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An evaluation framework for traffic calming measures in residential areas

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ABSTRACT

The paper evaluates the effectiveness of various traffic calming measures from the perspectives of traffic performance and safety, and environmental and public health impacts. The proposed framework was applied to four calming measures – two types of speed humps, speed tables, and chicanes – to demonstrate its usefulness and applicability. A field experiment using probe vehicles equipped with global positioning system devices was conducted to obtain vehicle trajectory data for use in more realistic simulations. In addition, a recently developed vehicle emissions model was used for more accurate evaluation of environmental and public health impacts. The results show that chicane is better than the other types of traffic calming measures considered, except in terms of vehicle emissions.

1. Introduction

Traffic calming measures associated with drivers' behaviors have been used successfully in cities for decades in response to safety-related neighborhood traffic concerns. Many prior studies, however, have focused on either traffic performance measures or the environmental impacts of traffic calming devices, rather than using a broader evaluation framework. Here we evaluate the effectiveness of various calming measures based on a more complete evaluation framework that considers traffic performance, traffic safety, and environmental and public health impacts using a microscopic approach, and consider four traffic calming measures. A microscopic traffic simulation model reflecting driving behaviors, such as deceleration rates, is derived from global positioning system (GPS) data. In addition, a recently developed vehicle emissions model was used for estimating vehicles' emissions by a post-processing routine.

2. Methodology and scenarios

Fig. 1 presents our analytical framework. Initially we select traffic calming measures that have similar characteristics, and then consider the driving behaviors associated with each measure. Speed variation, decelerations, and reduction sections were considered to capture driving behaviors. The data, including traffic volumes, vehicle characteristics, and various types of calming measures, were used to establish a traffic simulation environment in VISSIM (PTV Vision, 2008). Three performance measures – speed, acceleration noise, and emissions – where considered in evaluating the calming scenarios examined in the traffic simulations. Speed and acceleration noise were considered to capturing traffic calming performance and

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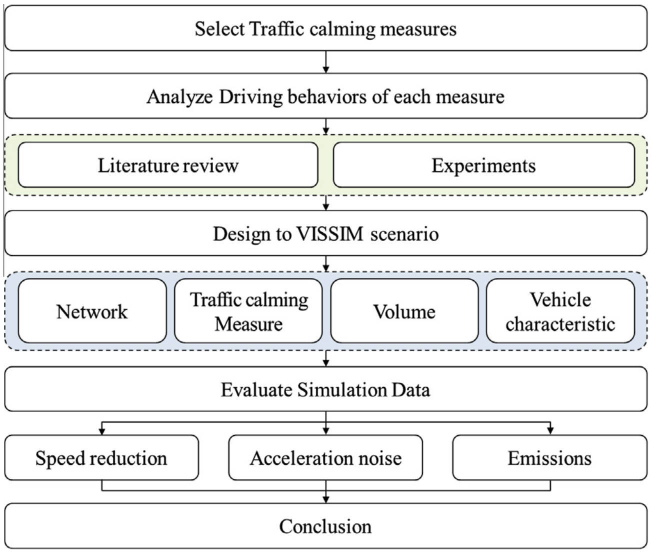

Fig. 1. Study procedure.

road safety. In addition, vehicle exhaust emissions, specifically, CO_2 and $PM_{2.5}$, were considered as a surrogate measure of environmental and public health impact.

Although various types of traffic calming measures exist, we focus on speed humps, speed tables, and chicanes, these being the measures typically installed in residential areas in Korea.

Speed humps span the width of the road and are typically 3–4 m (12–14 feet) in long. The height of speed humps ranges from 7 to 10 cm (3–4 in.). The length and height of speed humps affect vehicles' speeds where speed humps are installed (Marshall, 1993). Here we consider speed humps 3 m long (Scenario 1) and 4 m long (Scenario 2).

A speed table (Scenario 3) is a long speed hump with a flat section in the middle. It is typically long enough for entire wheelbase of a passenger car to rest on top. This design allows cars to at relatively higher speeds than they pass speed humps. Therefore, speed tables are often installed with normal speed limits in residential areas. Here we considered a speed table (7 cm in height and 6 m in long) often used in Korea.

For Scenario 4, a chicane, which is an artificial feature creating extra turns in a road, is selected. The chicane is used to slow down vehicles. Drivers are expected to reduce their speeds to negotiate the lateral displacement in the vehicle path. Chicanes can reduce the number and severity of traffic accidents (UK Department for Transport, 1997). Here, a chicane 100 m long is selected, a typical length in Korea.

3. Data collection and traffic simulation

Fig. 2 offers details of the study area where the traffic calming measures are located. In the area, five 3-m, three 4-m speed humps, five speed tables, and two chicane sections were installed. Two probe vehicles equipped with GPS devices were used to collect speed profiles every second and capture acceleration/deceleration rates and speed reduction areas. Ten college students participated in data collection, and each drove the given route once. Although the ten participants drove once in the area, we were able to collect more than 40 samples for each measure, except for the chicanes (20 samples), because multiple calming measures were installed. It would have been better to collect GPS data before and after installation of the measures to analyze their effectiveness, but the calming measures had already been installed in the study site that we selected. Statistical analysis of the data was conducted, and the results were applied to initial settings of the traffic simulation model to represent driving patterns for each calming measure. If distance between calming measures is not enough, the previous calming measures may influence driving behavior on the next measures. To identify this issue, we considered a minimum distance from minimum driving speeds to speed limits after passing traffic calming measures. The minimum distance can be estimated based on Roess et al. (2004):

$$\frac{V^2 - V_0^2}{2a} = S \tag{1}$$

where V is speed limits, V_0 is minimum driving speed, a is acceleration rate (2.286 m/s^2 for passenger car), and S is the minimum distance, or spacing. If a distance between traffic calming measures is less than S, then we assume that the previous measure is dependent on the next. The speed limits is 50 kph, most of the minimum driving speeds from the GPS data are 30 kph while passing calming measures, so S is 27 m.

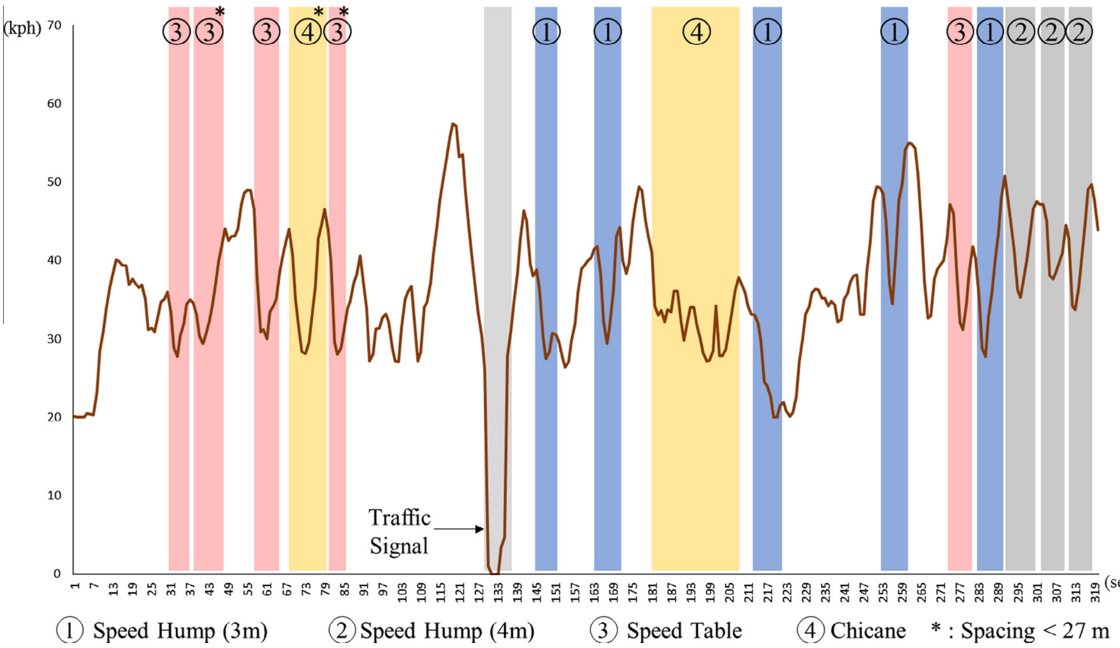

Fig. 2. Study area and GPS data.

As shown in Fig. 2, we identify the distances between calming measures and exclude three cases where the distance between calming measures is less than the minimum distance (27 m) for considering initial settings of the traffic simulation model to represent driving patterns. The descriptive statistics and distribution of driving speeds for the calming measures determined are seen in Table 1 and Fig. 3. As the table shows, Scenario 4 had the lowest average speed and standard deviation in the speed reduction area, and Scenario 3 had the highest average speed.

Fig. 3 presents the speed profiles of the speed reduction area of each scenario. Based on the speed profiles, the speed reduction area (from a point where participants start to decelerate their speeds for approaching calming measures to a point where traffic calming measures were installed) was defined. For Scenarios 1 through 4, the speed reduction areas are 20, 20, 40, and 100 m. As Fig. 4 shows, for the speed hump, the speed reduction area was relatively short and approaching speeds dropped more sharply than for other calming measures. On the other hand, approaching speeds were reduced smoothly and kept low at speed tables and chicanes.

Microscopic traffic simulation is widely used in evaluating traffic operational conditions because it can represent individual vehicle behaviors such as vehicle interactions, acceleration, and deceleration in response to details such as traffic signals and ramp metering (Chu et al., 2004; Boriboonsomsin and Barth, 2008). Further, microscopic traffic simulation can generate second-by-second vehicle trajectory data (e.g., an individual vehicle's second-by-second speed profile). VISSIM, which is one of the most popular microscopic traffic simulators, was selected.

The first step in performing microscopic traffic simulation is building a traffic simulation network, including the number of lanes and the highway geometry, using a high-resolution map (e.g., Google map) or a GIS layer and detailed traffic operational information (traffic signal phases, speed limits, and so on) to represent a study site. Once the traffic simulation network is built, origin and destination demands (O–D) must be estimated to match simulated and actual traffic volumes in the network. For freeway conditions, sensor data are typically used; on the other hand, turning movements are considered for arterials with traffic signals. Next, calibration procedures are performed to fine-tune traffic conditions such as link speed and link travel time by adjusting several parameters in the microscopic traffic simulation.

A hypothetical traffic link 140 m long and consisting of three segments was considered to assess the performance of each traffic calming device under identical conditions. Because of this simple traffic links, it was not necessary to build the simulation network using a high-resolution map and estimate O–D demands. However, we applied the same speed limits and average traffic volume of the study site in collecting the GPS data and considered the distribution of approaching speeds in

Table 1
Descriptive statistics of reduction area of each scenario.

Speed (in kph)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Average	32.14	33.15	33.29	30.95
Standard Deviation	4.203	4.214	4.156	3.189
Range	27.9–36.3	28.9–37.4	29.1–37.4	27.8–34.1

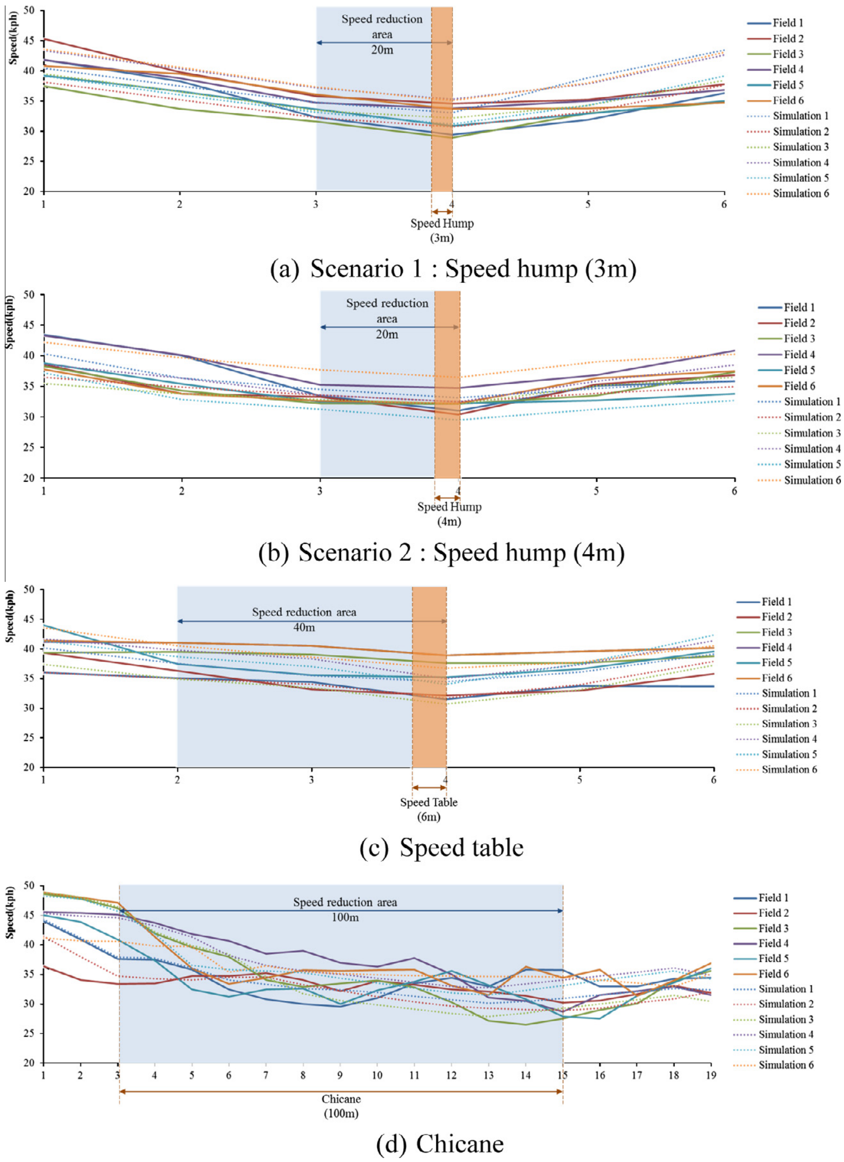

Fig. 3. Examples of speed profiles for observed and simulated data.

the speed reduction area of each calming device to represent driving behaviors when passing calming devices. Speed limits of 50 kph and traffic volumes of 300 vph were considered, based on data collection area and on Institute of Transportation Engineers/Federal Highway Administration (1999).

To capture driving behaviors in the evaluation of the traffic calming devices, simulated vehicles' deceleration rates for each calming measure were used. Unfortunately, current microscopic traffic simulation cannot model calming devices, so we considered an alternative way to represent traffic calming devices using a function called a "reduced speed area" in VISSIM. The reduce speed area can change simulated vehicles' speeds when entering a reduced speed area even though the speed limits remain the same as in the other segments. In the reduced speed area, we considered speed distributions characterized by the average speed and its standard deviation for each calming device, as determined from the GPS data (Table 1). The length of the speed reduction area for each calming device is discussed in the previous section. The conceptual illustration of each traffic calming scenario for running traffic simulation is shown in Fig. 4.

4. Performance measures

Speed is one of the key performance measures used to evaluate traffic calming devices. The main objective of installing traffic calming measures in residential areas is to reduce driving speeds. As some cases considering speeds for evaluating traffic calming measures, Hallmark et al. (2008) applied seven low-cost traffic calming treatments and evaluated them in

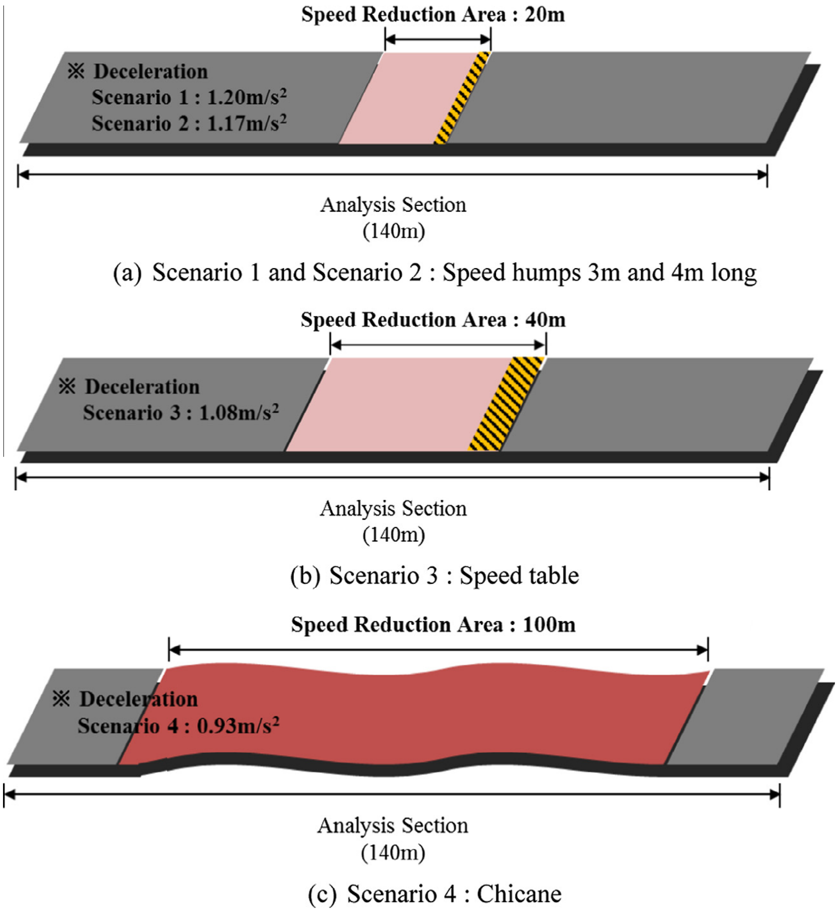

Fig. 4. Traffic simulations for each scenario.

five rural Iowa communities. To evaluate their effectiveness over time, before-and-after speed studies were conducted, with data from before installation of the traffic calming treatments compared to data from 1, 3, 9, and 12 months after installation. All of the treatments evaluated successfully reduced mean speed. Abate et al. (2009) studied speed variation for various gateway traffic calming strategies. They used speed data to measure the influence of the gateways on drivers' behavior entering urban areas using a before-and-after analysis.

Acceleration noise, the degree of speed variation measured from the speed profiles of individual vehicles, has often been used as a traffic parameter to quantify driver, roadway, and traffic condition interaction (Belz and Aultman-Hall, 2011). Here we used acceleration noise as a surrogate safety measure because it is a well-known parameter for evaluating the stability of traffic flow. Acceleration noise can be affected by traffic and roadway conditions and vehicle/driver behavior. Traffic conditions with greater acceleration noise imply higher potential for traffic accidents. Acceleration noise is defined as the standard deviation of acceleration or deceleration, and its functional form is represented by the following equation (Gerlough and Huber, 1975; Jones and Potts, 1962):

$$\sigma = \left\{ \frac{1}{T} \int_0^T [a(t) - a_{av}]^2 dt \right\}^{\frac{1}{2}} = \left\{ \frac{1}{T} \int_0^T a(t)^2 dt - (a_{av})^2 dt \right\}^{\frac{1}{2}} \tag{2}$$

where $a(t)$ is the acceleration or deceleration at time t, a_{av} is the average acceleration or deceleration, and T is the time in motion.

Vehicle emissions were considered in evaluating the environmental performance of the calming measures studied. The MOVES model, recently developed by the US Environmental Protection Agency, was selected for this purpose. MOVES can estimate vehicle emissions at the macro- and micro-scale levels. To better capture vehicle emissions under various scenarios of traffic operation strategies, a micro-scale emission model is considered. In using MOVES, we relied on the vehicle operating mode (OpMode) approach, which can estimate emissions resulting from vehicles' speeds and accelerations and decelerations from the second-by-second speed trajectory data for each individual vehicle.

Table 2
Calibration results between the simulated and observed data.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Average speed (in kph)				
Observed	32.14	33.15	33.29	30.95
Simulated	32.07	33.14	32.34	30.30
Difference	0.22%	0.03%	2.85%	2.1%
Average acceleration (in m/s^2)				
Observed	0.2264	0.2261	0.2132	0.0158
Simulated	0.2175	0.2170	0.2041	0.0167
Difference	3.94%	4.02%	4.29%	5.50%

Table 3
ANOVA and Post-hoc test for speed, acceleration noise, and vehicle emissions.

	ANOVA					Post-hoc test (subset for alpha = 0.05)					
	Sum of squares	*df*	Mean squares	*F*	Sig.	Scenario	Samples	1	2	3	4
Speed											
Between groups	1839.9	3	613.3	27430.9	0.000	4	30	31.6			
						3	30		38.6		
Within groups	2.59	116	0.022			2	30			40.8	
						1	30				41.5
Total	1842.6	119				Sig. probability		1.00	1.00	1.00	1.00
Acceleration noise											
Between groups	1.926	3	0.642	19062.6	0.000	4	30	0.77			
						3	30		1.02		
Within groups	0.004	116	0.000			2	30			1.06	
						1	30				1.09
Total	1.930	119				Sig. probability		1.00	1.00	1.00	1.00
CO_2											
Between groups	23.2	3	7.748	1908.5	0.000	2	30	22.1			
						1	30		22.5		
Within groups	0.47	116	0.004			3	30			22.6	
						4	30				23.3
Total	23.71	119				Sig. probability		1.00	1.00	1.00	1.00
$PM_{2.5}$											
Between groups	3.14	3	1.045	230.4	0.000	2	30	0.90			
						1	30	0.93			
Within groups	0.53	116	0.005			3	30		1.02		
						4	30			1.31	
Total	3.66	119				Sig. probability		0.25	1.00	1.00	–

OpMode consists of 71 modes based on vehicle specific power (VSP) and vehicles' speed bins and their acceleration/deceleration rates. Operating modes, including cruising, acceleration/deceleration, idling, and braking, are associated with emissions. VSP uses second-by-second vehicle trajectory data and is given by the following (US Environmental Protection Agency, 2010):

$$VSP = \frac{Av + Bv^2 + Cv^3 + mav + mv\sin\theta}{m_{fixed}} \tag{3}$$

where A is a rolling term, B is a rotating term, C is a drag term, m is the source mass (metric tons), m_{fixed} is a fixed mass factor (metric tons), v is the vehicle velocity (m/s), g is the gravitational constant, a is vehicle acceleration (m/s^2), and θ is the road grade.

To estimate vehicle emissions from the traffic simulation results, OpMode lookup-table approach that reduces computational time was used (Lee et al., 2012).

5. Results

To evaluate the performance for each traffic calming scenario, each scenario was run 30 times in VISSIM. Microscopic simulation is stochastic in nature (i.e., types of vehicles are released into the traffic network based on a random distribution), so numerous runs of each scenario are necessary to obtain reasonable estimates of mean statistics based on the central limit theorem.

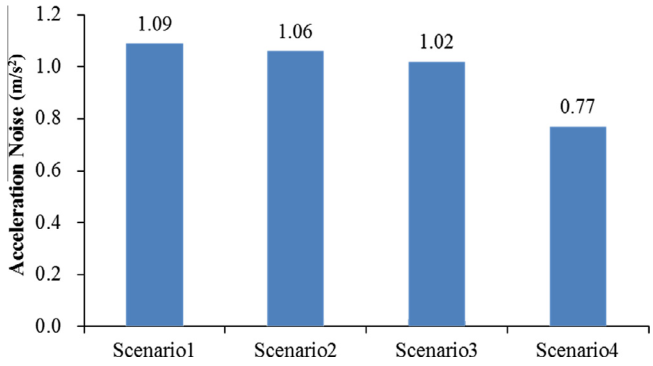

Fig. 5. Acceleration noise results.

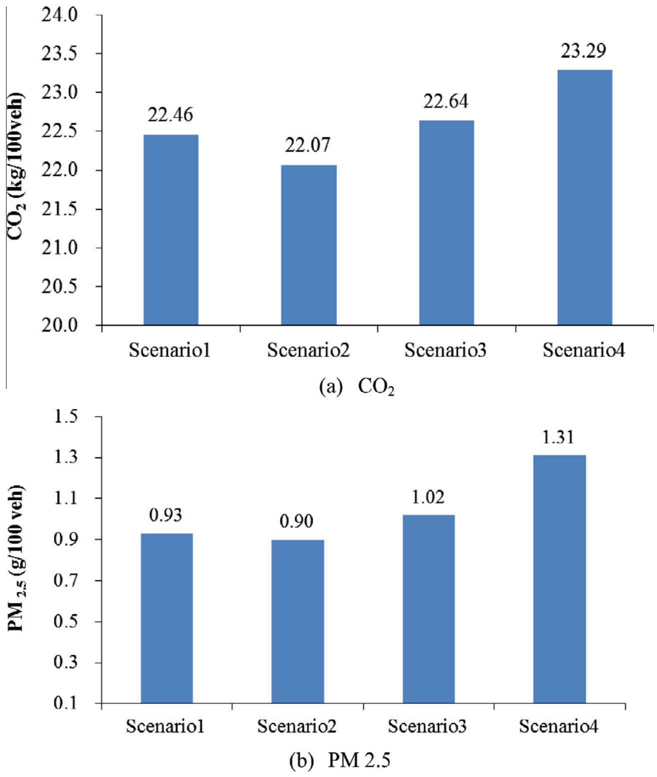

Fig. 6. Vehicle emissions under each scenario.

Before evaluating the performance for each scenario, simulated and observed speeds and accelerations in the speed reduction area of each scenario were compared. Fig. 3 shows the sampled speed profiles for each scenario based on the GPS data and the simulated data. Not every speed profile in the two sets can be perfectly matched, but the overall patterns of the speed profiles are quite similar for the two sets. However, in examining the average speeds of the speed reduction area for each scenario, more accurate calibration results can be discussed.

As Table 2 shows, differences in average speeds between the simulated and observed data are less than 1% for Scenarios 1 and 2, and less than 3% for Scenarios 3 and 4.[1] Additionally, the differences in the average acceleration between the simulated and observed data are approximately 4–5% for all scenarios. Based on *Z*-test, the null hypothesis of the average acceleration cannot be rejected at the 5% significance level as well. Our simulation network can be thus be considered well calibrated and suitable for capturing driving patterns for use in evaluating traffic calming measures.

[1] In addition, the two sets of data were compared using z-based statistical hypothesis tests. For all scenarios, the null hypothesis ($H_{\text{Observed}} = H_{\text{Simulated}}$) was not rejected at the 5% significance level.

Table 4
Overall results for the scenarios.

	Scenario 1 (speed hump 3 m)	Scenario 2 (speed hump 4 m)	Scenario 3 (speed table)	Scenario 4 (chicane)
Speed	3	4	2	1
Acceleration noise	4	3	2	1
Vehicle emissions	2	1	3	4

The results for each scenario generated from 1-h traffic simulations were analyzed by post-processing procedures. A single "analysis section" in the designed traffic simulation link was considered to evaluate all scenarios under the same traffic conditions (Fig. 4). The scenarios compared using an analysis of variance (ANOVA) and Tukey's post hoc test.

The average speeds in the analysis section were 40.78, 41.51, 38.55, and 31.6 kph for Scenarios 1 through 4. The chicane had the lowest average speed of the traffic calming measures considered, and the speed humps had the highest average speed. When compared to the speed limits of 50 kph, the average speed of the chicane decreased by approximately 37%. On the other hand, the average speed reduction rate of the speed humps was about 18% among the analyzed traffic calming measures.

ANOVA and Tukey's post hoc test were conducted to determine whether the average speeds of the scenarios are significantly different. As Table 3 shows, the average speeds of the scenario were significantly different according to the ANOVA. The post-host test indicates that the average speeds of the scenarios were significantly different at the 95% confidence level.

Fig. 5 illustrates the acceleration noise for each scenario. Drivers reduce their speeds rapidly and unexpectedly for their safety and comfort when passing traffic calming devices. As seen, the speed humps had higher acceleration noise, and the chicane had the lowest suggesting drivers maintain more uniform speeds when approaching and passing the chicane. Based on the statistical testing, acceleration noises was also found to be significantly different across the cases (Table 3).

CO_2 and $PM_{2.5}$ were selected as the vehicle emissions measurements used in evaluating the environmental impact of the traffic calming devices studied. CO_2 is one of the primary sources of greenhouse gases, and $PM_{2.5}$ consists of extremely small particles and liquid droplets in the ambient air and adversely affects public health, and long-term exposure contributes to respiratory diseases and mortality in local communities (Krewski et al., 2009).

Fig. 6 shows that the estimated emissions of CO_2 and $PM_{2.5}$ for speed humps were approximately 4% and 30% lower than those of the chicane. Unlike average speed and acceleration noise, the estimated emissions of CO_2 and $PM_{2.5}$ were lower for the two speed humps than for other two traffic calming measures because emissions from vehicles are increased at average driving speeds below 70–80 kph (Barth and Boriboonsomsin, 2008).

Table 3 summarizes the ANOVA and post hoc test results for emissions for all scenarios. The estimated emissions for all scenarios were significantly different, except for the $PM_{2.5}$ emissions of the two speed humps. Table 4 ranks the evaluation results for the scenarios by the three performance measures. Overall, the chicane was the most effective traffic calming device, based on the three criteria. However, as seen, chicanes generated the highest level of vehicle emissions among the traffic calming measures considered because the average speeds are lowest when passing the chicane. The speed variations in the cases of chicanes, however, were smaller than those of the other measures.

6. Conclusions

This paper develops a comprehensive evaluation method for traffic calming measures that considers traffic calming performance, safety, and environmental impact. The evaluation method is developed using a microscopic traffic simulation model to evaluate four traffic calming measures under identical conditions. Speed was used as a surrogate measure of traffic calming performance. Safety was evaluated in terms of acceleration noise. The environmental and health impacts of the measures considered were evaluated in terms of CO_2 and PM pollutants. The proposed comprehensive framework can be used as a useful decision-support tool for evaluating or selecting various traffic calming measures before implementation.

As an example, two types of speed humps, speed tables, and chicanes were considered for a local community in Korea. It was found that chicanes provided the best performance among the selected traffic calming devices considered in terms of speed reduction and acceleration noise but not in terms of environmental and public health impact. This means that the selection of one type of traffic calming measure for a local community depends on how the decision-makers of that community value the various performance measures. If the decision-makers place more weight on environmental and public health impacts for their community, they might select speed humps rather than chicanes for the community.

Acknowledgement

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