.02)	0.94 (0.87, 1.00)*	0.94 (0.85, 1.04)
	% with any car travel in past week	1	0.86 (0.74, 1.00)	0.80 (0.64, 1.00)†	0.82 (0.62, 1.07)	0.94 (0.88, 1.01)†	0.93 (0.87, 1.00)†	0.90 (0.81, 1.00)*
	Minutes of car travel in past week	0	−16.4 (−58.1, 25.2)	−28.5 (−60.8, 3.8)†	−30.1 (−79.1, 18.9)	−2.1 (−20.3, 16.1)	−5.8 (−32.3, 20.6)	−17.2 (−46.6, 12.3)

†p < 0.10, *p < 0.05, **p < 0.01, ***p < 0.001, for difference from the reference group. AT = active travel, LTN = low traffic neighbourhood, week = week. Analyses based on 4820 Waves of data from 2204 individuals. Analyses adjust for the baseline measure of the outcome in question and for gender, age, ethnicity, disability, household type, employment type, and the baseline number of cars in the household. Note that to simplify these analyses of longitudinal effects we have combined the 'Non-mini-Holland' and 'Low dose' groups into a single control group. We did this to increase study power, and on the basis of the similarity of these two groups in our main analyses. Our findings were similar in analyses which were limited to using the 'Non-mini-Holland control' as the reference control group.

Active travel outcomes by distance from routes

Table 10
Active travel outcomes by distance from routes: adjusted rate ratios/regression coefficients (95% CI)

		% doing any walking in the past week	Minutes of walking in the past week	% doing any cycling in the past week	Minutes of cycling in the past week	% doing any active travel in the past week	Minutes of active travel in the past week
Wave 2	≥5 km from MH routes	1	0	1	0	1	0

(*continued on next page*)

Table 10 (*continued*)

		% doing any walking in the past week	Minutes of walking in the past week	% doing any cycling in the past week	Minutes of cycling in the past week	% doing any active travel in the past week	Minutes of active travel in the past week
	2–4.9 km from MH routes	1.01 (0.96, 1.06)	21.5 (−5.5, 48.4)	1.10 (0.87, 1.38)	2.8 (−6.1, 11.7)	1.02 (0.98, 1.07)	24.2 (−4.1, 52.5)†
	<2 km from MH routes	1.06 (1.02, 1.11)**	29.3 (2.2, 56.5)*	1.15 (0.93, 1.41)	3.2 (−7.6, 14.1)	1.06 (1.02, 1.11)**	33.8 (4.6, 63.1)*
Wave 3	≥5 km from MH routes	1	0	1	0	1	0
	2–4.9 km from MH routes	1.01 (0.95, 1.08)	−13.7 (−46.4, 18.9)	0.86 (0.62, 1.17)	−3.5 (−13.5, 6.5)	1.00 (0.94, 1.06)	−17.3 (−50.7, 16.1)
	<2 km from MH routes	1.03 (0.98, 1.07)	23.6 (−7.0, 54.1)	1.29 (1.05, 1.58)*	10.6 (0.8, 20.5)*	1.03 (0.99, 1.07)	35.1 (3.1, 67.1)*
Wave 4	≥5 km from MH routes	1	0	1	0	1	0
	2–4.9 km from MH routes	1.01 (0.94, 1.09)	10.6 (−23.0, 44.2)	1.26 (0.96, 1.65)†	1.7 (−11.9, 15.2)	1.03 (0.96, 1.11)	13.6 (−22.7, 49.9)
	<2 km from MH routes	1.03 (0.97, 1.08)	16.8 (−8.7, 42.2)	1.40 (1.12, 1.73) **	5.7 (−5.8, 17.3)	1.05 (0.99, 1.11)†	21.6 (−6.0, 49.2)
Wave 5	≥5 km from MH routes	1	0	1	0	1	0
	2–4.9 km from MH routes	0.99 (0.92, 1.06)	−2.4 (−40.7, 35.9)	1.17 (0.86, 1.61)	19.0 (−23.8, 61.7)	0.98 (0.92, 1.05)	17.2 (−42.1, 76.5)
	<2 km from MH routes	1.08 (1.02, 1.14)**	50.4 (19.8, 81.1) **	1.38 (1.10, 1.74) **	13.3 (1.0, 25.7)*	1.08 (1.03, 1.14)**	64.1 (31.4, 96.8) ***

†p < 0.10, *p < 0.05, **p < 0.01, ***p < 0.001, for difference from the non-mini-Holland group. Analyses adjust for the baseline measure of the outcome in question and the baseline number of cars in the household, plus gender, age, ethnicity, disability, household type and employment type at follow-up.

Estimated costs per resident for selected LTNs

Table 11
Estimated costs per resident for selected LTNs

Scheme	Where	Cost	Estimated population in 2019 †	Cost per resident	Details of cost estimates
Permanent, high-quality LTNs	Waltham Forest mini-Hollands	4,558,097	55,994	£81.40	£4,558,097 for all 7 LTNs (including Mini-Holland funding plus complimentary contributions) + half the mini-Hollands monitoring budget. [funding information provided by Waltham Forest Cllr Clyde Loakes in personal communication to one of the authors on May 26, 2021]
Emergency Active Travel Fund LTNs, installed 2020	Outer London	2,338,495	129,859	£18.01	For schemes in 6 Outer London boroughs (Croydon, Ealing, Harrow, Hounslow, Newham, Waltham Forest): £1,457,517 in tranche 1 funding. (https://www.london.gov.uk/questions/2020/1657, attachment 1). These boroughs implemented 25 LTN areas. 5 other Outer London boroughs that also did LTNs: Brent, Enfield, Greenwich, Merton, Sutton. These latter 5 boroughs implemented 10 LTN areas. Pro rata, it is assumed the cost was 1,457,517 * (10 + 25)/25 = £2,040,523 Also added in Redbridge £297,971 for scrapped LTNs, as one could say some wasted money part of the 'cost of business'. Gives £2,338,495.

(*continued on next page*)

Table 11 (*continued*)

Scheme	Where	Cost	Estimated population in 2019 †	Cost per resident	Details of cost estimates
Emergency Active Travel Fund LTNs, installed 2020	4 LTNs in Lambeth (Ferndale, Railton, Streatham Hill, Tulse Hill)	1,000,000	37,960	£26.34	£568 k for the four LTNs excluding the cost of ANPR.
					Then pro rata £540 k was spent on ANPR across 5 LTNs in Lambeth = an estimated 540 × 0.8 £432 k for these 4 LTNS This gives a cost of 568 + 432 = £1,000,000 in total [funding information provided in personal communication from Lambeth council officer Nick McCoy to one of the authors on May 26, 2021. The information request was initially made in the context of analysing LTN monitoring reports, where data from Oval LTN wasn't suitable – hence that fifth Lambeth LTN is excluded]

† All population calculations based on ONS mid-year LSOA-level populations (https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/datasets/lowersuperoutputareamidyearpopulationestimates) plus LTN shape files, using % buildings inside LTN boundaries as proxy for % population.

Appendix 2

See Excel sheets separately provided (cost-benefit analysis calculations).

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