Journal of Transport & Health 30 (2023) 101601

Contents lists available at ScienceDirect

Journal of Transport & Health

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

Effects of Te Ara Mua – Future Streets suburban street retrofit on traffic speed and volume: Controlled before-after study

Jamie Hosking[a,*], Hamish Mackie[b], Alex Macmillan[c], Bert van der Werf[a], Melody Smith[a], Karen Witten[d], Alistair Woodward[a]

[a] Faculty of Medical and Health Sciences, Waipapa Taumata Rau, The University of Auckland, Private Bay 92019, Tāmaki Makaurau, Auckland, 1142, Aotearoa, New Zealand
[b] Mackie Research & Consulting, PO Box 106525, Tāmaki Makaurau, Auckland, 1143, Aotearoa, New Zealand
[c] Preventive and Social Medicine, Te Tari Hauora Tūmatanui, University of Otago, Te Whare Wānanga o Otāgo, Dunedin, Ōtepoti, 9054, Aotearoa, New Zealand
[d] SHORE and Whariki Research Centre, Massey University, PO Box 6137, Victoria Street West, Tāmaki Makaurau, Auckland, 1142, Aotearoa, New Zealand

ARTICLE INFO

Keywords:
Road traffic injuries
Speed
Traffic volume
Intervention
Street hierarchy
Human factors

ABSTRACT

Background: Traffic speed and volume are important determinants of road traffic injury rates for all travel modes, and high traffic speed and volume can deter walking and cycling. Te Ara Mua – Future Streets is a project in Māngere, Aotearoa New Zealand, that aims to make it safer and easier for people to get around their local neighbourhood, especially by walking and cycling. Key components include implementation of a street hierarchy and street design changes to reduce speeds on neighbourhood streets, as well as other components including improved active transport infrastructure.
Methods: We used tube counters to measure motor vehicle speed and volume before and after the intervention, at different levels of the street hierarchy: arterial, collector and local streets. A difference-in-differences approach was used to assess changes in the intervention area compared with a matched control area.
Results: We found post-intervention mean speed reductions of 8 km/h on local streets, and 5–6 km/h on collector streets, relative to the control area. Mean traffic volumes reduced by 17–24% on local streets, with no change on collectors or arterials. Both post-intervention time points showed similar results, indicating a sustained effect.
Conclusions: Overall, this intervention successfully reinforced a street hierarchy, creating local residential streets that are more conducive to road safety and active travel. Implementation of similar interventions in disadvantaged neighbourhoods could help reduce road traffic injury inequities within cities. The findings suggest a promising contribution to safer streets that are more attractive for walking and cycling. Our future research will evaluate broader impacts of this intervention on travel mode shift, injury rates and other health and social outcomes.

* Corresponding author. Faculty of Medical and Health Sciences, Waipapa Taumata Rau, The University of Auckland, Private Bay 92019, Tāmaki Makaurau, Auckland, 1142, Aotearoa, New Zealand.
E-mail addresses: jamie.hosking@auckland.ac.nz (J. Hosking), hamish@mackieresearch.co.nz (H. Mackie), alex.macmillan@otago.ac.nz (A. Macmillan), bert.vanderwerf@auckland.ac.nz (B. van der Werf), melody.smith@auckland.ac.nz (M. Smith), k.witten@massey.ac.nz (K. Witten), a.woodward@auckland.ac.nz (A. Woodward).

https://doi.org/10.1016/j.jth.2023.101601
Received 4 August 2022; Received in revised form 11 February 2023; Accepted 9 March 2023
Available online 23 March 2023
2214-1405/

1. Introduction

It is well known that higher traffic speed and volume are strongly associated with a higher risk of road traffic injuries and fatalities for all road users (Elvik, 2012). Consequently, interventions to reduce traffic speeds are an important way to improve road safety. Disadvantaged socio-economic groups and people living in poorer areas are consistently at higher risk of road traffic injury (Peden et al., 2004), highlighting the need for evidence-based interventions to reduce inequities, (Hosking, Woodward, Macmillan, Jones, Ameratunga, Smith) including systemic, structural and environmental changes. A range of environmental infrastructure approaches have been used to reduce traffic speeds. Evaluations of many speed reduction projects have found substantial reductions in crashes, injuries and fatalities (Bunn et al., 2003; Grundy et al., 2009; Mackie et al., 2013). For example, in many parts of the United Kingdom, 20 mph zones have been implemented, using engineering measures to slow traffic to no more than 20 miles an hour (32 km/h) (Grundy et al., 2009). 'Mini -Holland' projects have also been implemented in the United Kingdom, combining measures to calm and reduce local traffic with protected cycle lanes on main streets and cycle hubs at train stations (Aldred et al., 2019). The 'Self-Explaining Roads' approach, originating from the Netherlands, involves the identification of different road categories within a road hierarchy and design of each road type to have a distinct 'look and feel', with smaller local streets designed to achieve lower speeds without the need for posted speed limits and enforcement (Charlton et al., 2010; Theeuwes and Godthelp, 1995). However, despite there being many examples of evidence-based approaches for reducing injuries for the total population, there is relatively little evidence for effective strategies to reduce road traffic injury inequities.

Higher speeds and volumes of traffic are commonly associated with less walking and cycling. A shift in travel mode from car use to active travel, such as walking and cycling, is widely recognised as being important for improving health, as well as a wide range of other health, social and environmental benefits, such as reducing greenhouse gas emissions (World Health Organization, 2012; Macmillan et al., 2020). Morrison et al. (2004) observed generally higher numbers of people walking after a traffic calming intervention in Glasgow, Scotland, but the study design did not include a control group. Charlton et al. (Mackie et al., 2013) observed more people walking, and fewer motor vehicles, after a self-explaining roads intervention in Tāmaki Makaurau Auckland, Aotearoa New Zealand, but again there was no control group, and statistical significance was not reported. Evaluation of mini-Hollands, which include substantial walking and cycling infrastructure alongside traffic calming elements, suggested that these interventions increased active travel among residents by 40–45 min/week, mostly due to more walking (Aldred et al., 2021). More difficult to evaluate are feedback loops, in which increases in active travel may be associated with further speed reductions, leading to further increases in active travel, as suggested by modelling research (Macmillan et al., 2014). There are therefore several reasons to believe that interventions to lower traffic speeds may lead to mode shift from car use to active travel, while also improving safety, but studies with more robust designs are needed. Again, there is an absence of studies with a focus on examining health and social equity effects. Interventions to traffic speeds that are effective, and that can be successfully implemented in more deprived neighbourhoods, could help reduce inequities within cities in road traffic injuries, and may also promote walking and cycling in more deprived neighbourhoods.

Te Ara Mua (translation "the path ahead shaped by the past") Future Streets (hereafter Future Streets) is a controlled before-after intervention study involving suburb-wide infrastructure and street design changes that aimed to make it safer and easier for people to get around the local neighbourhood, especially by walking and cycling. The project was implemented in Māngere, a suburb of Tāmaki Makaurau Auckland that has long experienced transport and other structural inequities, in Aotearoa New Zealand.

The study design and intervention design have been described more fully elsewhere (Mackie et al., 2018; Macmillan et al., 2018). Briefly, the project was initiated by the multidisciplinary research team, with an initial partnership developed between the research team and Auckland Transport, the regional transport planning authority. We collaborated with a range of other groups and agencies, including the Local Board (one of 21 such agencies representing sub-areas within the Tāmaki Makaurau Auckland region), mana whenua (local Māori, indigenous New Zealanders, who have authority over their locality), and Waka Kotahi - New Zealand Transport Agency (involved in some local road funding as well as strategic planning for transport in Aotearoa New Zealand). The research team also undertook extensive community engagement to inform the intervention design. An initial funding commitment of NZ$1 million from Auckland Transport was later supplemented by further funding from that agency as well as Waka Kotahi and the Local Board, totalling approximately NZ$9 million for the infrastructural work.

The intervention had the overall goal of making streets safer and easier to use for walking and cycling, and traffic calming was a key design feature used to achieve this. The project was informed by self-explaining roads principles, including the delineation of a road hierarchy that categorises streets as arterial roads (highest speeds and vehicle volumes), collector streets (mid-level speeds and vehicle volumes), and local streets (lowest speeds and vehicle volumes, primarily residential streets). The project implemented changes in selected locations across Māngere, including enhanced infrastructure for walking and cycling on arterial and collector streets (e.g. separated cycle lanes, improved crossings), speed reduction measures on local streets and improved routes for walking or cycling through selected parks.

The objective of this study was to identify pre-post changes in vehicle travel in the Future Streets intervention area (Māngere Central), compared to a nearby control area (Māngere East). In particular, the objective was to assess changes in motor vehicle speed and volume, and changes in motor vehicle type (specifically, heavy vehicles). Consistent with the causal theory underlying the project (Macmillan et al., 2018, 2020; Mackie et al., 2018), later studies will investigate the impacts on walking and cycling uptake.

2. Material and methods

2.1. Setting and study design

Tāmaki Makaurau Auckland is the largest city (population 1.7 million) in Aotearoa New Zealand. As a result of more than half a century of car-focused urban design and urban sprawl, it is a heavily car-dependent city, with 81% of trips to work made by private motor vehicles and very low levels of walking (5%) and cycling (1%) (Stats NZ - Tatauranga Aotearoa, 2001). Following a suburb selection process, Māngere was chosen as the study location based on a list of selection criteria that included a road traffic injury rate that was higher than the city average, similar destination accessibility and road types, high levels of socio-economic deprivation and social and health inequities associated with structural racism. Area maps and a full description of area selection criteria were published previously (Mackie et al., 2018). Within Māngere, two smaller neighbourhoods were randomly assigned to be an intervention area (Māngere Central) and a control area (Māngere East). The intervention area and control area have similar characteristics (e.g. demographic profiles and street layouts) and are separated by a motorway (Fig. 1).. (Mackie et al., 2018)

2.2. Intervention

As described in depth elsewhere (Mackie et al., 2018), the design of the intervention was informed by the results of community engagement, evidence from transport planning literature, expertise within the design team and baseline data on traffic speed, volume and injuries. The design team included representatives from the research team, city council and local community, supported by other safety, disability, indigenous and walking and cycling expertise. Early in this process, design principles were developed to guide the intervention. The principles included a street/route hierarchy giving greater priority to pedestrians and cyclists, reducing traffic speed and making traffic speeds more consistent, improving people's ability to cross the road safely, and placemaking elements reflecting the identity and history of the indigenous peoples of Māngere (Raerino et al., 2021).

The desired street hierarchy category for each street was informed by the baseline street category assigned by the city council, traffic data, community engagement and the judgement of the design team. At baseline, signposted speed limits were 50 km/h for all streets, and although the intervention aimed to lower speeds on local streets, there were no changes to the signposted speed limits. Components of the final intervention included infrastructure to improve sense of security, facilitate walking and cycling and calm traffic, as well as planting, wayfinding elements, and references to local and indigenous culture (see map in Fig. 2 and images of

Fig. 1. Map of intervention (Central) and control (East) areas within Māngere.

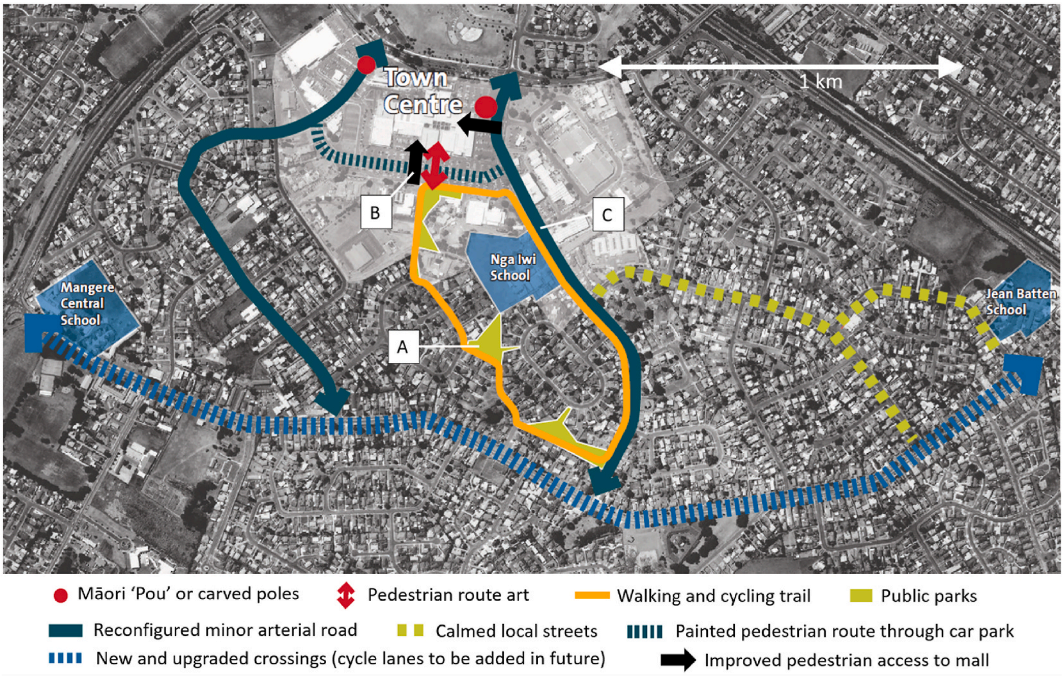

Fig. 2. Map of key intervention elements within intervention area. Note: images from locations A, B and C are available in Mackie et al., 2018) (Mackie et al., 2018).

intervention treatments in Fig. 3). Not all streets in the intervention area received changes, with priority given to collector streets and to those streets that at baseline were identified as unsafe by residents and as functioning in a way that did not match their expected category in the street hierarchy. Budget restrictions also meant that not all changes that were originally planned were able to be implemented, particularly in lower volume and lower risk streets such as cul-de-sacs. However, the highest priority changes were successfully implemented, and ultimately the project team considered that the final project elements that were implemented were sufficient to address the major safety and accessibility issues identified during the initial community engagement process. The intervention was implemented mostly in 2015 and 2016, with one further road treated in the first half of 2017.

2.3. Equipment

This paper focuses on traffic speed and volume measurements made using tube counters. Rubber pneumatic tubes were used to collect data using the MetroCount system (https://metrocount.com). Based on the pattern of tube activation by vehicle wheels, Based on the pattern of tube activation by vehicle wheels, vehicle types were classified, which enabled heavy vehicles of various types to be distinguished from light vehicles such as cars. It was not possible to reliably differentiate bicycles, which were also detected by the tubes, from motor scooters and other small motorbikes.

Measurements were undertaken in early to mid-Autumn (March and April) in 2014, 2017 and 2018. Data were collected over 24 h for at least 7 consecutive days, and 7-day periods were used for analysis in order to eliminate variation by day of the week. All observations were undertaken during March and April, with the exception of site 'control local 4a' in 2018, where additional observations were undertaken in late May and early June. For each site, 14 days of data were analysed, except for sites 'control arterial 1' and 'control collector 1' in 2014, where 7 days of data were analysed. As well as mean speeds, 85th percentile speeds were calculated as this value is commonly used to assess the appropriateness of speeds and used to guide street design (Global Road Safety Partnership, 2008).

2.4. Data collection sites

Sites for the tube counters were selected in the intervention area (9 sites) and control area (8 sites), spread across the three street types (arterials, collectors and local streets). One of the goals for selecting tube locations was to include all three categories in the street design hierarchy. However, we also collected video data at these locations in order to assess changes in road user behaviour, walking and cycling. Video data collection needs were also taken into account in selecting locations, though video data are not reported in this article and instead are reported elsewhere (Hirsch et al., 2022). As a result, data collection locations were not evenly shared across the street design hierarchy. In some cases we used more than one data collection site on the same street, if those sites were considered particularly important and had substantially different traffic characteristics (e.g. as reflected in 2014 data in Table 1) and in such cases

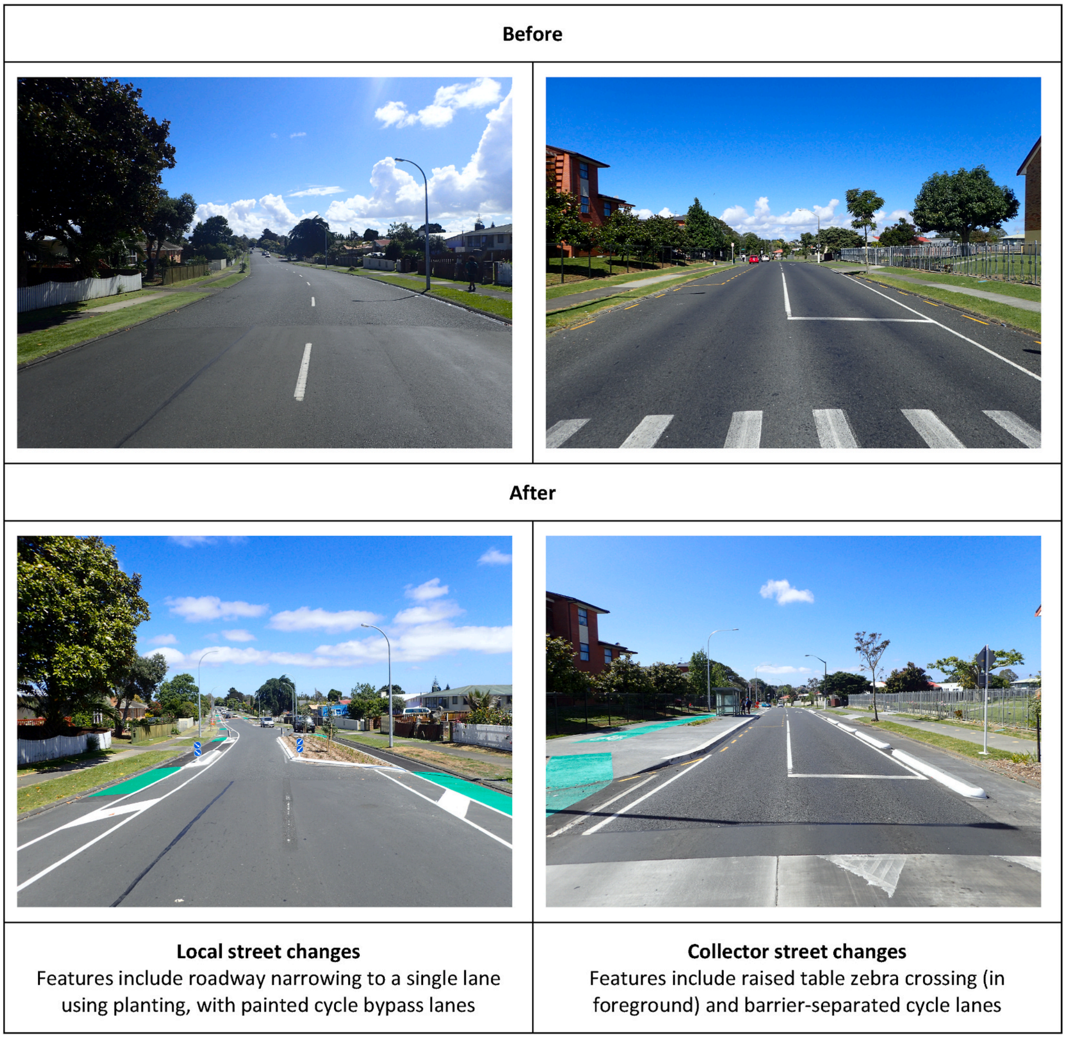

Fig. 3. Examples of intervention treatments on local and collector streets.

we treated the sites as being independent. Among the intervention area data collection sites, all but one street received street design treatments ('intervention local 2' was untreated). It was identified that baseline traffic behaviour on one particular street ('intervention local 1') was consistent with the collector street category, but the most desirable category in the street hierarchy for this street was local street, and so the treatment of this street reflected this desired change.

2.5. Weather data

Hourly weather data were obtained for the nearest data collection point (Māngere East) from Aotearoa New Zealand's National Climate Database using the CliFlo online portal (https://cliflo.niwa.co.nz/), which is provided by the National Institute of Water and Atmospheric Research (NIWA). In selecting weather variables, we followed Tin Tin et al. a study that was also set in Tāmaki Makaurau Auckland, and which investigated the relationship between weather variables and cycling (Tin Tin et al., 2012). Specifically, weather variables included maximum wind-speed (m/s), total amount of rain (mm), maximum temperature (°C) and total amount of sunshine (hours).

2.6. Statistical analysis

The primary hypothesis for this analysis was that the Future Streets intervention would reduce traffic speeds and volumes, and the proportion of heavy vehicles on local streets in Māngere, between 2014 and 2018. The secondary hypothesis was that initial changes in traffic speed and volume would be maintained between 2017 and 2018. To guide our analysis and make explicit our causal assumptions, we developed directed acyclic graphs (DAGs) (Greenland et al., 1999) representing the hypothesised effects of the Future

Streets intervention on motor vehicle traffic volume and speed (Supplementary Material).

Some of the variables represented in our DAG (Supplementary Material) were not included in the analysis. Traffic count and speed data were collected continuously, but as we were interested in changes in daily values, we analysed the data using daily counts and daily mean speed. For this reason, the time of day variable (included in our DAG) was not included in our multivariate models. Direction of travel (towards or away from the city centre) was not able to be reliably categorised for our data collection sites, so this variable was also not included in our models. Finally, the number of lanes was one per direction for all but one data collection site, so this variable was also not included. The effect of day of week was accounted for by analysing 7-day periods.

We used a 'difference in differences' (DID) analysis, in which the effect estimate was the change in the intervention area minus the change in the control area. Changes were calculated relative to a 2014 baseline (Card and Krueger, 2000). The DIDs were estimated by the interaction effects in a linear mixed model, with area as random effect and the interaction between year (2014, 2017 & 2018), intervention (intervention & control) and road type (arterial, collector &local) as fixed effects. In order to determine if there was a mediator effect of vehicle speed on vehicle count, or a mediator effect of vehicle count on vehicle speed, DIDs for each road type were calculated with and without the mediator included. Average Causal Mediation Effects (ACME) and the proportion mediated (Hicks and Tingley, 2011) were derived by taking the difference between the DID calculated without mediator and DID calculated with mediator. 95% confidence intervals for the ACMEs were calculated using bootstrap re-sampling (Bollen and Stine, 1990). All analyses were done in R, version 4.03 (R Core Team. R, 2020) using the lme4 package (Bates et al., 2015). The formula used was

response ~ (intervention*year + confounders [+ mediator]):RoadType + (1|site)

Counts were analysed on the logarithmic scale and speed was analysed untransformed. Residual analysis was done with the package DHARMa (Hartig, 2021).

We took an 'intention to treat' approach, including the untreated street in the intervention area with other measurements in the 'intervention' group of streets in the analysis.

3. Results

3.1. Street-by-street results

Table 1 shows traffic volumes, and mean and 85th percentile speeds, for each data collection site for the years 2014, 2017 and 2018. Data were not available in 2018 for one intervention area arterial and one intervention area collector site, due to technical problems. In the control area, there was little change in mean traffic speeds between 2014 and 2018, but most control sites saw an increase in traffic volumes. In both intervention and control areas, baseline traffic volumes tended to be highest for arterials and lowest for local streets, with collector streets in between, though one control area local street site ('control local 3') was an exception to this pattern. Mean traffic speeds at baseline did not show as consistent a pattern by street type, especially in the control area. The highest mean speed at baseline in the control area was on site 'control local 3', designated a local street. This demonstrated a poor match between street design speeds and each street's category in the street hierarchy at baseline.

Table 1
Traffic volume and speed, intervention and control sites, in 2014, 2017 and 2018.

Site name			Traffic speed – mean (km/h)			Traffic speed – 85th percentile (km/h)			Daily traffic volume		
	Area	Street type	2014	2017	2018	2014	2017	2018	2014	2017	2018
Control arterial 1	**Control**	**Arterial**	38.66	39.06	39.46	48.02	48.50	49.07	20,482	21,414	20,683
Control collector 1		**Collector**	45.64	45.35	46.88	53.00	53.25	54.67	10,457	11,665	11,366
Control local 1a		**Local**	40.82	40.86	40.30	48.38	47.94	46.95	1238	1489	1419
Control local 1b			48.06	46.08	48.70	55.39	53.22	56.20	4359	4744	4377
Control local 2			39.37	36.58	38.17	47.44	44.74	47.35	1784	1885	1661
Control local 3			49.55	48.02	49.41	55.18	53.87	55.45	10,168	11,569	11,259
Control local 4a			38.69	37.70	38.05	44.13	43.22	45.96	4644	5558	7059
Control local 4b			45.12	43.21	43.39	51.93	49.69	49.77	5903	7122	6759
Intervention arterial 1	**Intervention**	**Arterial**	50.29	41.10	n/a	55.86	46.76	n/a	17,661	19,949	n/a
Intervention arterial 2a			48.87	47.90	49.29	54.08	54.13	56.02	17,241	20,490	18,520
Intervention arterial 2b			50.54	50.97	50.82	56.26	57.31	57.33	25,112	27,180	25,996
Intervention collector 1a		**Collector**	39.40	32.17	n/a	47.88	38.62	n/a	9883	9280	n/a
Intervention collector 1b			44.79	43.59	44.17	52.20	50.32	50.98	5509	6631	6433
Intervention collector 1c			30.48	22.02′	23.66	39.14	28.73	30.61	13,173	13,925	12,493
Intervention local 1		**Local**	48.95	32.87	34.62	55.63	39.11	41.13	6368	4915	4710
Intervention local 2			45.55	45.05	45.45	52.79	52.33	52.85	2501	2925	2719
Intervention local 3			39.06	26.66	27.57	48.14	32.83	33.81	1660	1676	1447

n/a: data not available for this site/year combination. Traffic volume represents motorised vehicles and is the sum of both directions.

3.2. Changes in traffic speed and volume

Changes in volume and speed are shown in Fig. 4. The difference-in-differences analyses in these figures represent changes in the intervention area, relative to changes in the control area. Traffic volumes on intervention area local streets reduced by 16% in 2017 and 24% in 2018, but there was no significant change on arterial or collector streets (Table 2). There was no further significant change in traffic volume between 2017 and 2018 on arterial, collector or local streets, consistent with maintenance of the initial effect but no further effect. Post-intervention traffic volume reductions in local streets were due to the streets that received treatments, with no reduction in traffic volume seen on the untreated local street in the intervention area ('intervention local 2'; Table 1).

There were significant speed reductions on intervention area collector and local streets in both 2017 and 2018, with greater reductions in mean speeds for local streets (8 km/h) than collector streets (5 km/h, Table 2). As with changes in volumes, the changes in speed appeared to occur between 2014 and 2017, with the effect being maintained, but with no additional effect, between 2017 and 2018.

3.3. Speed distribution

Arterial streets in the intervention area showed very similar speed distributions in all three years (Fig. 5).. However, local streets saw a substantial shift in the speed distribution, towards lower speeds. Speed reductions were seen in two of the three local street data collection sites, but in the untreated third site ('intervention local 2') there were no changes in mean speed (Table 1). This led to a slightly bimodal speed distribution on local streets. The distribution of speeds on streets in the control area was unchanged between 2014 and 2018.

A more pronounced bimodal speed distribution emerged on collector streets in 2017 and 2018 (Fig. 5). At two of the three intervention collector sites, treatments included zebra crossings with grade separation to slow traffic, and speeds at these sites (measured at midblock locations away from specific traffic calming devices) reduced in 2017 and 2018 (Table 1). At the third intervention collector site ('intervention collector 1 b'), there were no crossings and no treatments specifically aiming to slow speeds, although there was some narrowing of the roadway due to new curb separated cycle lanes. There was little change in mean speeds at this third site, though 85th percentile speeds were marginally lower at follow-up.

3.4. Mediation analysis

The mediation analysis for the proportion of the change in traffic volume that was mediated by the change in traffic speed found significant mediation on local streets only. In 2017, 39.1% of the change in volume on local streets was mediated by change in speed, and in 2018 the figure was 31.1%. Analysis of whether changes in speed were mediated by changes in volume found that mediation was either not statistically significant, or not large enough to be meaningful (0.4 km/h effect of mediator on intervention streets in 2017 only, and <0.5 km/h effect of mediator on local streets). Specifically, we found no evidence that reduced traffic volumes had a mediation effect that increased speeds.

3.5. Heavy vehicles

The proportion of heavy vehicles on the sole control area collector street at baseline was unexpectedly high (9.3%) compared with other street types, which ranged from 1.9 to 4.5%. Possible explanations include nearby construction works or traffic diversions that selectively affected heavy vehicles, though we were unable to confirm this. Given this unexpected finding, we did not undertake a difference-in-differences analysis of heavy vehicles. There was no evidence that the proportion of heavy vehicles reduced in the intervention area, including on local streets. The recorded change between 2014 and 2018 in heavy vehicles on intervention area local

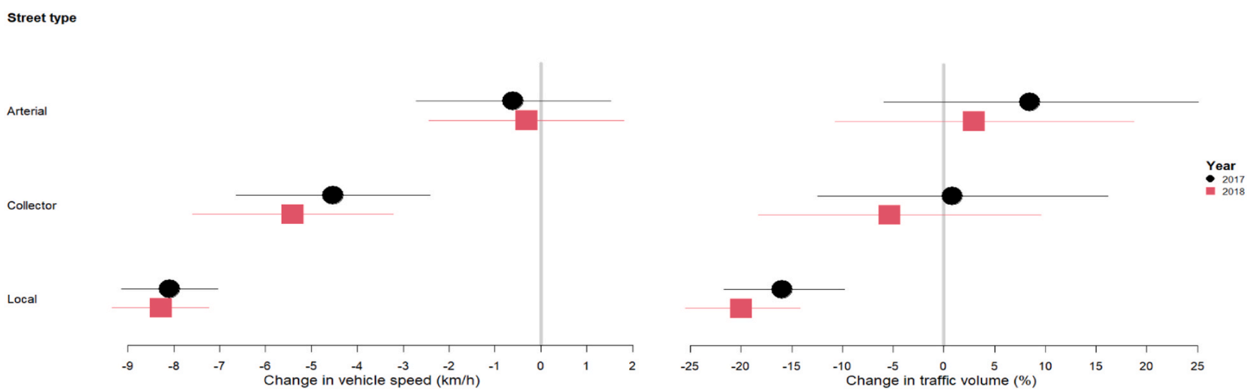

Fig. 4. Difference-in-differences analysis of changes in traffic volume and speed for 2017 and 2018 compared with baseline (2014). Note: Negative values indicate that the change in the intervention area is more strongly negative than the change in the control area.

Table 2
Difference-in-differences analysis of changes in traffic speed and volume, by street type and year.

Street type	Year	Change in traffic speed relative to control area, km/h (95% CI)	Change in traffic volume relative to control area (95% CI)
Arterial	**2017**	−0.60 (−2.73, 1.53)	8.5% (−5.9, 25.1)
	2018	−0.32 (−2.45, 1.81)	3.0% (−10.7, 18.7)
Collector	**2017**	**−4.53 (-6.64, -2.42)**	0.8% (−12.4, 16.1)
	2018	**−5.41 (-7.6, -3.22)**	−5.4% (−18.3, 9.6)
Local	**2017**	**−8.10 (-9.15, -7.05)**	**−16.0% (-21.7, -9.8)**
	2018	**−8.29 (-9.34, -7.24)**	**−20.0% (-25.5, -14.2)**

Note: change s are in comparison to 2014 baseline and represent changes in intervention area relative to control area. CI: confidence interval. Statistically significant results in bold.

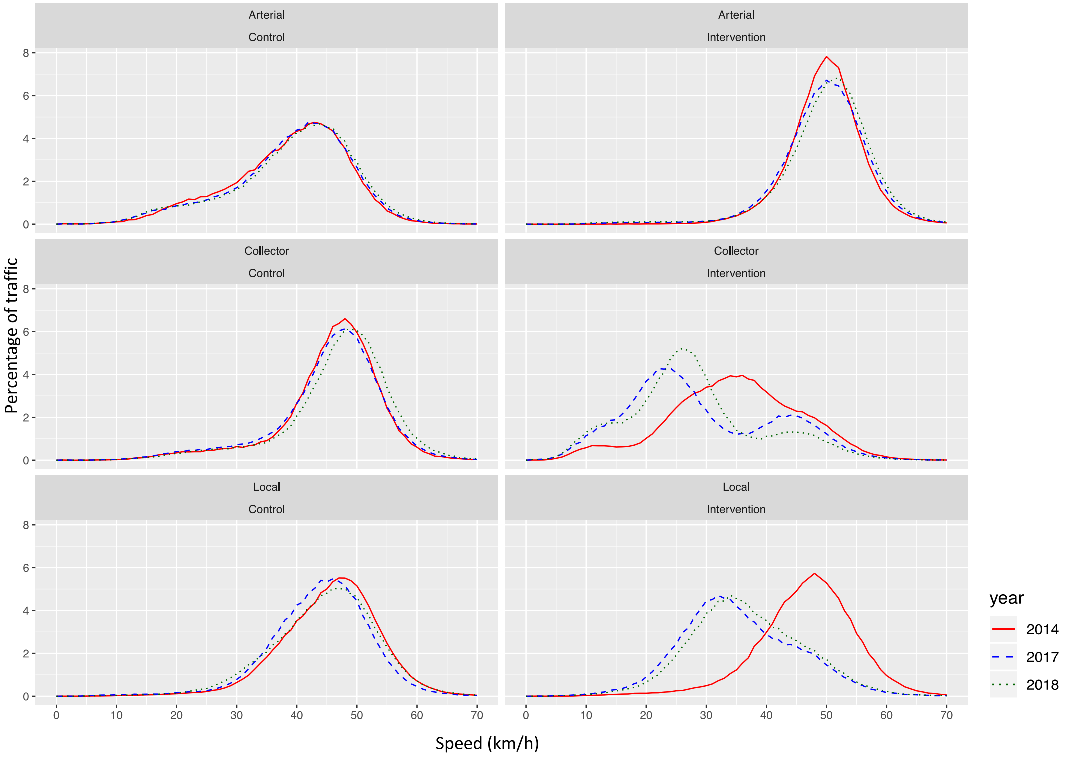

Fig. 5. Changes in traffic speed distribution on arterial, collector and local streets from pre-intervention (2014) to post-intervention (2017 and 2018).

streets (from 1.9% to 2.1%) was minimal, and was smaller than the increase on control area local streets (from 2.6% to 4.1%), but we did not undertake formal statistical significance testing for this comparison.

4. Discussion

4.1. Key findings

This study evaluated the effects of the Te Ara Mua – Future Streets neighbourhood-level street design changes on traffic speeds and volumes. In our follow-up years of 2017 and 2018, we found an 8 km/h mean speed reduction in intervention area local streets, and a 5–6 km/h reduction in speeds in intervention area collector streets, after taking account of the changes seen in the control area. Intervention area traffic volumes reduced by 17–24% on local streets relative to the control area, with no significant changes in traffic volumes on arterials or collector streets. These changes in traffic speed and volume after the intervention are important, because they enable local streets, in particular, to function as intended in the road hierarchy. Post-intervention speeds on local streets were close to 30 km/h, a reduction that should be sufficient to substantially reduce the risk of deaths and serious injuries on these streets, and may also increase people's willingness to walk, cycle and wheel (Amiour et al., 2022; Winters et al., 2017). In keeping with our causal theory and logic model, changes occurred early and were maintained over time. Also consistent with our causal theory, about a third of the reduction in traffic volumes on local streets was mediated through reductions in speeds. Conversely, there was no evidence that traffic volumes had a mediating effect on speeds.

4.2. Comparison with other research

Traffic volume reductions were seen only on local streets in the intervention area, not on arterial or collector streets. Potential mechanisms for traffic volume reductions on local streets include reduced car use by local residents, and diversion of traffic away from local streets (to arterials and collectors, or away from the neighbourhood altogether). There were non-significant increases in traffic volumes on intervention arterials, relative to the control area, which would be consistent with some diversion of traffic from local streets to arterials, though other explanations are possible. Between 2017 and 2018, there were small non-significant reductions in traffic volumes for all three street types in the intervention area. If these reductions had been significant, they would have been consistent with mode shift occurring between 2017 and 2018. However, this study of traffic speed and volume was not designed to conclusively determine whether the intervention reduced car use, and we will investigate this further in future using longitudinal door-to-door surveys of local residents about changes in travel mode (Macmillan et al., 2018). Morrison et al. (2004) and Mackie et al. (2013) also observed more people walking after traffic calming, and Mackie et al. observed lower traffic volumes after traffic calming, but as with our analysis they were unable to conclusively determine whether these findings represented mode shift or other factors such as traffic diversion or trips foregone.

When designing this study, we hypothesised that the Te Ara Mua – Future Streets intervention may lead to mode shift among local residents. However, changes in travel mode may not emerge immediately and may be delayed. Goodman et al. (2014) studied the effect of new or improved walking and cycling routes in three UK towns, and found increases in walking, cycling and physical activity at two-year follow up, but not at one-year follow up. In contrast, the evaluation of mini-Hollands in London (Aldred et al., 2021) found similar increases in active travel, relative to control areas, at one, two and three year follow-up. Changes in speed have previously been shown to occur shortly after traffic calming measures have been constructed (Charlton et al., 2010).

4.3. Strengths

A major epidemiological strength of this study was the inclusion of a well-matched but also well-separated control area. Many evaluations of natural experiments are highly susceptible to confounding, and matching of control areas is considered particularly important (Knapp et al., 2019). Our control area allowed us to account for background trends in traffic volume, an important feature since many of the control area streets experienced increases in traffic volume over the course of this study. Had this comparison not been available, we would have underestimated the effects of the intervention on traffic volume. Inclusion of a third time point also provided further information about the trajectory of change, identifying that changes occurred between the first two time points, and were sustained between the second and third time points. Evaluations of natural experiments that include more than two time points are uncommon (Knapp et al., 2019). An additional strength of this project is measurement of a wide range of different outcomes. Future publications from Future Streets, reporting different outcomes, will help assess whether the local street traffic volume changes we observed were due to mode shift or traffic diversion, and will also investigate intervention effects on other relevant health, social and environmental outcomes, as well as enabling the epidemiological testing of feedback mechanisms, including the relationship between mode share and vehicle speed and volume. Other strengths of the broader Future Streets project include having a clearly defined *a priori* causal theory, participatory intervention co-design and a strong equity focus (Macmillan et al., 2018).

4.4. Limitations

This study was limited by having only a small number of measurement sites for each street type. Nevertheless, our measurements were sufficient to identify substantial reductions in traffic speeds and volumes on local streets. Results also suggested that the intervention effect was likely to be largely limited to local streets in the intervention area that were treated, since the sole untreated local street in the intervention area, 'intervention local 2', saw no reductions in traffic speed or volume between 2014 and 2017. This finding also suggested that the traffic volume reductions seen on other local streets during this period were more likely to be due to traffic diversion rather than community-wide mode shift. Although traffic diversion from local to arterial streets shifts traffic-related hazards (e.g. air pollution, noise, traffic danger) from one location to another rather than reducing those hazards, diversion may be associated with some benefits, particularly if it increases the perceived safety and walkability of local streets. Shifting traffic from local to collector or arterial roads may also help reinforce a street hierarchy in which different street categories within the hierarchy have a more distinct 'look and feel', helping to encourage driver behaviour that is appropriate for the street on which they are driving, consistent with the principles of self-explaining roads (Charlton et al., 2010). While there may be equity implications of diverting traffic and traffic-related hazards from local to arterial streets, this will be influenced by a complex mix of factors, including land and property values and the presence/absence of formal infrastructure, such as public transport routes, separated cycle lanes or raised crossings (Wen et al., 2020; Welch et al., 2016; Grimes and Young, 2010). A clearer picture of traffic distribution effects within neighbourhoods could be gained by monitoring traffic on all or most neighbourhood streets, but assessing whether mode shift is occurring is likely to require direct survey measurements of resident travel patterns, as is being undertaken in the wider Future Streets project (Macmillan et al., 2018).

4.5. Implications for practice and future research

Our findings suggest that suburban street retrofitting can be an effective strategy for reducing traffic speeds and volumes on local residential streets. As both traffic speeds and volumes are strongly correlated with road traffic injury risk, this is likely to substantially improve road safety on local streets. The successful implementation of this project in a relatively deprived neighbourhood indicates opportunities to reduce inequities in road traffic injuries by implementing similar interventions in other disadvantaged neighbourhoods, although this may need to be supplemented by compelling community engagement about the rationale for traffic speed and volume reduction on local streets. We plan to specifically measure effects on crash and injury rates in future research. Although we found evidence of speed reduction on local streets that received treatments, we did not observe speed reductions on a local street that was within the intervention area but was not itself treated. This suggests that area-wide speed reductions would require more widespread street design changes than we were able to implement within our project budget, or that area-wide changes in driver behaviour may take longer to emerge than the time period covered by this analysis.

5. Conclusions

The Te Ara Mua – Future Streets suburban street retrofit project reduced traffic speeds and volumes on local residential streets, and reduced speeds on collector streets, reinforcing a more organised and functional street hierarchy. These changes are expected to improve road safety and reduce barriers to walking and cycling on those streets. There are some signs that traffic volume reductions may be due to traffic being diverted away from local streets. Our findings suggest that deliberate application of a street hierarchy can lead to more appropriate behaviours by people driving on local streets, supporting road safety and active travel. Future papers from this project will investigate longer-term project impacts, including travel mode shift, as well as effects on injury rates, local air quality and other health and social outcomes.

Funding

This work was supported by the Ministry of Business, Innovation and Employment [grant number MRACO1501]. The funder had no involvement in the collection, analysis and interpretation of data, in the writing of the report, or the decision to submit the article for publication.

CRediT authorship contribution statement

Jamie Hosking: Conceptualization, interpretation, Writing – original draft. **Hamish Mackie:** Conceptualization, Investigation, interpretation, Writing – review & editing. **Alex Macmillan:** Conceptualization, interpretation, Writing – review & editing. **Bert van der Werf:** Formal analysis, interpretation, Data curation, Writing – review & editing. **Melody Smith:** Conceptualization, interpretation, Writing – review & editing. **Karen Witten:** Conceptualization, interpretation, Writing – review & editing. **Alistair Woodward:** Conceptualization, interpretation, 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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jth.2023.101601.

References

Aldred, R., Croft, J., Goodman, A., 2019. Impacts of an active travel intervention with a cycling focus in a suburban context: one-year findings from an evaluation of London's in-progress mini-Hollands programme. Transport. Res. Pol. Pract. 123, 147–169.
Aldred, R., Woodcock, J., Goodman, A., 2021. Major investment in active travel in Outer London: impacts on travel behaviour, physical activity, and health. J. Transport Health 20, 100958.
Amiour, Y., Waygood, E.O.D., van den Berg, P.E.W., 2022. Objective and Perceived Traffic Safety for Children: A Systematic Literature Review of Traffic and Built Environment Characteristics Related to Safe Travel. International Journal of Environmental Research and Public Health (accessed.
Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Software 67 (1), 1–48.
Bollen, K.A., Stine, R., 1990. Direct and indirect effects: classical and bootstrap estimates of variability. Socio. Methodol. 20, 115–140.
Bunn, F., Collier, T., Frost, C., Ker, K., Roberts, I., Wentz, R., 2003. Traffic calming for the prevention of road traffic injuries: systematic review and meta-analysis. Inj. Prev. : journal of the International Society for Child and Adolescent Injury Prevention 9 (3), 200–204.
Card, D., Krueger, A.B., 2000. Minimum wages and employment: a case study of the fast-food industry in New Jersey and Pennsylvania: reply. Am. Econ. Rev. 90 (5), 1397–1420.
Charlton, S.G., Mackie, H.W., Baas, P.H., Hay, K., Menezes, M., Dixon, C., 2010. Using endemic road features to create self-explaining roads and reduce vehicle speeds. Accid. Anal. Prev. 42 (6), 1989–1998.

Elvik, R., 2012. Speed limits, enforcement, and health consequences. Annu. Rev. Publ. Health 33 (1), 225–238.

Global Road Safety Partnership, 2008. Speed Management: a Road Safety Manual for Decision-Makers and Practitioners. Global Road Safety Partnership, Geneva.

Goodman, A., Sahlqvist, S., Ogilvie, D., oboti, Consortium, 2014. New walking and cycling routes and increased physical activity: one- and 2-year findings from the UK iConnect study. Am. J. Publ. Health 104 (9), e38–e46.

Greenland, S., Pearl, J., Robins, J.M., 1999. Causal diagrams for epidemiologic research. Epidemiology 10 (1), 37–48.

Grimes, A., Young, C., 2010. Anticipatory Effects of Rail Upgrades: Auckland's Western Line. Motu Economic and Public Policy Research, Wellington.

Grundy, C., Steinbach, R., Edwards, P., Green, J., Armstrong, B., Wilkinson, P., 2009. Effect of 20 mph traffic speed zones on road injuries in London, 1986-2006: controlled interrupted time series analysis. BMJ 339, b4469.

Hartig, F., 2021. DHARMa: residual diagnostics for hierarchical (Multi-Level/mixed) regression models. R package version 0.4.1. https://CRAN.R-project.org/package=DHARMa.

Hicks, R., Tingley, D., 2011. Causal mediation analysis. STATA J. 11 (4), 605–619.

Hirsch, L., Mackie, H., Crombie, C., Bolton, L., Wilson, N., Cornille, Z., 2022. Road user interaction changes following street improvements from Te Ara Mua – future Streets: a case study. J. Transport Health 25, 101384.

Hosking J, Woodward A, Macmillan A, Jones R, Ameratunga S, Smith M. Can Transport Interventions Contribute to Health Equity? A Systematic Review of whether the Effects of Transport Interventions Differ by Ethnicity and Socio-Economic Status. (submitted for publication.

Knapp, E.A., Bennett, W.L., Wilson, R.F., et al., 2019. Methods and risks of bias in natural experiments in obesity: opportunities for the future informed by a systematic review. Obesity 27 (12), 1950–1957.

Mackie, H.W., Charlton, S.G., Baas, P.H., Villasenor, P.C., 2013. Road user behaviour changes following a self-explaining roads intervention. Accid. Anal. Prev. 50, 742–750.

Mackie, H., Macmillan, A., Witten, K., et al., 2018. Te Ara Mua - future Streets suburban street retrofit: a researcher-community-government co-design process and intervention outcomes. J. Transport Health 11, 209–220.

Macmillan, A., Connor, J., Witten, K., Kearns, R., Rees, D., Woodward, A., 2014. The societal costs and benefits of commuter bicycling: simulating the effects of specific policies using system dynamics modeling. Environ. Health Perspect. 122 (4), 335–344.

Macmillan, A.K., Mackie, H., Hosking, J.E., et al., 2018. Controlled before-after intervention study of suburb-wide street changes to increase walking and cycling: Te Ara Mua-Future Streets study design. BMC Publ. Health 18 (1), 850.

Macmillan, A., Smith, M., Witten, K., et al., 2020. Suburb-level changes for active transport to meet the SDGs: causal theory and a New Zealand case study. Sci. Total Environ. 714, 136678.

Morrison, D.S., Thomson, H., Petticrew, M., 2004. Evaluation of the health effects of a neighbourhood traffic calming scheme. J. Epidemiol. Community 58 (10), 837–840.

Peden, M., Scurfield, R., Sleet, D., et al., 2004. World Report on Road Traffic Injury Prevention. World Health Organization, Geneva.

R Core Team. R, 2020. A language and environment for statistical computing. https://www.R-project.org.

Raerino, K., Macmillan, A., Field, A., Hoskins, R., 2021. Local-indigenous autonomy and community streetscape enhancement: learnings from Māori and Te Ara mua—future streets project. Int. J. Environ. Res. Publ. Health 18 (3), 865.

Stats NZ - Tatauranga Aotearoa, 2001. Main means of travel to work, for the employed census usually resident population count aged 15 years and over, 2006, and 2013 Censuses. 2020. http://nzdotstat.stats.govt.nz/wbos/Index.aspx?DataSetCode=TABLECODE8180#. (Accessed 15 December 2020).

Theeuwes, J., Godthelp, H., 1995. Self-explaining roads. Saf. Sci. 19 (2), 217–225.

Tin Tin, S., Woodward, A., Robinson, E., Ameratunga, S., 2012. Temporal, seasonal and weather effects on cycle volume: an ecological study. Environ. Health 11 (1), 12.

Welch, T.F., Gehrke, S.R., Wang, F., 2016. Long-term impact of network access to bike facilities and public transit stations on housing sales prices in Portland, Oregon. J. Transport Geogr. 54, 264–272.

Wen, H., Gui, Z., Zhang, L., Hui, E.C.M., 2020. An empirical study of the impact of vehicular traffic and floor level on property price. Habitat Int. 97, 102132.

Winters, M., Buehler, R., Götschi, T., 2017. Policies to promote active travel: evidence from reviews of the literature. Current Environmental Health Reports 4 (3), 278–285.

World Health Organization, 2012. Health in the Green Economy: Health Co-benefits of Climate Change Mitigation. Transport Sector. World Health Organization, Geneva.