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Assessing the Dual Impact of Traffic Calming and Pollution Control in an Educational Campus Setting

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Abstract

Traffic accidents are significant conern in any community and pose a hazard to the well-being and public health of the citizens. Traffic calming measures (TCMs) are implemented to improve road safety for both vehicle drivers and pedestrians. Such measures are designed to discourage drivers from drivingat a high speed and increase awareness of the surrounding environment. However, TCMs such as speed bumps and speed humps result in acceleration-and-deceleration driving pattern, which can lead to increasedemissions from the vehicles. This research aimed to explore the dual impact of TCMs - both positive and negative - with the focus on the traffic calming implementation in Chulachomklao Royal Military Academy Main Campus (CRMA), Thailand. Vehicular speeds and driving patterns were monitored across road sections with different types of TCMs. The researchers use the gathered speed data and driving patterns to calculate emission associated with each TCM. The result is presented and discussed illustrated that TCMs with stop-and-go strategies produced higher rate of pollution than the slow-go strategies. However, the stop-and-go TCMs are more commonly installed across the campus. These findings highlight the need to balance safety benefits with environmental impact when choosing TCMs for traffic management.

Keywords:

road safety,
traffic calming measures,
dual impact analysis,
emissions

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1. Introduction

It is intuitive that drivers prefer saving commute time. The notions of speed such as "getting to the destination quicker"and "ability to drive fast and smooth" contrast with road safey and public welfare. Traffic Accidents are a significant concern in any urban environment, impacting public health, safety, and socio-economy [1].According to WHO, Thailand as one of the highest road traffic fatality among ASEAN countries, has suffered over 500 billion baht or about 6% of GDP annually to compensate road traffic and injuries between 2017 and 2021 [1][2]. Especially areas with high vehicle traffic and pedestrian interaction pose higher risk of accidents. To address these issues, traffic calming measures (TCMs) are implemented to reduce vehicle speeds, promote driver awareness, and enhance road safety [3].

In the higher education campus areas,interactions between walking pedestrians, bicyclists, and car drivers are considered high [4]. To mitigate risk of collisions, several TCMs such as speed bumps, road humps, and road narrowing have been widely implemented and proven effective in reducing traffic speeds, leading to lower accident rates [4][5]. In the previous research conducted at Chulachomklao Royal Military Academy Main Campus (CRMA), the installation of TCMs resulted in significant improvements in vehicular speed control and pedestrian safety [6]. These strategies forced drivers to decelerate, thereby creating safer environments for street users and reducing the likelihood of accidents.

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Despite the contribution of TCMs to road safety, unintended environmental impacts become a drawback. TCMs such as steep speed bumps and stop signs induce stop-and-go traffic patterns which require frequent acceleration and deceleration. Hazards from the emissions such as CO_2, NO_x, particulate matter, and brake and tire particles may increase as a result of fluctuating driving caused by the TCMs implementation.

This research extends the scope of the previous studies by evaluating both the safety and environmental impacts of traffic calming at CRMA. Specifically, this study investigates the dual impact of TCMs by comparing their effectiveness in reducing traffic accidents with their impact on vehicular emissions. By analyzing vehicle speeds and emissions, this study aims to provide insights into how TCMs can balance the trade-offs between traffic safety and environmental sustainability.

2. Literature Review

2.1 Background and Theory

2.1.1 Traffic Calming Measures (TCMs)

The concept of **traffic calming** originated in Europe during the 1960s, particularly in the Netherlands, with the introduction of Woonerf streets, which prioritize pedestrians and cyclists over vehicles. The goal was to address safety concerns and improve quality of life in densely populated urban areas. This idea gradually spread across Europe and the world, influencing urban planning policies in places like Germany, the UK, and the US [7][8].

By the 1980s, traffic calming had become a standard practice in cities seeking to reduce traffic accidents, air pollution, and noise, while simultaneously improving the environment for non-motorized users.

The primary goal of traffic calming measures (TCMs) is to reduce vehicle speeds and minimize accident risk, particularly in areas frequented by pedestrians, cyclists, and vulnerable road users. Research has demonstrated a strong correlation between vehicle speed and accident severity. Reducing speed by even a small margin can significantly lower the risk of fatal injuries, particularly for pedestrians [3].

Beyond safety, traffic calming also aims to enhance the livability of neighborhoods by reducing traffic-related noise, pollution, and making streets more walkable. TCMs create a safer environment for non-motorized traffic and can help in promoting alternative modes of transportation like cycling and walking [3][9].

2.1.2 Environmental and Traffic Impact

While TCMs are effective for reducing speeds and accidents, they can lead to increased emissions due to the acceleration and deceleration cycles caused by vertical deflection devices like speed bumps and speed humps. The frequent need for vehicles to brake, slow down, and then accelerate contributes to higher emissions of CO_2, NO_x, and particulate matter (PM) [10]. Figures 1 and 2 proposed by Ritner et al. illustrate the emission concentration during acceleration and deceleration.

The pollution impact from these acceleration and deceleration cycles can be estimated using the following emission equation proposed by [11][12]:

$$E_{acc/dec} = \frac{1}{VKT} \cdot \sum_{i=1}^{n} \left(EF^{i}_{\frac{acc}{dec}} \cdot d^{i} \right) \qquad \text{eq.1}$$

where:

$E_{acc/dec}$	is the total emissions during acceleration or deceleration,
$EF^{i}_{acc/dec}$	is the emission factor for each speed increment i,
d^{i}	is the distance traveled during that speed increment,
VKT	is the vehicle kilometers traveled

This model helps estimate the incremental emissions caused by acceleration and deceleration events at each TCM. The use of Vehicle-Specific Power (VSP) models can further refine emissions estimates based on vehicle weight, engine type, and road conditions [13].

Additionally, the emissions from non-exhaust sources such as brake wear and tire wear are increasingly recognized as significant contributors to PM10 and PM2.5 pollution. These particles are generated when vehicles brake or when tires make contact with road surfaces. The emissions from brake and tire wear can be estimated using the following models:

Brake Dust Emissions Model [11]:

$$E_{brake} = \left(\frac{m_{brake} \cdot EF_{brake}}{VKT} \right) \qquad \text{eq.2}$$

where:

E_{brake} is the brake dust emission rate (g/km),
m_{brake} is the mass of the brake pads worn (g),
EF_{brake} is the emission factor for brake wear (g/km),
VKT is the vehicle kilometers traveled.

Tire Wear Emissions Model [11]:

$$E_{tire} = \left(\frac{m_{tire} \cdot EF_{tire}}{VKT}\right) \qquad \text{eq.3}$$

where:

E_{tire} is the tire wear emission rate (g/km),
m_{tire} is the mass of the tire worn (g),
EF_{tire} is the emission factor for tire wear (g/km),
VKT is the vehicle kilometers traveled.

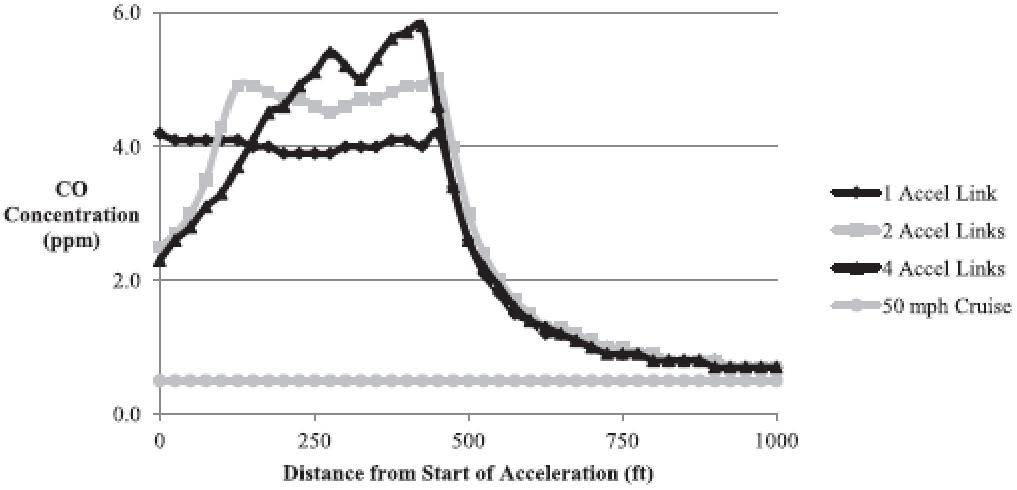

Figure 1: *CO concentration near a single roadway given a different number of acceleration sublinks (Riner et al., 2013)*

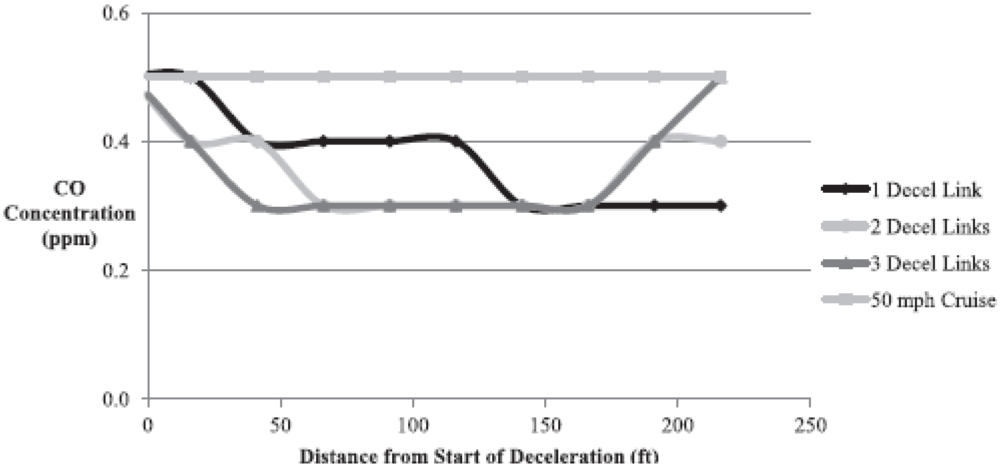

Figure 2: *CO concentration near a single roadway given a different number of deceleration sublinks (Riner et al., 2013)*

Research suggests that non-exhaust emissions such as brake dust and tire wear can contribute significantly to particulate matter pollution in urban areas, particularly PM10 and PM2.5. In fact, for certain vehicle types, non-exhaust emissions may surpass exhaust emissions, making them a key area of focus in air quality assessments [11][14].

In university settings, traffic calming is vital due to the high volume of pedestrians and cyclists and the need for reduced vehicle speeds around dormitories, academic buildings, and recreational areas. Universities like Stanford and Cornell have introduced raised crosswalks, speed humps, and pedestrian priority zones to manage traffic flow and enhance campus safety [4][5].

The design and placement of TCMs in university campuses must strike a balance between ensuring the safety of pedestrians and minimizing environmental impacts, especially in urban campuses where pollution levels are already a concern. Research on university campuses has shown that appropriately designed traffic calming measures can significantly reduce vehicle speeds and accidents without causing significant environmental degradation.

2.1.3 Spot speed study

Spot speed studies are conducted to estimate the vehicular speed on a particular location on a highway. The speed is normally expressed in miles per hour (mph) or kilometers per hour (kph). In this research the comparison of vehicular speed between the two TCMs were determined based on this theory. To investigate the problem further, the following key measures have been introduced [6].

Average speed

Average speed is the arithmetic means of all observed vehicle speeds. It is given as

$$\bar{u} = \frac{\Sigma f_i u_i}{\Sigma f_i} \qquad \text{eq.4}$$

where:

$\bar{u}$ = arithmetic mean
f_i = number of observations in each speed group
u_i = midvalue for the ith speed group
N = number of observed values

The formula can also be written as:

$$\bar{u} = \frac{\Sigma u_i}{N} \qquad \text{eq.5}$$

where:

u_i = speed of the ith vehicle

Median speed

Median Speed is the speed at the middle value in a series of spot speeds that are arranged in ascending order.

Modal speed

Modal speed refers to the speed value that occurs most frequently in a sample of spot speeds.

The ith-percentile spot speed

The ith-percentile spot speed refers to the speed value below which I percent of the vehicles travel.

Speed deviation of speeds

This value is a measure of the spread of individual speeds. It is estimated as

$$S = \sqrt{\frac{\Sigma(u_j - \bar{u})^2}{N-1}} \qquad \text{eq.6}$$

where:

S = standard deviation
$\bar{u}$= arithmetic mean
u_j = jth observation
N = number of observations

However, speed data is frequently presented in classes where each class consists of a range of speeds. The standard deviation can be determined as

$$S = \sqrt{\frac{\Sigma(f_i u_i^2) - (\Sigma f_i u_i)^2 / \Sigma f_i}{\Sigma f_i - 1}} \qquad \text{eq.7}$$

where:

u_i = midvalue of speed class i
f_i = frequency of speed class i

Sample size

The basic assumption made in determining the minimum sample size for speed studies can be determined as

$$N = \left(\frac{Z\sigma}{d}\right)^2 \qquad \text{eq.8}$$

where:

N = minimum sample size

Z = number of standard deviations corresponding to the required confidence = level 1.96 for 95 percent confidence level (Table 2).

σ = standard deviation (mph)

d = limit of acceptable error in the average speed estimate (mph)

Table 1:*Z-value and confidence level*

Confident Level (%)	**Constant Z**
68.3	1.00
86.6	1.50
90.0	1.64
95.0	1.96
95.5	2.00
98.8	2.50
99.0	2.58
99.7	3.00

2.2 Review of Literature

Research in the field of traffic calming has largely focused on its safety benefits, environmental impacts, and its role in promoting pedestrian-friendly environments. Studies have examined the trade-offs between reducing traffic speeds and improving safety, while also addressing the negative consequences on vehicle emissions due to acceleration and deceleration cycles.

Mao and Koorey (2010) conducted an important study evaluating the effectiveness of TCMs, such as speed humps and raised intersections, in controlling vehicle speed. Their findings showed that while these measures were highly effective in reducing speeds and improving pedestrian safety, they also increased emissions due to the stop-and-go driving patterns induced by such devices [15].

Ghafghazi and Hatzopoulou (2015) expanded on this by simulating the air quality impacts of traffic calming schemes in dense urban neighborhoods. Their research found that NOx and CO2 emissions were significantly higher in areas with vertical deflection devices, such as speed bumps, as vehicles were forced to slow down and then accelerate after each device [13]. This increase in emissions is primarily due to the acceleration and deceleration cycles that result in greater fuel consumption and higher emission rates compared to steady driving.

To better understand these dynamics, Ritner et al. (2013) applied the MOVES and CAL3QHC models to account for emissions from acceleration and deceleration at intersections equipped with TCMs. Their research emphasized that during acceleration, vehicle emissions, especially particulate matter (PM), increase disproportionately compared to cruising or idling. They recommended using sublink segmentation in models to more accurately predict pollutant concentrations near intersections, particularly those involving frequent stop-and-go traffic [11]. Their modeled CO concentration comparison is illustrated in Figure 3.

In addition to exhaust emissions, recent studies have highlighted the significance of non-exhaust emissions, such as brake dust and tire wear particles, which contribute to PM10 and PM2.5 pollution. Grigoratos and Martini (2015) conducted a comprehensive review of non-exhaust traffic-related emissions, concluding that brake wear and tire wear are major sources of particulate pollution in urban areas. They found that, in some cases, non-exhaust emissions exceeded those from exhaust, particularly in areas with frequent braking and acceleration [16]. Their work emphasized the need to address non-exhaust emissions in the overall assessment of traffic calming strategies.

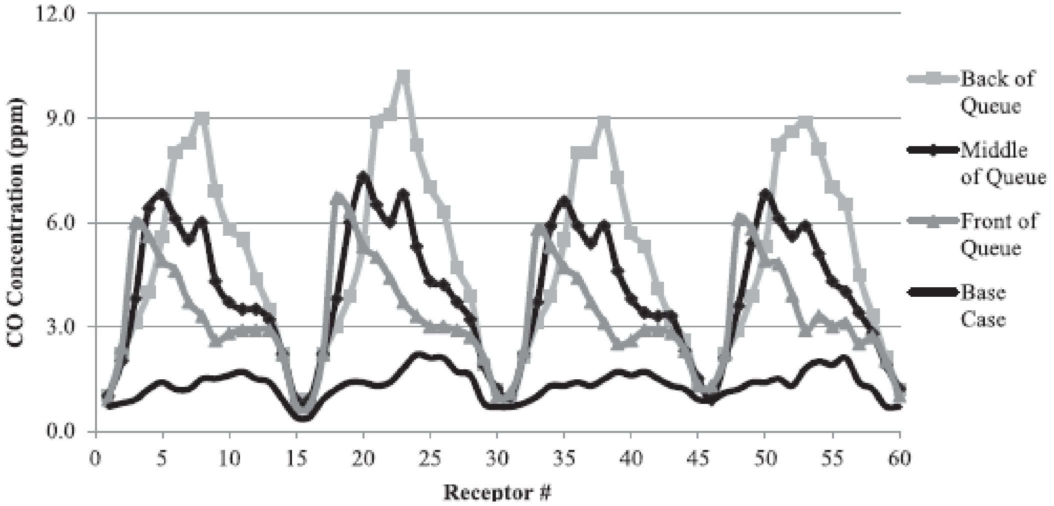

Figure 3: *CO concentration comparison (Ritner et al., 2013)*

The Handbook Emission Factors for Road Transport (HBEFA) provides emission factors for both brake dust and tire wear, which can be used to model non-exhaust emissions. These emission factors, combined with VSP models for exhaust emissions, allow for a more holistic view of the air quality impacts of TCMs [17].

Moreover, Hülsmann et al. (2014) studied the effects of traffic calming on emissions using a multi-agent traffic simulation model (MATSim) linked with the Operational Street Pollution Model (OSPM). They found that while traffic calming reduces traffic speeds, it also leads to higher localized concentrations of pollutants, particularly in urban canyons where air dispersion is limited [18]. Their findings underscore the importance of considering both traffic flow dynamics and meteorological factors when assessing the overall impact of TCMs on air quality.

Figure 4: *TCMs implementation in CRMA campus*

Elvik (2001) performed a meta-analysis of area-wide urban traffic calming schemes, concluding that while TCMs effectively reduce road injuries and fatalities, they also result in increased fuel consumption and emissions due to the frequent deceleration and acceleration events required by these measures. Elvik recommended more comprehensive approaches that balance the benefits of traffic calming with the environmental costs, suggesting the use of horizontal deflection devices, such as chicanes, which can reduce speeds without causing as many stop-and-go events [19].

Additionally, in the context of university settings, studies have shown that implementing traffic calming can reduce vehicular speeds and improve pedestrian safety but must be carefully designed to avoid adverse environmental impacts. Cornell University and Stanford University have both implemented raised crosswalks, speed humps, and pedestrian-only zones to manage traffic on their campuses. These efforts have successfully reduced speeds and accidents but have also highlighted the need for continuous monitoring of air quality around these areas [4].

3. Methods

The methodology for this research follows a structured approach to evaluate the effects of different Traffic Calming Measures (TCMs) on vehicle speeds and their associated environmental impacts. The process consists of five main phases: study area selection, data gathering, analysis of TCMs and traffic data, environmental impact analysis, and comparison of different TCMs.

3.1 Study Area and Traffic Calming Devices

This study is conducted within the Chulachomklao Royal Military Academy (CRMA) campus, where several traffic calming measures (TCMs) have been implemented, including speed bumps, speed humps, and raised pedestrian crossings. The campus presents a unique mix of motorized and non-motorized traffic, making it ideal for studying the dual impacts of TCMs on road safety and environmental emissions. The campus map and TCMs locations can be found in Figure 4.

3.2 Data Collection

3.2.1 Traffic Calming Devices

Speed bumps and speed humps are selected as the primary TCMs due to their widespread use on campus.Each traffic calming device will be assessed based on its location, speed reduction effects, and the number of vehicles passing through. The location of the traffic calming device installed is illustrated in Figure 4.

3.2.2 Vehicle SpeedData

Vehicle speed data will be collected using radar speed guns, which will be positioned at strategic points along the road sections equipped with traffic calming devices. The radar guns will capture both pre-TCM speeds (before the vehicle encounters the traffic calming measures) and post-TCM speeds (after crossing the traffic calming devices).

To account for the setup of the campus roads and the position of the radar guns relative to moving vehicles, the radar speed guns will be adjusted to an angle of 15 degrees from the vehicle's path. This angular adjustment ensures that the recorded speed data accurately reflects the vehicles' actual velocities, accounting for the deviation from the line of travel. Figure 5 illustrates the layout of vehicle speed measure with 10-degree angle. Since the vehicle was not traveling directly at the radar, the speed measured was slightly lower than the actual speed. For this reason, the masured speed must be adjusted to compensate for the cosine effect. The cosine effect adjustment can be determined as follows:

$$measure\ speed = v_m = v_0 cos\beta = v_0 \cdot \left(\frac{R}{(R^2+d^2)^{0.5}}\right) \qquad \text{eq. 9}$$

where:

v_0	is actual speed
β	is cosine effect angle
R	is target range to radar
d	is antenna distance to middle of target lane

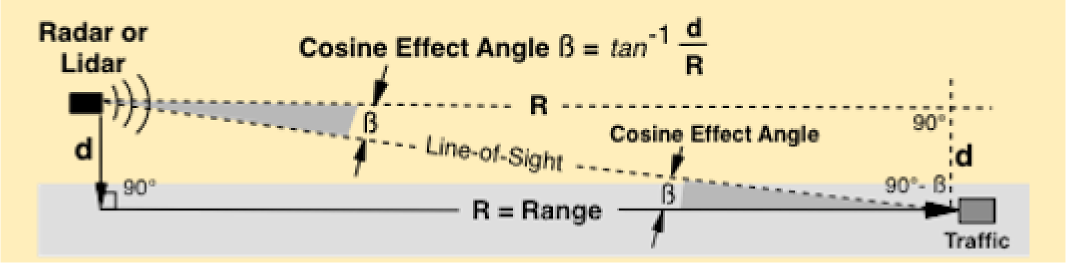

Figure 5: *cosine effect setup (police radar information center, n.d.)*

Speed measurements will be recorded continuously over a period of 4 weeks, covering both peak and off-peak hours to ensure the capture of a variety of traffic conditions. Vehicle speeds will be averaged to provide a baseline for comparison against speed reduction due to the TCMs.

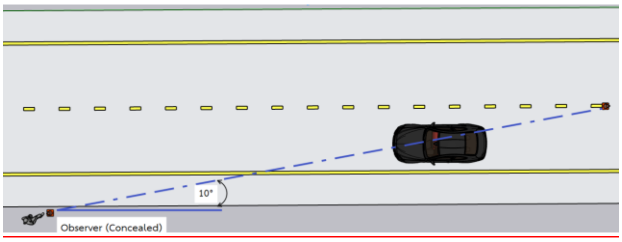

Figure 6: *observation for spot speed study (Khumpraphan, 2024)*

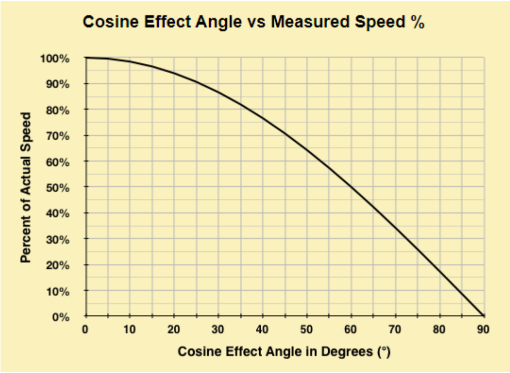

Figure 7: *Speed-angle adjustment for spot speed study (Police Radar Information Center, n.d.)*

3.3.2 Emissions Estimation

Given the constraints on budget and resources, real-time emissions monitoring (such as Portable Emissions Measurement Systems, PEMS) will not be employed in this study. Instead, emissions will be calculated and estimated based on established models for exhaust and non-exhaust emissions, as described in Section 2.

3.3 Analysis of TCMs and Traffic Data

To assess the impact of TCMs on traffic flow, several speed-related metrics were calculated:

- Average Speed: The arithmetic mean speed of vehicles before and after passing over the traffic calming devices.
- Median Speed: The middle value in the range of observed vehicle speeds.
- Speed Deviation: A measure of variability in vehicle speeds, calculated using the formula:

$$\sigma = \sqrt{\frac{\left(\Sigma(v_j - \bar{v})^2\right)}{N-1}} \qquad \text{eq.10}$$

where:

σ is the standard deviation,
$\bar{v}$ is the average speed,
v_j is the individual observed speed.

3.4 Environmental Impact Analysis

Using the emissions estimates from Section 3.2.2, the environmental impact of each traffic calming measure was assessed. Emissions of CO_2, NO_x, and PM were compared across the different TCMs to identify which measures contributed most significantly to pollution.

3.5 Comparison of Different TCMs

The final phase of the research involved comparing the effectiveness of each TCM in reducing vehicle speeds and their associated environmental impacts. The speed bumps, speed humps, and road diet strategies were evaluated based on:

- The percentage reduction in average vehicle speed

- The estimated increase in emissions due to the stop-and-go nature of the TCMs
- The overall safety benefits, including the reduction in accident rates.

The findings from the above analyses were synthesized to provide recommendations on the most effective TCMs for improving both road safety and environmental quality. The study emphasized the need to balance speed reduction with minimizing vehicle emissions, particularly for measures that induce frequent acceleration and deceleration.

4. Results and Discussion

This section presents the results from the study of traffic calming measures (TCMs) on the Chulachomklao Royal Military Academy (CRMA) campus, analyzing both the traffic speed reduction and environmental impacts. The findings from the collected speed data, calculated emissions, and the comparison between different TCMs are discussed in detail below. Figure 8 describes speed bump profile installed across the campus. It is noted that the design of speed bumps and speed humps should conform to the Department of Public Works and Town & Country Planning (DPT) Standards [20].

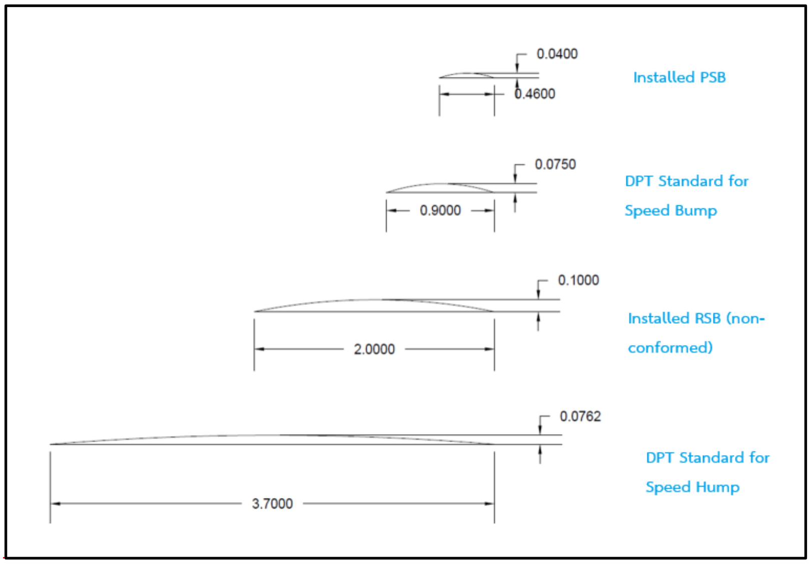

Figure 8: *speed bump profiles that were installed across the campus*

4.1 Impact on Vehicle Speeds

4.1.1 Observed speed without TCM

There was a period of time during the resurfacing and implementation of roadways across the CRMA campus that several parts of the campus did not have any vertical deflection TCM installed. The researchers found that beneficial to the research as the free speed result can be obtained to compare after the implementation of TCMs.

The researchs observed that the vehicles on the experiment routes were about 62 kph (39 mph). The maximum speed observed reached over 100 kph (62 mph). The result from this session was used as a baseline to compare average vehicle speeds between TCMs in this study.

4.1.2 Observed speed over PSB

The researchers monitored vehicle speed over the sharp speed bump or PSB (as depicted in the first picture in Figure 8) across the campus. According to DPT standards, a speed bump should have its width between 30 – 90 cm (12 – 35 inches) and no greater than 7.5 cm (2.95 inches) height. It was found that speed bumps installed across the campus conform to the DPT standards.

The researchers observed that the average speed on the road segments was about 57 kph (36 mph), which is about 8% from the observation in 4.1.1. The highest speed observed on the segments with PSB installed was 90 kph (56 mph).

While the vehicles traveled on the road segments with PSB installed, the vehicles tended to start decelerating 30 meters (100 feet) before reaching PSB and returned to their average travel speed on the segment about 30 meters (100 feet) after passing PSB. At the PSB, the vehicle’s traveled speed was reduced to around 20 kph (12 mph) on average.

4.1.3 Observed speed over RSB

In mid-2024, the new design of speed hump or RSB was introduced and was implemented in some road sections in the campus. The design is depicted as the third photo in Figure 8. It is noted that the newly design speed humps do not conform to the DPT standards, for both speed bump and speed hump standards.

The average speed of the vehicles on the RSB installed road segment was observed at 53 kph (33 mph). The vehicle started to decelerate before reaching RSB about 30 meters (100 feet) and returned to the normal travel speed of 30 meters (100 feet) after the RSB. Unlike vehicle speed over the PSB, the vehicles almost came to a full stop before going over the RSB. It was also observed that the acceleration rate was about the same as PSB after passing the devices. It was also observed that the highest speed measured was 90 kph (56 mph).

4.1.4 Observed speed on road diet experiment

The researchers conducted an experiment for road diet scenarios where the researchers temporarily reduced lane width to observe vehicular speed under this TCM.

The findings showed that the speed profile along the road section, as opposed to PSB and RSB, was flattened. This means that road narrowing did not induce stop-and-go traffic pattern as occurred in PSB and RSB cases. The average speed was also lower than the other two at around 27 kph (17 mph) with the highest speed observed being 40 kph (25 mph). Table 2 illustrates the impacts of each TCMimplemented in the campus.

Table 2: *Summary of TCMs installed in the campus*

Traffic Calming Device	**Route**			
	Car	**Car**	**Car**	**Car**
Speed Bump			-6.10%	-5.10%
Road Narrowing	-4.30%	-13.50%	**-55.10%**	-33.30%
Newly Installed Speed Bump			-12.20%	

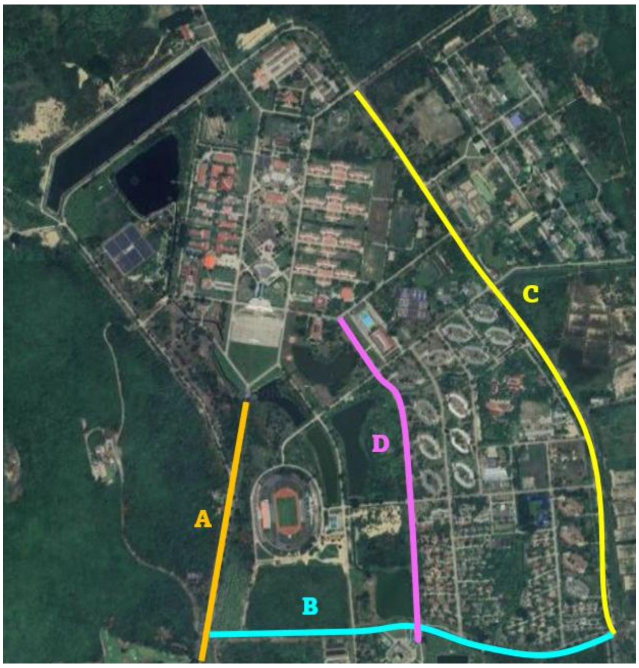

Figure 9: *experiment locations*

4.1.5 Discussion

The observed vehicle speed data across the CRMA campus clearly indicates that the implementation of Traffic Calming Measures (TCMs), such as Physical Speed Bumps (PSB), Raised Speed Humps (RSB), and road diets, effectively reduced speeds compared to the baseline scenario without any TCMs. In the absence of TCMs, vehicles traveled at an average speed of 62 kph, with some reaching speeds of over 100 kph. The sharp reduction in speed observed after the installation of PSBs and RSBs suggests that these devices successfully force drivers to decelerate before crossing, with PSBs reducing speeds by 8% and RSBs by approximately 14.5% on average. These findings demonstrate the impact of vertical deflection devices on controlling vehicle speeds in campus settings.

However, while both PSBs and RSBs effectively slow down vehicles, their mechanisms of action differ. PSBs induce a gradual deceleration, with vehicle speeds dropping to around 20 kph before resuming normal speeds, which allows for smoother traffic flow. On the other hand, RSBs caused vehicles to almost stop before crossing, which may be beneficial for areas with high pedestrian traffic but may result in more disruptive traffic patterns. The road diet experiment produced a different speed profile, with vehicles traveling more consistently at lower speeds (27 kph on average), without the sharp stop-and-go pattern observed in the other TCMs. This suggests that road narrowing may be a preferable option in certain areas where smoother, more continuous traffic is desired.

In summary, while PSBs and RSBs are highly effective in reducing speeds, they also introduce a more aggressive driving pattern with frequent acceleration and deceleration, which could increase vehicle emissions. Road diets, though less aggressive in slowing down traffic, create a smoother driving experience with consistent speeds, making them suitable for environments where lower speeds are needed but without the need for severe reductions. The choice of TCM depends on the balance between achieving speed reduction and minimizing traffic disruptions, with the data from this study offering valuable insights for future campus traffic management.

4.2 Environment Impacts

The environmental impacts of traffic calming measures (TCMs) were assessed through the estimated emissions of CO_2, NO_x, and particulate matter (PM10 and PM2.5), with calculations derived from the models described in Section 2. These emissions were calculated for various TCMs such as speed bumps, speed humps, and road diets.

4.2.1 Exhaust Emissions

The acceleration and deceleration induced by traffic calming measures significantly increase exhaust emissions due to frequent stop-and-go driving patterns. For the selected TCMs, the estimated emissions were calculated based on the MOVES model and observed vehicle speeds.

a. Speed Bumps

Speed bumps cause a substantial increase in exhaust emissions as vehicles must decelerate sharply and then accelerate to resume their previous speed. The following results were observed:

- CO_2 emissions increased by 12% at speed bumps compared to sections without TCMs.
- NO_x emissions rose by 10%, largely due to the higher fuel consumption caused by frequent deceleration and acceleration.
- The particulate matter (PM10 and PM2.5) emissions showed an increase of approximately 15%, which is attributed to the sudden braking required at speed bumps.

This increase in emissions is consistent with findings from Ghafghazi and Hatzopoulou (2015), who noted similar trends in their simulation of TCMs in urban neighborhoods [8].

b. Speed Humps

Speed humps, which provide a gentler vertical deflection compared to speed bumps, resulted in a more moderate increase in emissions:

- CO_2 emissions increased by 8%, which is slightly lower than speed bumps but still significant due to the acceleration needed after deceleration.
- NO_x emissions rose by 7% in areas with speed humps.
- The PM10 and PM2.5 levels were also higher by about 10% compared to road segments without TCMs.

These findings reflect the less aggressive speed reduction characteristics of speed humps, which allow vehicles to maintain a more constant speed and reduce the need for sharp acceleration.

c. Road Diets

The road diet approach, involving lane narrowing, had the least impact on emissions. Vehicles were observed to maintain a steady speed without the frequent acceleration seen with vertical deflection devices. The results showed:

- A 4% increase in CO_2 emissions,
- A 3% rise in NO_x emissions, and
- PM emissions increased by only 5%, as the smoother traffic flow reduces the braking and acceleration events associated with higher particulate generation.

These results indicate that road diets, while less effective in reducing speeds drastically, are environmentally more favorable than speed bumps and humps, especially in terms of emissions.

In the case of road diets, even without significant stop-and-go traffic, emissions can still increase due to several factors. Vehicles operating at lower speeds, such as the 27 kph observed in the road diet scenario, tend to run less efficiently compared to their optimization for moderate highway speeds (50-70 kph), leading to higher emissions of CO_2 and NO_x. Additionally, the increased travel time resulting from slower speeds extends the period the engine is running, causing overall emissions per kilometer to rise. Minor fluctuations in driver behavior, such as slight accelerations when adjusting to lane narrowing or road conditions, can also contribute to higher emissions, though less significantly than the stop-and-go patterns induced by vertical deflection devices. Thus, while road diets minimize the need for sharp acceleration and deceleration, the combined effects of lower speeds, longer travel time, and minor speed adjustments still lead to moderate increases in emissions, albeit lower than those observed with speed bumps or humps.

4.2.2 Non-Exhaust Emissions

Non-exhaust emissions, such as brake dust and tire wear particles, were estimated using the models presented in Section 2. These emissions are significant contributors to PM10 and PM2.5 concentrations and are particularly concerning in areas with frequent braking.

a. Brake Dust

Non-exhaust emissions from brake wear were highest at speed bumps, where vehicles braked more frequently and sharply:

- Brake dust emissions increased by 16% at speed bump locations due to the repeated braking and subsequent acceleration needed.
- At speed humps, brake dust emissions rose by 12%.

b. Tire Wear

Tire wear particles are generated as vehicles pass over traffic calming devices, particularly vertical deflection measures like speed bumps and humps:

- Tire wear emissions were found to increase by 10% near speed bumps and by 8% near speed humps.
- For road diets, where vehicles maintained a steadier speed, tire wear emissions increased by only 5%.

These results align with research conducted by Grigoratos and Martini (2015), which found that non-exhaust emissions can surpass exhaust emissions in urban environments with high levels of braking and accelerating traffic [16].

4.2.3 Air Quality Modeling

Using the CAL3QHC model, the dispersion of pollutants near the TCMs was simulated. The model indicated that pollutant concentrations were 20% higher near intersections with speed bumps, particularly within a 50-meter radius. The frequent braking and acceleration caused localized increases in CO_2 and NO_x concentrations, leading to hot spots where air quality deteriorated significantly.

In contrast, speed humps caused a 15% increase in pollutant concentrations, and road diets showed only a 5% increase in localized pollution levels. These findings suggest that while road diets are less effective in slowing down traffic as compared to speed bumps, they result in a much smaller environmental footprint in terms of emissions.

The results of the OSPM simulations, which modeled pollution dispersion in street canyon-like environments within the campus, further highlighted the limited air dispersion near vertical deflection devices, where emissions tend to accumulate.

4.2.4 Discussion on Environmental Trade-offs

The environmental impacts of TCMs reveal a clear trade-off between improving road safety and managing pollution levels. Vertical deflection devices like speed bumps and speed humps offer significant reductions in vehicle speeds, leading to safer road conditions. However, the stop-and-go driving patterns they induce result in substantial increases in emissions, both from exhaust sources (CO_2, NO_x, PM) and non-exhaust sources (brake dust, tire wear).

Road diets, on the other hand, are a more environmentally sustainable option, leading to minimal increases in emissions while still providing moderate speed reduction benefits. These findings suggest that, where feasible, a combination of horizontal deflection measures and less aggressive TCMs might offer a better balance between safety improvements and environmental sustainability.

Further research could explore alternative TCMs that combine the safety benefits of speed bumps with lower environmental costs, such as dynamic speed limits or smart traffic control systems that adjust to real-time traffic conditions.

4.3 Comparison between Different TCMs

When comparing the different Traffic Calming Measures (TCMs), Physical Speed Bumps (PSB), Raised Speed Humps (RSB), and road diets show varying levels of effectiveness and environmental impact. PSBs are the most effective at reducing vehicle speeds, with a speed reduction of 8% compared to 14.5% for RSBs and 55.1% for road diets. However, PSBs induce the most significant increase in emissions, with CO_2, NOx, and PM10/PM2.5 emissions rising by 12%, 10%, and 15%, respectively, due to frequent acceleration and deceleration.

In contrast, road diets offer more modest speed reductions but are more environmentally favorable, with only 4% CO_2 and 3% NO_x increases. RSBs represent a compromise, providing moderate speed reductions while causing fewer emissions than PSBs, with CO_2 and NO_x emissions increasing by 8% and 7%, respectively. Overall, the data indicates that while PSBs are more effective for slowing down vehicles, they come at a higher environmental cost compared to road diets, which provide more sustainable traffic control with less disruption to traffic flow.

Table 3: *summary of the environmental impacts for each TCMs implemented in CRMA campus*

TCM Type	**CO_2 Increase**	**NO_x Increase**	**PM10/PM2.5 Increase**	**Brake Dust**	**Tire Wear**	**Localized Pollution**
PSB	12%	10%	15%	16%	10%	20%
RSB	8%	7%	10%	12%	8%	15%
Road Diet	4%	3%	5%	5%	5%	5%

4.4 Discussion

The findings from this study reveal that TCMs are highly effective at reducing vehicle speeds and improving road safety, but they come with trade-offs, particularly in terms of environmental impacts. PSBs, while reducing speeds significantly, lead to higher CO_2, NO_x, and PM emissions due to the frequent acceleration and deceleration cycles they induce. RSBs offer a middle ground, achieving safety benefits with a slightly lower environmental cost, while road diets have the least impact on emissions but may not be as effective in reducing speeds in high-risk areas.

These findings suggest that the choice of TCMs must carefully balance safety improvements with environmental sustainability. In areas with heavy pedestrian traffic and higher accident risks, PSBs or RSBs may be justified despite their higher emissions, whereas road diets may be more suitable in areas where smoother traffic flow and reduced emissions are the primary concerns. A hybrid approach, combining vertical deflection measures like RSBs with horizontal deflection devices, could be explored to optimize both safety and environmental outcomes.

5. Conclusion and Recommendations

5.1 Conclusion

This study assessed the dual impact of Traffic Calming Measures (TCMs) on both traffic safety and environmental sustainability within the Chulachomklao Royal Military Academy (CRMA) campus. Physical Speed Bumps (PSBs), Raised Speed Humps (RSBs), and road diets were evaluated based on their ability to reduce vehicle speeds and their associated emissions. The findings demonstrate that while all TCMs effectively reduce speeds and improve road safety, they also lead to varying increases in CO_2, NO_x, and PM10/PM2.5 emissions, particularly due to the stop-and-go driving patterns caused by PSBs and RSBs.

PSBs were the most effective at reducing vehicle speeds but also caused the highest increase in emissions, while road diets had the least environmental impact but were less effective at slowing traffic. RSBs provided a balance between speed reduction and emissions, making them a viable option for areas where safety is critical but environmental concerns must also be considered.

5.2 Recommendations

To maximize the benefits of TCMs while minimizing their environmental impact, this study recommends adopting a hybrid approach that combines vertical deflection devices like RSBs with horizontal measures such as road diets or chicanes. This combination can help maintain lower speeds without causing excessive increases in emissions. In areas with high pedestrian traffic or accident risks, the use of RSBs is advised, while road diets may be more suitable for areas with moderate traffic flow where environmental sustainability is a priority.

Further research should explore the development of dynamic TCMs, such as smart traffic management systems that adjust speed limits and traffic flow in real-time to balance safety with environmental considerations. Additionally, continuous air quality monitoring around TCM installations will be crucial for assessing the long-term impacts on local environments and ensuring that the benefits of reduced traffic accidents are not outweighed by increased emissions.

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