Traffic calming: effects on emissions and air quality

Literature review

Prepared for Emission Impossible

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1 Introduction

1.1 Background

EMM has been commissioned by Emission Impossible, on behalf of Auckland Transport and Waka Kotahi, to review the effects of physical traffic calming measures (including intersection treatments) on vehicle exhaust emissions. This report presents the findings of the review. The review covers both greenhouse gases (GHGs) and the pollutants that are relevant to local air quality.

The review has been designed to support Auckland Transport's Speed Management Plan by providing information on the co-benefits of speed-reduction measures, and to inform the selection of specific measures.

1.2 Objectives of review

The review aims to address the following questions:

- what are the effects of physical traffic calming measures on emissions, when considering the changes in vehicle operation?
- what are the effects of different intersection treatments (eg roundabouts, traffic signals) on emissions?
- which types of traffic calming measure are best for emissions, and how can schemes be designed to mitigate any adverse impacts (eg spacing, profile, material used)?
- how do traffic calming measures impact local air quality?
- would it be feasible to develop a method, tool or model to test different traffic calming scenarios?

1.3 Reviewing approach

The review of traffic calming considered the literature available online, and was comprehensive in its coverage. The focus was on research papers in scientific journals (through ScienceDirect) that provided primary, quantitative evidence, but given the relatively limited scientific literature the scope was extended to include the grey literature such as research reports (notably from the Transport Research Laboratory in the UK). Any literature more than 25 years old, or unavailable online, was not reviewed. It is worth noting that a detailed review was conducted by NCCHPP (2011), and the literature cited in that document is also summarised in our review.

For intersection treatments there is a significant amount of literature, and it was not feasible to conduct a comprehensive review within the study. The results from a limited selection of broadly representative studies were therefore considered.

1.4 Structure of review

The remainder of this review is structured as follows:

- Chapter 2 provides a brief overview of the principles involved, to provide context for the review, including types of traffic calming and intersection treatment, the mechanisms by which these influence emissions from vehicles and traffic, and typical assessment methods;
- Chapter 3 summarises the literature on traffic calming and intersection treatment, as these relate to emissions and air quality; and
- Chapter 4 provides the summary and conclusions of the review.

2 Overview of principles

2.1 Traffic calming

Traffic calming is the use of physical measures to control vehicle speed and traffic volume, thus improving the safety of pedestrians. Traffic calming measures are therefore often implemented in residential areas. They may be implemented on isolated roads, or as a combination of different devices in an area-wide approach.

Traffic calming measures typically involve vertical and/or horizontal deflections of the vehicle path, as well as other devices, and some examples are provided in Table 2.1. It is worth noting the following here:

- The terminology in the literature relating to traffic calming is inconsistent. In this review, we have used the terms for specific measures in Table 2.1. Where an alternative term has been used in an original document, this has been changed to ensure more consistency in the review (for example, one document referred to speed cushions as 'speed lumps').
- In principle, a mini-roundabout could be classified as a traffic calming measure or an intersection treatment. For the purpose of this report, mini roundabouts have been classified as traffic calming measures. This is partly because, as with other traffic calming measures, they are typically implemented on minor roads without traffic signals, and partly because various studies in the literature have effectively considered them to be traffic calming.

Various measures are also described in the Auckland Transport Speed Management Toolbox (Parts A, B and C) and in the Waka Kotahi standard safety intervention toolkit[1].

2.2 Intersection treatment

In this review, intersection treatments are considered for larger junctions where traffic signals or larger roundabouts would be appropriate. This could encompass many different approaches, including the following:

- installing new traffic signals at a junction;
- replacing a roundabout with traffic signals (or vice versa);
- junction realignment;
- improved signal phasing;
- signal coordination (eg 'green wave'); and
- priority lanes.

A detailed evaluation of these various aspects was beyond the scope of the review. Instead, the review highlights a limited number of studies and provides some general findings.

1 https://www.nzta.govt.nz/resources/standard-safety-intervention-toolkit/

Table 2.1 Examples of traffic calming measures

General approach	Specific measure	Description and intended effect
Vertical deflection	Road hump	Raised, rounded section of road (typically up to 100 cm high). Used to slow traffic down on approach in order to be safely navigated. Sometimes referred to as 'speed hump' in the literature.
	Speed bump	Raised areas across the road that is typically less than around 0.3 m in width and is crossed at very low speed.
	Speed cushion	Similar to road hump, but narrower to allow larger vehicles to pass unaffected. Sometimes referred to as 'speed lump' in the literature.
	Speed table	Similar to road hump, but with a longer, flat top (typically 6-9 m long). Can be combined with a pedestrian crossing, and can be used at an intersection on a minor road.
	Textured pavement	Often used in high pedestrian areas to indicate to drivers that they are on a shared road. This shared road system means that drivers need to have a greater awareness of their surroundings and maintain a lower speed.
	Rumble strip	Strip that is placed across the road to induce a vibration in the vehicle which alerts the driver.
Horizontal deflection	Road narrowing	Street is narrowed to reduce vehicle speed and allow more space for pedestrians, cyclers or green infrastructure.
	Chicane	Typically an S-shaped curve in the road, either produced by the road path itself or raised islands in the road. Can either be one-way or two-way.
	Pinch point	Narrowed sections of road, often made by raised boundaries which extend from the side of the road and only allows the passage of one vehicle at a time.
	Pedestrian island	A built-up section of the road separating opposing traffic. Can be used to shift the travel path or visually narrow the width of the road, inducing drivers to reduce their speed. Also provides a safer way for pedestrians to cross the road.
	Mini-roundabout	A round island at an intersection that is used to both reduce speed and organise traffic.

2.3 How measures affect emissions

The main factors that govern emissions (and fuel consumption) are the vehicle type, the fuel used, the vehicle technology, and the driving conditions. Other factors include vehicle weight, road gradient, vehicle load and the use of auxiliary equipment such as air conditioning.

With respect to traffic calming and intersection treatments, vehicle operation is one of the most important considerations. For example, traffic calming measures have a distinct influence on vehicle operation that often involves a reduction in speed and more frequent changes in speed, and these can lead to increases in both fuel consumption and emissions. The severity of a traffic calming measure will affect the speed reduction achieved at the measure. The number of measures employed on a given length of road should also be an important factor in determining changes in emissions, since whatever effect one measure has on emissions, the effect can be magnified if more measures are employed. However, the spacing can also be defined so that a low speed is maintained.

The considerations mentioned above for traffic calming are also relevant to the assessment of signalised intersections and roundabouts, although in these cases the effects of stopping and idling time also need to be taken into account.

2.4 How impacts have been assessed

Various methods have been employed in the literature to assess the impacts of traffic calming and intersection treatment on emissions and air quality. These have typically involved direct measurement, modelling, or a combination of both.

Emissions have been measured in situ by equipping vehicles with portable emissions measurement systems (PEMS), or using remote sensing systems. An alternative approach has involved instrumenting vehicles to measure driving patterns in situ, and then using these driving patterns to develop driving cycles which can be used as the basis for emission measurement on vehicles in a laboratory (using a chassis dynamometer).

The driving patterns can also be used as the input to emission models. The relationships between emissions and average trip speed are well-established, and various emission models use these relationships. However, average speed models are not very well suited to the evaluation of traffic calming measures, and cannot be used to specifically analyse idling as a separate event (eg at signalised intersections). The concept of 'driving dynamics' has therefore been developed to enable model developers to describe vehicle operation using additional parameters. In qualitative terms, dynamics can perhaps be thought of as the 'aggressiveness' of driving, involving a more precise description of vehicle operation (eg rates of acceleration and deceleration) and emission behaviour during a series of short time steps (often one second). This information commonly forms the basis of 'microscale' emission models, in which emissions can be calculated for any operational profile. Microscale emission models have been used to assess traffic calming in some studies, and have also been used in conjunction with traffic models.

In a limited number of studies the impacts of traffic calming on air quality have been measured, typically using relatively low-cost samplers, or estimated using an atmospheric dispersion model.

In general, the literature has focussed on the pollutants that are regulated at vehicle type approval: carbon monoxide (CO), nitrogen oxides (NO_X), hydrocarbons (HC) and particulate matter (PM). In some cases, unregulated pollutants have been considered, such as specific hydrocarbon compounds. In relation to GHGs, the main pollutant that has been reported is CO_2.

3 Literature review

3.1 Traffic calming

The effects of traffic calming on the environment have been studied since around the early to mid-1990s. In the following sections we have summarised the literature relating to GHG emissions, air pollutant emissions and near-road air quality. Much of the early work was conducted by the UK Transport Research Laboratory (TRL) between around 1995 and 2005, and involved reviews, the measurement of driving patterns, laboratory emission tests, remote sensing of emissions, emission modelling and air quality monitoring. However, the TRL work necessarily focused on the vehicles that were in circulation at the time (mostly up to Euro 1 for light vehicles and Euro III for heavy vehicles). Advancements in emission-control technology mean that the results of the TRL work (and other studies of the time) are probably less relevant in 2022. Nevertheless, the findings have been summarised here for completeness. Some of the information presented below has also been taken from the literature review by NCCHPP (2011).

3.1.1 Greenhouse gas emissions

Several initial TRL investigations used real-world driving patterns in combination with a microscale emission model (MODEM) for passenger cars. For example, Cloke et al (1999) investigated the area-wide effects of speed cushions in the Leigh Park Area Safety Scheme in Havant, Hampshire. It was found that there was a net reduction in emissions from the traffic on roads with traffic calming measures. This was despite the fact that emissions per vehicle-km were adversely affected by changes in vehicle operation. For cars, the changes in vehicle operation led to an increase in CO_2 emissions per vehicle-km of around 10%. However, traffic diversion onto roads within, and outside, the scheme had a greater effect on vehicle emissions than the change in driving patterns. When the changes in traffic volume were taken into account, and including an estimate of the effects on emissions from heavy-duty vehicles (HDVs) based on average speed, daily emissions on links with speed cushions reduced by around 10%. When summated over all the links covered by the scheme, total daily CO_2 emissions were found to have reduced by 8%.

In a similar study, TRL monitored the environmental effects of the Gloucester Safer City Project (Boulter et al 2003). The Safer City Project involved a city-wide approach to controlling traffic speed, and included a range of traffic management and traffic calming measures. The monitoring started in 1996, and continued until 2002. A link-based approach was used to examine the evolution of exhaust emissions from road traffic on main roads in the city. Driving patterns and emissions from vehicles and traffic were determined for each year. Emissions from cars were estimated using the MODEM model, and emissions from HDVs were calculated based on average speed. The introduction of the measures resulted in an increase in CO_2 emissions of 2%. However, there were no significant differences between the changes in overall traffic emissions on links where measures had been introduced and the changes on unaffected links.

TRL also measured the impacts of traffic calming on exhaust emissions from cars (Boulter et al 2001). The study involved the development of driving cycles for vehicles passing through nine different types of traffic calming scheme, followed by measurements of emissions in the laboratory using a chassis dynamometer. The laboratory measurements were conducted on twelve petrol cars (pre-Euro 1 and Euro1) and three diesel cars (Euro 1). Exhaust emissions of CO_2 were measured in each test, as well as regulated pollutants.

The results clearly indicated that the traffic calming measures increased the emissions of CO_2 per vehicle-km:

- for pre-Euro 1 petrol cars, CO_2 emissions increased by between 7% and 28%.
- for Euro 1 petrol cars, CO_2 emissions increased by between 18% and 38%.
- for Euro 1 diesel cars, CO_2 emissions increased by between 15% and 40%.

The more 'severe' traffic calming measures (eg road humps) tended to result in the greatest speed reductions and the largest increases in emissions. Speed cushions and horizontal deflections (excluding mini roundabouts) tended to result in the smallest increases in emissions.

The results of a large TRL test program were report by Latham et al (2005). TRL measured emissions from HDVs over a range of traffic management/calming and other driving cycles, and developed a predictive emission model for the evaluation of schemes. The project involved measurements on 50 different vehicles, including HGVs ranging from 7.5 tonne trucks up to 44 tonne articulated vehicles, midi-buses, single-decker buses and double-decker buses. In addition to the different vehicle types, vehicles compliant with different emissions legislation were tested – ranging from pre-Euro I to Euro IV. For HGVs and buses, average emission factors were determined, normalised to vehicle weight. However, the study did not provide information on the actual effects of specific measures, and these can only be inferred from the report. For example, for HGVs and buses, CO_2 emissions over the 'road humps' cycle were approximately 10% higher than emissions over an 'urban non-congested' control cycle. Similar inferences could be made for other types of traffic calming and pollutants, although this would require some effort.

In another UK study, Daham et al (2005) equipped a Euro 1 petrol car with PEMS to measure the effects of speed cushions on emissions under real-world driving conditions. The results for a road with speed cushions were compared with those for a non-calmed road with the vehicle driven at a similar average speed. The speed cushions were associated with an increase in CO_2 emissions of 90%. The increase in CO_2 was larger than the increases reported by TRL. However, it is worth noting that the test vehicle was quite heavy due to onboard equipment, and an aggressive driving style was employed, whereby the vehicle slowed down more than was necessary when traveling over the cushions (the car was slowed down to 16 km/h at the speed cushions and accelerated to 32-48 km/h after the cushions).

Ahn & Rakha (2009) investigated the impacts of traffic calming on routes in Arlington and Ashburn, Virginia. In the first part of the study ('corridor' analysis), the authors compared various measures (intersection with 'stop' signs, roundabouts and road humps) with a control road on the same route. In the second part of the study, they investigated conditions before and after the installation of speed cushions and speed bumps on specific roads ('before and after' analysis). The study combined second-by-second 'floating-car' global positioning system (GPS) data with a microscale emission model (VT-micro). Traffic calming driving cycles for use in the model were developed using the GPS data. The study focussed primarily on a 'composite' petrol LDV made up of six typical cars and three typical light commercial vehicles. In the corridor analysis, the signed intersection resulted in a 114% increase in fuel consumption relative to the control road. The roundabouts led to a 35% increase in CO_2 emissions, whereas the road humps were responsible for a 52% increase. In the before and after analysis, CO_2 emissions increased by 48% when speed cushions were implemented, whereas speed bumps increased emissions by 29%. The authors also modelled a generic 'low-emitting vehicle' and a generic 'high-emitting vehicle', although the relative increases in emissions from these were consistent with those for the composite vehicle.

Ghafghazi (2013) investigated the effects of road humps, speed bumps and a 30 km/h speed limit on a road network in Montreal, Canada. A microsimulation model of the road network was developed, driven by a regional traffic assignment model. The Motor Vehicle Emissions Simulator (MOVES) was used to calculate emissions of CO, NO_X and CO_2 from traffic, and the Operational Street Pollution Model (OSPM) was used to calculate near-road concentrations of NO_2. Eight scenarios were tested, with different configurations of measures on single road corridors and across the network, and the results were compared with those for a base case with a network-wide speed limit of 50 km/h. Total VKT on the network decreased slightly due to the implementation of traffic calming. In spite of this decrease, network-wide emissions increased slightly. For measures on isolated corridors, network-wide emissions of CO_2 increased by 1.5%. For the area-wide measures, network-wide emissions of CO_2 increased by 4%. However, on the roads with traffic calming the increases in emissions were more substantial. For example, implementing speed bumps along isolated corridors increased CO_2 emissions along the corridors by 15-81%, depending on the road. Speed bumps resulted in higher increases in emissions than road humps. This was because speed bumps required a slowing down to 5 km/h, whereas the road humps only required a reduction to 25 km/h.

The study by Jazcilevich et al (2015) considered the effects of speed bumps on a secondary road in Mexico City. A PEMS was installed in four vehicles: a petrol pick-up truck, a diesel bus, an LPG minibus and a petrol car. These represented the main vehicle types in the study area. Emissions of CO, HC, NO_X, PM_{10} and CO_2 were measured continuously along routes on similar streets with and without speed bumps. In general, increases in emissions were measured as a result of traffic calming. For CO_2, emissions increased by between 31% and 58%, depending on the vehicle type.

Ribeiro (2015) conducted a study into a wide variety of traffic calming devices, including speed tables, road humps, continuous sidewalks and textured pavements within an urban neighbourhood in the city of Lisbon. The effects of the measures on emissions were measured by equipping a passenger car (diesel, Euro 4) with a portable gas analyser, and comparing the roads with traffic calming with comparable control roads. For all the traffic calming measures there was a reduction in speed that ranged from 20% to 36%. In most cases this led to an increase in CO_2 emissions compared with the control case. Speed tables located in a 30 km/h zone resulted in the largest increase in CO_2 emissions (107%). However, another speed table on a road with a 50 km/h speed limit showed a reduction in CO_2 emissions of 6%, and road humps were also associated with a small reduction in CO_2 (3%).

An assessment of the geometry and spacing between road humps and speed tables was reported by Obregón-Biosca (2020). The methodology involved floating car measurements of vehicle operation, and microsimulation traffic modelling using AIMSUN. Emissions were also calculated using algorithms in AIMSUN. The results indicated that the size and shape of the traffic calming devices were the most important factors for reducing speed. The most efficient cases achieved reductions in speed of 50% to 70% for road humps and 10% to 65% for speed tables. Only limited information on emissions was provided. The author recommended that spacing between traffic calming devices should be no less than 100 m to allow for consistent acceleration and deceleration, and to minimise emissions. It was found that when an optimised spacing of 389 m was used for speed tables, there was an average reduction in CO_2 emissions of around 6%.

The effects on emissions of various hypothetical configurations for flat-top road humps were evaluated by Pérez-Sansalvador et al (2020). The authors used a microscale traffic and emissions model to determine emissions of CO_2, NO_X, VOC and PM. For simplicity, only light-duty petrol vehicles were considered. The relative effects of different traffic calming configurations were not reported. However, it was noted that for roads with a low number of vehicles, road humps greatly increase CO_2 emissions (as well as NO_X and PM).

Electric vehicles (EVs) are likely to become more prevalent in the fleet in the coming decades, and so the impact of traffic calming devices on their energy consumption is worth considering. In the study by Donkers et al (2020), the effects of several factors – including traffic calming – on EV energy consumption were assessed using a microscale model. The study area included urban roads in the city of Nieuwegein in the Netherlands. Three types of driving style were simulated (eco-driver, normal driving, and aggressive driving). When examining the effects of traffic calming (speed bumps in a 30 km/h zone, with an 80% speed reduction), it was found that, across the three driving styles, there was an average increase in energy consumption (kWh) of between 132% (eco-driver) and 371% (aggressive driver). Stopping at traffic lights from 30 km/h gave an increase in energy consumption of between 62% (eco-driver) and 163% (aggressive driver).

3.1.2 Air pollutant emissions

An early review by TRL (Boulter and Webster 1997) concluded that studies of the effects of traffic calming based on single sections of road had produced a wide range of results. This was particularly evident in the case of NO_X, for which some studies showed decreases of up to 30%, whilst others showed large increases. It was suggested that the variation in these results may have been due to both the variability of emission measurements performed on test vehicles (including those used to develop models) and the different techniques employed in the studies.

TRL investigated the effects of traffic calming on CO emissions using remote sensing (Boulter 1999). Remote sensing surveys were conducted before and after the introduction of flat-top road humps and speed cushions at residential road locations in Gloucester (UK). During each survey the speed, acceleration, and levels (% by volume) of carbon monoxide (CO) in the exhaust plumes of many individual vehicles were measured. The mean speed on the roads where humps had been installed was reduced from 45 km/h before calming to 27 km/h near one of the humps, and to 33 km/h at a site between humps. For speed cushions the mean speed was reduced from 43 km/h before calming to 36 km/h between cushions, and 24 km/h near the cushions. The mean %CO in the exhaust gas recorded near the hump and between humps were higher than the level recorded before calming by 30% and 38% respectively. The increases in the mean %CO near and between speed cushions were 32% and 20%. It was estimated that traffic calming would cause the average *mass* of CO emitted per vehicle-km to increase by between 50% and 73%.

Several of the studies mentioned in Section 3.1.1 also included emissions of local air pollutants. For example, in the Havant modelling study by Cloke et al (1999), speed cushions led to an increase in car emissions per vehicle-km of CO and HC of around 20%, and a decrease in NO_X of about 10%. When the changes in traffic volume were taken into account, daily emissions on links with speed cushions reduced by around 10% for CO and HC, and by around 20% for NO_X. When summated over all the links covered by the scheme, daily emissions were found to have reduced by 6% for CO, 5% for HC, and 15% for NO_X.

The TRL study by Boulter et al (2001) also included measurements of emissions of CO, HC, NO_X and PM (diesel vehicles only). The effects on CO and HC emissions per vehicle-km were variable. For NO_X emissions, only the diesel cars showed a consistent increase (between 17% and 39%, depending on the type of measure). The effects on NO_X emissions from petrol cars included increases and decreases, and tended to be smaller. Emissions of PM from the diesel cars changed by between -1% and +82%, depending on the type of measure. As with CO_2, the more 'severe' traffic calming measures usually resulted in the largest increases in emissions.

For the Gloucester Safer City Project, Boulter et al (2003) found that the introduction of the safety measures equated to average increases in CO and HC emissions per vehicle-km (cars) of 4.4% and 4.9% respectively, and a decrease in NO_X emissions of 1.5%. However, there were no significant differences between the changes in overall traffic emissions on links where measures had been introduced and the changes on unaffected links.

In the PEMS study by Daham et al (2005), emissions from a Euro 1 petrol car increased when driven on a road with speed cushions compared with a non-calmed road. The increases were 117% for CO, 148% for HC and 195% for NO_X. Emissions of five unregulated hydrocarbon compounds (toluene, formaldehyde, acetaldehyde, 1,3-butadiene and benzene) also increased significantly.

In the corridor analysis by Ahn & Rakha (2009) emissions of CO, HC and NO_X from the composite LDV increased by 20%, 31% and 56% due to roundabouts. Road humps were responsible for increases of 44%, 51% and 110%, respectively. In the before and after analysis, speed cushions led to increases in CO, HC and NO_X of 47%, 54% and 98%, respectively. Speed bumps resulted in additional emissions of 9% for CO, 20% for HC and 19% for NO_X.

In the study by Ghafghazi (2013) in Montreal, for measures on isolated corridors the network-wide emissions of CO and NO_X increased by 0.3% and 1.4%, respectively. For the area-wide measures, network-wide emissions of CO and NO_X increased by 1.2% and 2.2%, respectively. No results for CO and NO_X emissions on isolated corridors were reported.

Jazcilevich et al (2015) found that speed bumps on a secondary road in Mexico City generally caused emissions of CO, HC, NO_X and PM_{10} to increase. For the four types of vehicle in the study, CO emissions increased by between 20% and 135%. For HC, the change was between -3% and +42%. For NO_X, the change was between -13% to +23%. PM_{10} was only measured for the diesel bus, and a large increase in emissions (670%) was measured.

Ribeiro (2015) found that NO_X emissions from a Euro 4 diesel car increased for a range of traffic calming measures, and most significantly for road humps and speed tables on a road with a 50 km/h speed limit (345% and 263% respectively). Traffic calming in a 30 km/h zone increased NO_X emissions by 92%.

Obregón-Biosca (2020) found that the optimised spacing for speed tables reduced emissions of HC, NO_X and PM by 15%, 6% and 21%, respectively.

3.1.3 Local air quality

Some studies have considered the impacts of traffic calming on near-road air quality, either through direct measurement or modelling. The results from these studies are summarised below.

Air quality impacts were investigated in some of the TRL studies mentioned earlier in the review. For example, Cloke et al (1999) measured the concentrations of benzene and NO_2 using diffusion tubes at four kerbside sites within the Leigh Park traffic calming scheme, as well as at two control sites outside the scheme. After the traffic calming measures had been installed, the adjusted concentrations of benzene and NO_2 within the scheme showed modest reductions (5% and 1%, respectively). Although the changes in benzene concentration on the individual roads within the scheme were not statistically significant, they were consistent with the estimated changes in HC emissions on the corresponding roads. The changes in NO_2 concentration were, however, less consistent with the changes in NO_X emissions, indicating that NO_2 concentrations were not directly related to vehicle activity, but more to local atmospheric chemistry.

Boulter et al (2001) used minimum and maximum changes in emissions due to traffic calming, in conjunction with the DMRB dispersion model, to predict how local air quality would be affected. Concentrations of CO, benzene, 1,3-butadiene, and NO_2 were estimated. For the four pollutants, all the calculated concentrations at distances beyond 10 m from the road centre were well below the national air quality standards. It was noted that, given the volume of traffic on each of the roads in question, air pollution would probably not have been a major problem either before or after calming.

In order to determine the changes in air quality during the multi-year Gloucester Safer City Project, Boulter et al 2003 established a city-wide network of roadside monitoring sites, along with a background site at a local school. CO, benzene, NO_2 and PM_{10} were measured using relatively low-cost equipment. During the Safer City Project, the general reductions in emissions from traffic coincided with good or improving roadside air quality. For example, the concentrations of benzene and NO_2 at the roadside sites decreased significantly during the study. However, the introduction of the safety and traffic management measures did not greatly affect local concentrations. For example, between March and September 2001 traffic calming measures were installed along Hucclecote Road. CO, benzene and NO_2 concentrations were monitored before and after the introduction of the measures. Although concentrations decreased, the changes were not statistically significant. During the period of the Safer City Project, it was considered that changes in vehicle technology and fuel quality were more important determinants of emissions.

Owen (2005) investigated the air quality impacts of six 20 mph zones (including road humps and traffic lights) in the north-west of England. The concentrations of NO_2 and benzene in ambient air were measured using diffusion tubes at three sites within each zone, both before and after implementation, and at control sites outside the zones. An emissions estimation and simple dispersion modelling study was also undertaken using traffic survey data collected in the zones. The ambient air quality measurements and the modelling predictions did not show any significant impacts of the 20 mph zones.

The air quality modelling by Ghafghazi (2013) showed that traffic calming had a smaller effect on concentrations of NO_2 than on NO_X emissions. On average, near-road NO_2 levels increased between 0.1% and 9% with respect to the base case. Speed bumps produced larger increases in NO_2 levels than road humps.

Studies conducted by Baltrenas et al (2017) and Januševičius et al (2019) examined the changes in roadside air quality due to prefabricated speed bumps and asphalt road humps at 10 similar sites in Lithuania. Pollutant concentrations were measured using a mobile laboratory before and after the installation of the traffic calming devices, as well as at control sites. Baltrenas et al (2017) measured PM_{10} using a beta-attenuation monitor, and found that increases in concentration of around 55-60% occurred at both types of traffic calming device. Januševičius et al (2019) focused on concentrations of NO, NO_2 and CO, and found that there was an increase at each site. For the speed bumps, the NO_2 concentration increased by a factor of 1.7 to 6. The corresponding factors for NO and CO were 1.4 to 10.5 and 1.5 to 5.3, respectively. For the road humps, NO_2 concentration increased by a factor of 1.1 to 2.4. The corresponding factors for NO and CO were 1.6 to 8.9 and 1.3 to 2.6, respectively.

3.2 Intersection treatment

There is a significant amount of literature on emissions associated with signalised intersections and roundabouts. The results from a limited selection of studies are provided below.

In a traffic safety project in the Swedish town of Växjö, 21 intersections on arterial roads were replaced with small roundabouts. One of the intersections was originally signalised, whereas the others were 'yield-regulated'. Várhelyi (2002) investigated the effects of the project on emissions and fuel consumption. Diving patterns were recorded using an instrumented car before and after the changes, and emissions were calculated using a model (petrol cars only, 30% of which were Euro 1 compliant). The results showed that replacing the signalised intersection with a roundabout reduced emissions, whereas replacing the yield-regulated intersections with roundabouts increased emissions as a result of the slowing down of traffic. For the signalised intersection, CO emissions decreased by 29%, NO_X emissions decreased by 21%, and fuel consumption (or CO_2) decreased by 28%. For the yield-regulated intersections, CO emissions increased on average by 4%, NO_X emissions increased by 6%, and fuel consumption (or CO_2) increased by 3%.

In Minnesota, Hallmark et al (2011) equipped a Tier II petrol car with PEMS to compare the impacts of roundabouts, signalised intersections and stop-sign intersections under real-world driving conditions. The measurements were conducted on two road corridors with low volumes of traffic, and only movements across the intersections were considered. The study found that CO_2 emissions for roundabouts were, on average, 2% to 12% lower than those for four-way intersections, but between 25% lower and 21% higher than those for signalised intersections. Stopping is not always required at signalled intersections, and a steady speed can be maintained. The roundabouts were associated with, on average, 14% to 65% lower NO_X emissions than the four-way intersections. However, emissions at the signalised intersections were frequently lower than those at the roundabouts (NO_X and HC emissions were, on average, 51%-22% and 30%-22% lower). CO varied significantly for both the four-way intersections (-46% to 67%) and signalised intersections (-43% to 14%) compared with the roundabouts.

Two other studies have investigated the effects on vehicle emissions of converting a signalled intersection to a roundabout (Mandavilli et al 2003; Meneguzzer at al 2017). The studies used different approaches. Mandavilli used SIDRA to model emissions, and Meneguzzer used direct vehicle measurement (PEMS). In both cases, data were obtained before and after the conversion. A measurable decrease in vehicle emissions was observed in both studies; with the decreases ranging from 13%-59% for CO_2, 21%-42% for CO and 18%-65% for HC. However, different results were obtained for NO_X emissions. While in Mandavilli (2003) a decrease between 18%-65% was observed, in Meneguzzer NO_X emissions were always lower for the signalised intersections, with an average increase of 49% of NO_X recorded for the roundabout.

Flow between traffic signals can also have a significant influence on traffic emissions, as during high traffic intensity the increased volume can increase both idling time and start-stop movements. An assessment of the effects traffic signal coordination was made by De Coensel et al (2012). The authors considered how improving traffic flow by introducing a 'green wave' traffic mode could reduce vehicle emissions. The study utilised a microscale traffic model (Paramics) and the VERSIT+ emission model to assess CO_2, NO_X and PM_{10}. A simplified emission model set-up was applied. This was designed to be representative of the Dutch vehicle fleet. The set-up also consisted of an urban arterial road with a speed limit of 50 km/h, with five-consecutive traffic signals spaced at a distance of 200 m. The results showed that a reduction of emissions between 10% and 40% could be achieved when completing a successful green wave run.

Deschle et al (2022) examined the effects of improving traffic flow through signalised intersections on CO_2 and NO_X emissions from HDVs. Real-time data were collected from five Euro VI trucks using an on-board Smart Emissions Measurement System (SEMS) coupled with GPS. The trucks were driven across various regions of the Netherlands. Intersections were identified on Open Street Maps, and 2 km segments, centred on the intersections, were analysed. The results showed that, by avoiding a single stop, reductions in fuel consumption, CO_2 emissions and NO_X emissions could be achieved.

4 Summary and conclusions

4.1 Summary

4.1.1 Overview

This review has summarised the literature on the effects of traffic calming measures and intersection treatments on vehicle exhaust emissions and near-road air quality.

In the last 25 years there has been a significant amount of research. However, studies have varied in terms of the methods used, the assumptions made, and the nature of the traffic calming measures investigated. For example, researchers have considered either real-world traffic calming measures or hypothetical situations, have considered different specific designs (eg road hump height) and different configurations (eg road hump spacing), have applied either direct measurement or modelling, and have looked at various types of vehicle. In addition, different assumptions have been made in terms of the baseline situation with no traffic calming, as well as the effects on traffic volume on the calmed roads as well as other roads.

In terms of the types of traffic calming measure assessed in the literature, there has been much more focus on vertical displacements (such as road humps) than horizontal displacements (such as chicanes). This is probably due to the greater abundance of vertical deflections, as well as their larger impact on speed.

4.1.2 Traffic calming

The results in the literature for GHG and air pollutant emissions – stated as the percentage changes in CO_2 and NO_X emissions per vehicle-km *on the affected roads only* – are summarised in Table 4.1. Here, NO_X is taken to be the most relevant pollutant in terms of local air quality. On a road with traffic calming, any increase in emissions per vehicle-km would tend to be moderated by a reduction in traffic volume, and any reductions in emissions per vehicle-km would tend to be enhanced.

Given the observations above, the results for CO_2 are reasonably consistent. For example, for the more severe vertical deflections (as typically implemented), CO_2 emissions per vehicle-km on calmed roads have usually been shown to increase by between around 30% and 60%, and the values outside this range can generally be explained by methodological considerations. For example, Daham et al 2005 assumed aggressive driver behaviour, Ribeiro (2015) only equipped one vehicle with a low-cost (hand-held) air pollution monitor, and the result provided by Obregón-Biosca (2020) represents an optimised configuration involving a wide spacing of measures.

On a 'local network' basis[2], the overall effects of traffic calming on CO_2 emissions are smaller (probably less than 10%). However, it is difficult to generalise here, as the overall effect will depends on several factors, such as:

- how the local network is defined (eg the spatial extent or roads included);
- how many roads on the network have traffic calming;
- the severity and combination of the traffic calming measures;
- how much traffic is diverted onto non-calmed roads; and
- the speed limits and vehicle operation on the non-calmed roads.

[2] Here, the 'local network' is taken to mean the area over which the traffic calming has an influence, and not the entire road network.

Table 4.1 Summary of literature for CO_2 and NO_X emissions

Study	Notes	Method	Vehicle type	Vehicle fuel	Vehicle technology	Traffic calming measure(s)	Effect on CO_2 per vehicle-km	Effect on NO_X per vehicle-km
Cloke et al (1999)	Leigh Park Area Safety Scheme, Havant, UK	Real-world driving patterns and microscale emission model (MODEM) for cars, average speed for HDVs	Traffic mix	Petrol/ diesel mix	Up to Euro 1/ Euro I	Speed cushions	+10%	-10%
Boulter et al (2001)	Effects of traffic calming on car emissions, various UK schemes	Laboratory emission measurements on 12 cars over driving cycles for roads before and after traffic calming	Car	Petrol	Pre-Euro 1	Various	+7% to +28%[(a)]	-21% to +19%[(a)]
					Euro 1	Various	+18% to +38%[(a)]	-22% to +34%[(a)]
				Diesel	Euro 1	Various	+15% to +40%[(a)]	+17% to +39%[(a)]
Boulter et al (2003)	Gloucester Safer City Project, UK	Real-world driving patterns and microscale emission model (MODEM) for cars, average speed for HDVs	Traffic mix	Petrol/ diesel mix	Up to Euro 1/ Euro I	Various traffic management and traffic calming	+2%	-2%
Daham et al (2005)	UK	PEMS (1 vehicle)	Car	Petrol	Euro 1	Speed cushions	+90%	+195%
Ahn & Rakha (2009)	Virginia, US	Model	Composite LDV	Petrol	N/A	Signed intersection	+114%	N/A
						Mini-roundabouts	+35%	+56%
						Road humps	+52%	+110%
						Speed bumps	+29%	+19%
						Speed cushions	+48%	+98%
Ghafghazi (2013)	Montreal	Model	Traffic mix	N/A	N/A	Speed bumps	+15% to +81%[(b)]	N/A
Jazcilevich et al (2015)	Mexico City	PEMS (4 vehicles)	Car	Petrol	Tier I	Speed bumps	+35%	-13%
			Pickup	Petrol	Tier I	Speed bumps	+40%	+23%
			Minibus	LPG	Carburettor	Speed bumps	+31%	-5%
			Bus	Diesel	Euro V	Speed bumps	+58%	+5%
Ribeiro (2015)	Lisbon	Portable gas analyser (1 vehicle)	Car	Diesel	Euro 4	Speed tables, 30 km/h limit	+107%	+198%
						Speed tables, 50 km/h limit	-6%	+345%
						Road humps	-3%	+263%
Obregón-Biosca (2020)		Model	N/A	N/A	N/A	Speed tables	-6%	-6%

(a) Depending on type of measure.
(b) Depending on road.

There is little consensus on the effects of traffic calming on air pollutant emissions, which are inherently more variable than those of CO_2. The factors mentioned in Section 4.1 have led to considerable variation in the reported results for NO_X, ranging from decreases of around 20% to increases of several hundred percent. Moreover, no information has been identified for the most recent technologies (eg Euro 5 and Euro 6 for light vehicles). In addition, much of the available literature refers to passenger cars, and there is little information for heavy vehicles.

Some studies have highlighted the potential benefit of optimising the implementation of traffic calming devices (Obregón-Biosca 2019; Pérez-Sansalvador et al 2020).

There are fewer examples of where the effects of traffic calming on ambient air quality have been studied, but the available information suggests that there is unlikely to be a significant impact. Traffic calming measures have typically been introduced on residential roads with low traffic volumes. Consequently, even though traffic calming generally results in increased emissions per vehicle it is unlikely that that it would result in poor local air quality.

4.1.3 Intersection treatment

While there is a significant body of literature on the effects intersection treatment on vehicle emissions, for the purpose of this review a small selection was taken to be representative. In the chosen studies there was a general consensus that improving traffic flow across intersections can reduce CO_2 emissions. For example, converting a signalled intersection to a roundabout can reduce CO_2 emissions by between around 3% and 25% per vehicle-km. However, from studies such as Hallmark et al (2011), the effects on emissions can vary with the implementation approach, driving style and traffic volume. When considering traffic signals at intersections, the implementation of a green wave effect for traffic flow can have significant impact on reducing emissions for both light and heavy vehicles.

4.2 Conclusions

We have concluded the following from this review:

- Even though traffic calming configurations have been reported, and different assessment methods have been used, the effects on CO_2 emissions per vehicle-km on calmed roads have been reasonably consistent (eg for the more severe vertical deflections, an increase of between around 30% and 60% on the affected road).
- On a local network basis, taking into account the effects of traffic diversion and other factors, the overall effects of traffic calming on CO_2 emissions are smaller (probably less than 10%), although it is difficult to generalise.
- For air pollutants there is much more variation in the results, to the extent that a simple conclusion is not possible.
- Major gap in the literature relates to information for recent vehicle technologies and heavy vehicles.
- Even though traffic calming generally results in increased emissions per vehicle-km, it is unlikely that that it would result in poor local air quality given the low traffic volumes (and the effects of traffic diversion) that are typical for calmed roads.
- From the literature alone it would not be straightforward to develop a tool to differentiate between different types of traffic calming measure in terms of their impacts on emissions. This is because:
  - a wide range of traffic calming measures and configurations is possible (e.g. profile, material, spacing), and these factors will affect how vehicles are operated;

- only a limited range of traffic calming measures and conditions have been reported in the literature;
- various other factors influence the overall impact, including the year (which affects the distribution of emission standards in the fleet), the local traffic mix, the operating conditions before calming, and the extent to which traffic volume is affected; and
- many of the results in the literature have been derived empirically, and cannot be separated from the conditions under which they were obtained, including the method used to determine effects (which explains much of the variation in the results).

This suggests that the best way to differentiate between traffic calming measures in a systematic way would be to develop a tool which includes a combination of a microscale traffic model (or some other algorithm which allows driving patterns to be determined) and a microscale emissions model which covers an appropriate range of vehicle types and emission standards. However, to our knowledge no microscale emission models are available in New Zealand. An alternative would be to use an Australian model such as PΔP model (Smit 2014). However, given the likely (small) magnitude of emissions on the types of road that typically feature traffic calming, it is our view that the effort involved would not be worthwhile.

As an alternative, a qualitative/categorical approach to ranking measures could be investigated. For example, traffic engineers could provide estimates of the effects of different measures on driving patterns, and these could be used to infer changes in emissions based on speed and other speed-related statistics.

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