Journal of Safety Research 75 (2020) 78–86

Contents lists available at ScienceDirect

Journal of Safety Research

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

Effects of speed humps on vehicle speed and pedestrian crashes in South Korea

Jiho Yeo [a], Jooyoung Lee [a], Junhan Cho [b], Dong-Kyu Kim [c], Kitae Jang [a,*]

[a] The Cho Chun Shik Graduate School of Green Transportation, Korea Advanced Institute of Science and Technology, Munji-ro, Yuseong-gu, Daejeon 340-51, Republic of Korea
[b] Samsung Traffic Safety Research Institute, Samsung Fire & Marine Insurance Bldg., 355 Gangnamdae-ro, Seocho-gu, Seoul 066-26, Republic of Korea
[c] Department of Civil and Environmental Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 151-744, Republic of Korea

A R T I C L E I N F O

Article history:
Received 11 October 2019
Received in revised form 24 January 2020
Accepted 4 August 2020
Available online 17 August 2020

Keywords:
Traffic safety
Traffic calming measures
Speed control devices
Speed hump
Crash analysis

A B S T R A C T

Introduction: Speeding is a crucial risk factor for pedestrian safety because it shortens reaction time while increasing the impact force in collisions. Various types of traffic calming measures to prevent speeding have been devised. A speed hump—a raised bump installed in the pavement—has been widely used for this purpose. *Method:* To evaluate the effectiveness of speed humps, the speed profiles of vehicles passing speed humps were analyzed along with pedestrian crash records near speed humps. *Results:* The speed profiles showed that vehicles gradually diminished their speeds starting 30 m ahead of speed humps and, immediately after passing the humps, accelerated to regain their original speeds within a distance of 30 m. This speed reduction effect is substantial on both local and major roads: 18.4% and 24.0% reduction in speeds, respectively. The analysis of pedestrian crash records revealed that, inside the zones of speed reduction effect near speed humps (i.e., ±30 m from speed humps), fewer pedestrian crashes per roadway distance occurred and pedestrian injuries were less severe, compared with events outside the effect zones. This safety improvement was greater on major roads than local roads. *Practical Applications:* This work finds that the speed reductions that occurred near speed humps were gradual and influential ±30 m from their locations, suggesting that the hump installations should be close enough to the pedestrian crossings. It is noteworthy that, albeit that speed humps are more prevalent on local roads, the benefits of speed reduction effects from speed humps were more pronounced on major roads than on local roads. Therefore, speed humps on major roads can be considered a more effective measure for pedestrian safety.

1. Introduction

In South Korea, there were 4,185 deaths due to traffic crashes in 2017, which is a substantial reduction over the last two decades (Korea Road Traffic Authority, 2019). Despite the reduction, the high risk of pedestrian crashes and fatalities still remains a serious safety concern in South Korea. An average of 1,762 pedestrians died annually from 2013 to 2017, accounting for 38.4% of total traffic fatalities (Korea Road Traffic Authority, 2019). Among various factors, speeding is considered a critical risk factor for pedestrian safety because speeding increases the forces directed against pedestrians in a collision and reduces the reaction time of drivers as well as pedestrians (Gårder, 2004; Liu et al., 2002; Otte, 1999). To mitigate the effects of speeding, various speed control devices and traffic calming measures have been deployed where special care for pedestrians is required, such as school zones and pedestrian-crash hotspots. A speed hump—a raised device installed on the pavement—is the most prevalent speed control device. Because it induces vertical deflection of a passing vehicle, vehicles tend to diminish their speeds to pass the artificial obstacles more comfortably.

A group of previous studies examined the effect of speed humps on vehicle speeds in case-control studies to compare vehicle speeds on roadway sections with and without speed humps (Antić, Pešić, Vujanić, & Lipovac, 2013; Ewing, 1999; Marek & Walgren, 1998; Smith, Knapp, & Hallmark, 2002; Smith, 2002). Although before-after studies are the standard method for evaluating the effects of traffic calming measures, cross-sectional studies were also conducted (Barbosa, Tight, & May, 2000; Barbosa, 1995; Johansson, Rosander, & Leden, 2011; Moreno & García, 2013; Moreno, García, & Romero, 2011) to complement practical limitations of before-after studies (e.g., sample size, study period).

* Corresponding author.
E-mail addresses: jiho@kaist.ac.kr (J. Yeo), mose585@kaist.ac.kr (J. Lee), junhan.cho@samsung.com (J. Cho), dongkyukim@snu.ac.kr (D.-K. Kim), kitae.jang@kaist.ac.kr (K. Jang).

https://doi.org/10.1016/j.jsr.2020.08.003
0022-4375/

The outcomes of these studies showed that vehicles indeed lowered their speeds when passing the speed humps. It was reported that the range of changes in vehicle speeds was between −4% and −42% (Barbosa, 1995; Barbosa et al., 2000; Ewing, 1999; Smith et al., 2002; Smith, 2002) and that the vehicles started to slow down 160–205 feet (49–62 m) before the humps, accelerated after passing the humps, and recovered their original speed 60–85 feet (18–25 m) after passing the humps (Smith, 2002). However, the quantitative effects of speed reduction are as yet unclear because the degree and the distance of speed reductions that were induced by speed humps varied widely across study sites. Moreover, although the influential area of speed humps is as important as the magnitude of speed reduction, there is little research deriving the influential area of speed humps.

Another group of studies conducted before-and-after comparative analysis using traffic crash data near the speed humps and reported that pedestrian safety was enhanced after installing speed humps. Afukaar and Damsere-Derry (2010) found a 37.5% reduction in casualty crashes. Chen et al. (2013) found reductions of 20% of all and 41% of pedestrian crashes in mid-blocks, and 14% and 12% at intersections. Cottrell, Kim, Martin, and Perrin (2006) found a reduction of 10% of all crashes, but this was not statistically significant. Ewing and Dumbaugh (2009) found a reduction of 14% for all crashes, but again this was not statistically significant. Engel and Thomsen (1992) found a reduction of 72% for all crashes. Although crash reduction effects of speed humps have been investigated in many studies, these studies did not factor in the exact distances where the speed humps were influential even though it is a crucial factor for accurate effect evaluation.

In addition, speed humps can also affect the degree of injury as well as the occurrence of crashes, but there is little research reporting on the relationship between crash severity and speed humps using a detailed statistical model. One study matched large-scale hospital-based injury records of child pedestrians with the installation of speed humps near their residential neighborhood and evaluated the effect of speed humps on crash severity (Tester, Rutherford, Wald, & Rutherford, 2004). The study demonstrated the protective effect of speed humps on child pedestrians. However, this study might have included some confounding effects because a pedestrian crash did not always occur near the victim's residence.

To shed light on these issues, we investigated the effects of speed humps on both speed reduction and traffic safety. Specifically, we examined when speed reduction occurs near speed humps and verified their statistical significance using large-scale driving records. The remainder of this paper is organized as follows: Section 2 describes observations and experiments used to obtain driver speed profiles near speed humps and to estimate the distance and degree of speed reduction. Section 3 explains geo-query of traffic crashes that occurred inside the zone of an estimated distance of speed reduction and analyzed the effect of speed humps on crash occurrences and severity of the injury. Section 4 presents conclusion of the research with the key findings and implications for deploying speed humps.

2. Effect of speed humps on vehicle speeds

To evaluate the speed profiles of vehicles that passed the speed humps, we collected data in various ways. First, we designed experiments to collect speed data from vehicles that were driven by seven recruited drivers along a roadway section with multiple speed humps. For the same section, we made observations of other vehicles passing over the speed humps (Section 2.1). The degree and distance of speed reduction near speed humps that were measured in the roadway section were then validated using a large number of taxi trajectories (Section 2.2).

2.1. Speed reduction pattern

2.1.1. Study site and data collection

To control for the effects of various influential factors, we selected a study site and data collection time based on the following criteria:

i) The roadway section should have multiple speed humps to prevent the possible effect of varying driver groups because a similar set of drivers would pass the target humps if they were on the same roadway section.
ii) During data collection, traffic on the roadway section should be able to move mostly at its desired speed (not necessarily below the speed limit) without any substantial interactions between vehicles.
iii) The speed data should be collected only during time periods of normal operation on clear days (i.e., no special event near the roadway section).

Based on these criteria, three speed humps along a 1.84-km stretch of East Pangyo Street in the city of Pangyo (Gyeonggi Province, South Korea) were selected, as shown in Fig. 1. It is a newly built, wide, four-lane road that provides good driving conditions, mostly free-flowing.

We conducted an experiment with seven recruited drivers between 10 .m. and 4 p.m. on March 26 and 27, 2015. The participants were aged 20–30 years (5 males and 2 females). They were hired to drive a car equipped with a GPS logger over five round trips of the study site. Because the participants' awareness may unintentionally bias the driver behavior, the details on the experiments were not explained to the participants, although they knew they were participants of an experiment.

After the experiments, we compared the observation and experiment data to examine whether the participants' awareness of experiments induces bias to their driving. Observations were made using Universal Medium Range Radar (UMRR) equipment providing relative locations of detected vehicles with speeds detected every 75 ms[1]. Monitoring equipment was placed at the targeted set of humps, and trajectories of all passing vehicles were collected from 10 a.m. to 4 p.m. on June 17 and August 7 of 2015.

2.1.2. Analysis of speed profiles

Speed profiles of the seven drivers who participated in the experiment were plotted with boxplots in locations relative to the speed humps, each of which is marked 0; in Fig. 2, a negative sign on the x-axis indicates upstream of the speed hump, and vice versa. The distribution of speed data that were collected within each 10-m interval was presented as a boxplot.

Boxplots for each speed hump in Fig. 2(b)–(d) show similarity in driver speed-making behavior—vehicles started to diminish their speeds, accelerate immediately after passing the humps, and recovered to their original speeds around 30-m of the humps. The driver deceleration and acceleration patterns near speed humps were consistent with those in previous observational studies (Barbosa et al., 2000; Moreno et al., 2011; Pau & Angius, 2001; Smith et al., 2002).

It is worth noting that speed variation was relatively small near the speed humps and became greater farther from the humps, especially more than 40 m away. This indicates that the installa-

[1] Up to 256 objects could be tracked simultaneously with ±1.5% range accuracy and ±0.28 m/sec speed accuracy.

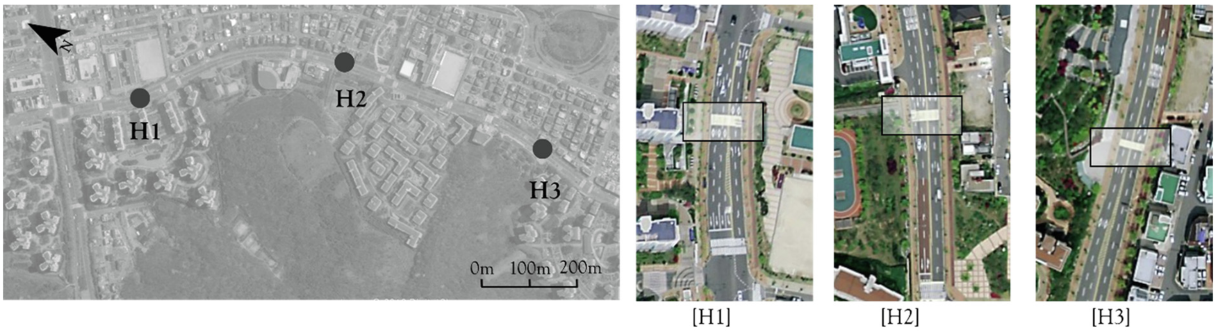

Fig. 1. Study site on East Pangyo St., Pangyo City, South Korea.

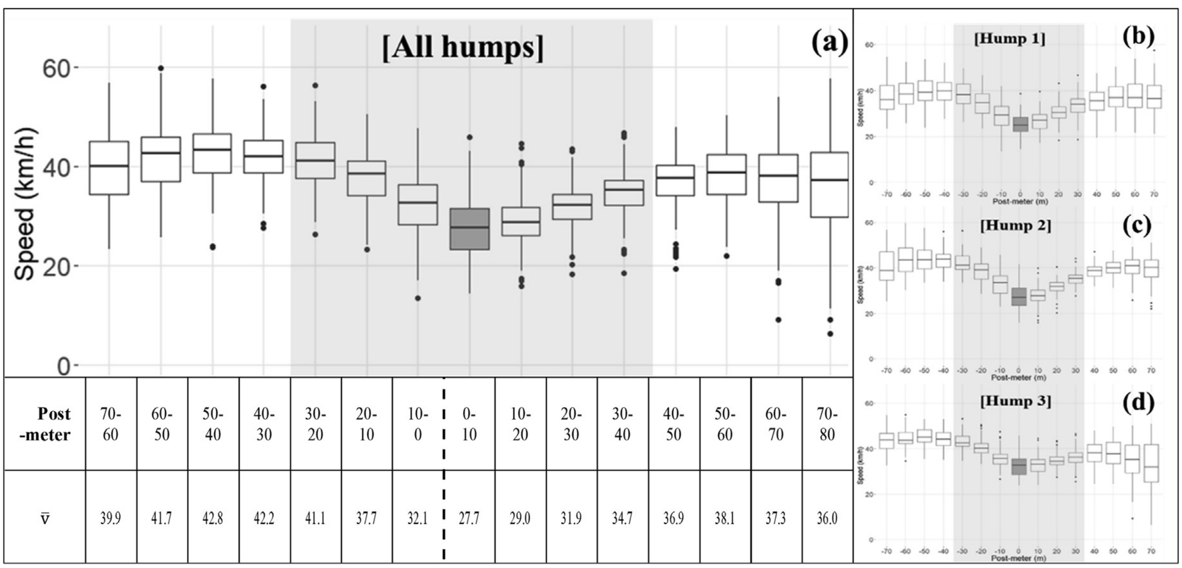

Fig. 2. Speed profiles with mean speeds in the experiment.

tion of speed humps is also effective in reducing speed variation, which shows their potential to control drivers having more extreme speeds.

To estimate the degree of speed reduction, we aggregated and plotted the speed data in Fig. 2(a). The boxplots in the figure indicate that the vehicle median speed, noted as the solid lines in the middle of the boxes, was about 40 km/h prior to speed reduction and after the speed recovery, and 27.7 km/h at the hump. This is about a 30% reduction in speed.

To validate the outcomes in the experiment with seven drivers, we constructed boxplots of speed data at 10-m intervals, which were observed from vehicle trajectories in Fig. 3. Using radar, we collected 298 trajectories of vehicles that passed the three speed humps (122 trajectories at hump 1; 87 at hump 2; and 89 at hump 3). The speed profiles that were collected separately from experiments and observations were similar, implying that the participants drove vehicles as comparable as other vehicle drivers along with our study sites.

The outcomes in this study site showed that vehicles started to diminish their speeds 30 m before the speed hump, reached a minimum speed at the hump, and recovered to their original speed 30 m after passing the hump. The amount of speed reduction at the three speed humps was about 12 km/h on average, which is a 30% reduction from the cruising speed. These outcomes were based on the experiments and observations performed at the study site to control for possible confounding factors. Even so, outcomes could differ across sites because site-specific attributes could influence driver behavior. As reported in the next section, we collected city-wide taxi trajectory data to validate these outcomes.

2.2. Verification

To examine the effect of speed humps at a larger scale, we obtained the driving records of 1,334 taxis over 22 consecutive days between August 10 and 31 of 2019 from the Korea Transportation Safety Authority (eTAS, 2019). A massive amount (21,568 vehicle·hours) of driving records were collected in the city of Pohang (Gyeongsangnam Province, South Korea) where a data collection system is well established. The records include information on vehicle position, time, speed, and brake sensor in seconds. Because we obtained the data from taxis, we queried the driving records of at least 30 consecutive seconds (to exclude data sets with missing information) with an average speed over 10 km/h (to exclude data during passenger waiting or slow searching).

For the analysis, we selected 363 speed humps out of 1,748 speed humps in the city, which were located mid-block, to avoid the possible effects of traffic signals or traffic interactions in the intersections (See Fig. 4). Based on the distance of speed reduction reported in Section 2.1., we divided the roadway sections that included a speed hump into: (i) inside the zone of influence of the speed hump (a roadway segment ±30-m from the speed

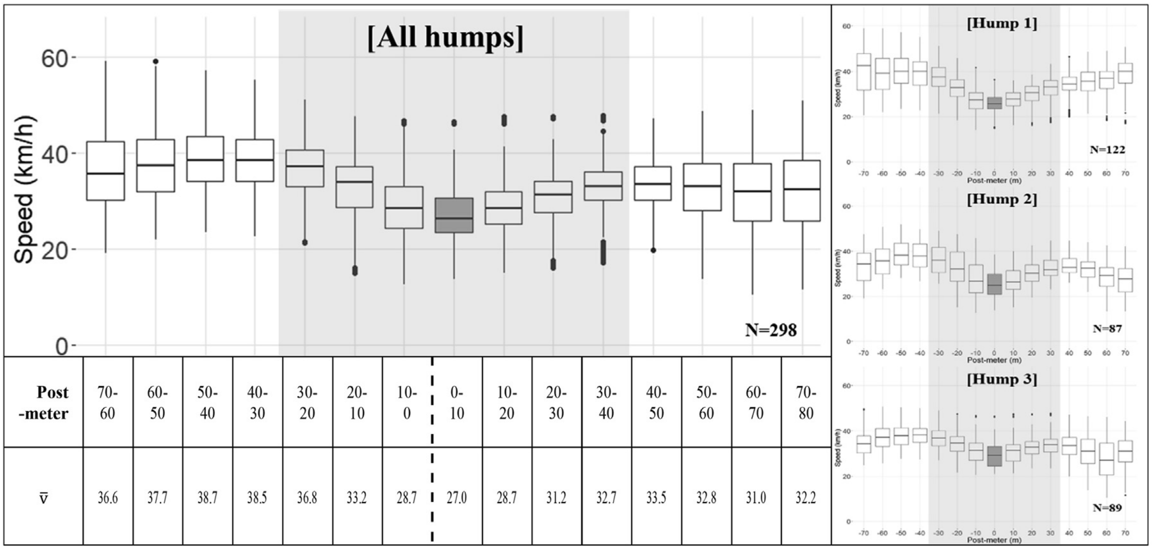

Fig. 3. Speed profiles with mean speeds in the observations.

Fig. 4. A magnified view of a part of the study site.

hump), and (ii) outside the zone of influence of the speed hump (roadway segments at least 30 m from the speed hump).

The taxi driving records were also grouped into two categories: driving records that were collected (i) inside the zones influenced by speed humps and (ii) outside the zones influenced by speed humps. This categorization was processed using a geospatial analysis tool in ArcGIS (Sandhu & Chandrasekhar, 2006) and Python (Jordahl, 2014), with geo-coded location information of speed humps and driving records.

Furthermore, because vehicle speeds are greatly influenced by roadway types, a speed distribution was constructed for each category in two different roadway functional classifications: major and local roads. There are six classes of roadway in South Korea: expressway, major arterial, minor arterial, collector, local and alley (Ministry of the Interior and Safety (MOIS), 2019). We classified minor arterials and collectors as major roads and local and alley as local roads. Expressways and major arterials were removed from the analysis because they do not have speed humps.

The speed distributions were displayed in Fig. 5, and the average and 85th percentile speeds of vehicles were estimated for each category. As shown in the figure, the comparisons of average and 85th percentile speeds show that the difference of speed inside and outside the zones of influence of speed humps is statistically significant on both major and local roads. On local roads, the average speed of vehicles inside the zones of influence was 20.17 km/h—18.4% lower than outside the zones of influence (29.20 km/h). On major roads, the average speed inside the zones of influence of speed humps was 29.20 km/h (24.0% less than 38.43 km/h). It is worth noting that the degree of speed reduction effect was greater when comparing 85th percentile speeds. Compared with the speeds outside the influence of speed humps, the 85th percentile speed on the local road was 25.0% lower inside the zones

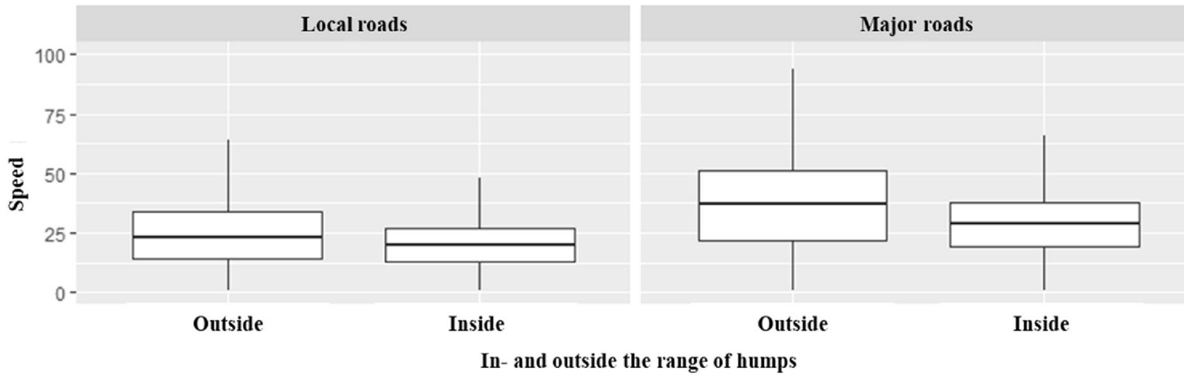

Fig. 5. Vehicle speeds inside and outside zones of influence of 363 speed humps.

of influence, while it was 26.7% lower on major roads. These outcomes confirm, based on the larger data set, that the speed reduction effect near speed humps is reproducible across sites.

3. Crash analysis

We examined pedestrian crash data that occurred on the entire roadway network in South Korea (see Section 3.1), and statistically evaluated the effect of speed humps (i.e., speed reduction effect) on crash occurrence (see Section 3.2) and severity (see Section 3.3).

3.1. Description of crash data

Two years (2015–2016) of traffic crash records that were collected and maintained by the Korean National Police Agency were used for the crash analysis. For the two years of the study period, 468,199 crashes were reported, of which 101,509 crashes (21.7%) were pedestrian-related (Korea Road Traffic Authority, 2019). The crash data included information on time and location of crashes, attributes of crashes (e.g., crash types and primary crash factors), attributes of drivers and victims, weather and environmental conditions, and vehicle types. However, because these records do not include information on speed humps, we geographically matched locations of crashes and speed humps and added an indicator variable to show whether the crash occurred within the zone of influence of speed humps (i.e., ±30 m from speed humps). A description of the crash data is provided in Table 1.

Table 1
Descriptive statistics of the crash data (only pedestrians).

Variables	Categories	Percentage
Time of the day	Day	52.19%
	Night	47.80%
Car type	Passenger car	70.79%
	Van	7.80%
	Freight	12.49%
	Other	8.90%
Weather	Dry	85.91%
	Cloudy	4.07%
	Rain	8.98%
	Fog	0.10%
	Snow	0.43%
	Other	0.49%
Location	Sidewalk	3.00%
	Shoulder	6.58%
	Traffic lane	6.01%
	Crosswalk	60.49%
	Other	23.90%
Road Segment	Intersection	33.94%
	Link Crosswalk	11.82%
	Other	54.22%
Gender (Drivers)	Male	76.76%
	Female	23.23%
Age (Drivers)	Younger than 65	90.34%
	Older than 65	9.66%
Age (Pedestrians)	14–65 olds	64.36%
	Younger than 14	11.50%
	Older than 65	24.13%
Road type	Local roads	40.78%
	Major roads	59.21%
Hump	Not-installed	87.50%
	Installed	12.49%

3.2. Effect of speed humps on crash occurrence

We compared the numbers of pedestrian crashes inside and outside the zones of influence of speed humps. The outcomes of simple comparison, however, could be biased by unobservable factors unless we controlled for other circumstances (Clarke, 2005). Hence, we plotted 300-m grids on the entire road network of South Korea and calculated the number of pedestrian crashes per unit distance separately for major roads and local streets in each grid cell. This procedure allowed the reduction of the effect of unobserved variables because environments did not vary substantially within a grid cell.

Fig. 6 illustrates the procedure. Crashes and speed humps were represented by red dots and yellow dots, respectively. Roadway segments within the zones of influence of speed humps (±30 m from the speed humps) were plotted using green solid lines. Using geographic analysis, we declared crashes to be under the influence of speed humps if red dots (the crashes) overlapped a solid green line (roadway segments under the influence of speed humps). Out of 101,509 pedestrian crashes in 2015 and 2016, 12.6% of crashes occurred on local roads under the influence of speed humps, while 7.6% of crashes were on major roads under the influence of speed humps.

In South Korea, there were 7,272 and 5,054 grid cells that included major roads and local roads, respectively. For each cell, we measured the length of local and major roads, and counted the numbers of crashes inside and outside the influence of speed humps. For each cell i, we estimated a_i^{in}, which is the number of crashes per kilometer inside a certain distance from the speed hump. To verify that the effects of speed humps realized within 30 m, we have set the distance incrementally by 10-m from 10 to 50 m; and estimated the averages, $\bar{a}_i^{in}$, across cells for each distance, as shown in Table 2. The number of crashes per kilometer was the smallest within 10 m from the speed humps. As the dis-

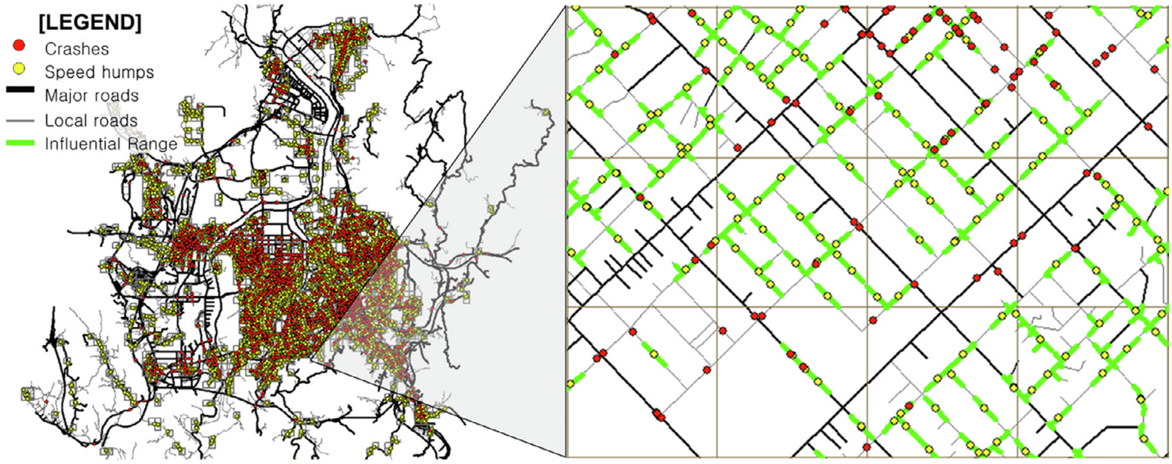

Fig. 6. Geographic analysis to identify crashes within the zones of influence of speed humps.

Table 2
Means of crashes per kilometer within various distances from the speed humps.

Road hierarchy	The number of crashes per kilometer ($\bar{a}_i^{in}$)					Number of grids
	10 m	20 m	30 m	40 m	50 m	
Local roads	1.68	1.78	1.81	1.80	1.78	4,673
Major roads	2.36	2.45	2.58	2.61	2.62	2,085

tance increases, the number of crashes steadily increases until 30 m, which overlaps with the distance where the speed reduction occurred. Hence, the comparisons of crash occurrences between inside and outside the influence of speed humps were made for the 30-meter distance.

For the 30-m influence zone, the numbers of crashes per kilometers inside the influence of speed humps, a_i^{in}, and outside the influence of speed humps, a_i^{out}, for local and major roads were estimated. Then, the means of a_i^{in} and a_i^{out} across all grid cells were estimated on local and major roads (See Table 3). On major roads, $\bar{a}_i^{in}$ was 2.58 crashes/km while $\bar{a}_i^{out}$ was 3.57 crashes/km. On local roads, $\bar{a}_i^{in}$ was 1.81 crashes/km and $\bar{a}_i^{out}$ was 2.14 crashes/km. On both types of roads, fewer crashes per distance occurred inside the zones of influence of speed humps. To statistically test these differences, paired t-tests were performed for the differences between pairs of $\bar{a}_i^{in}$ and $\bar{a}_i^{out}$. For both major and local roads, the differences between $\bar{a}_i^{in}$ and $\bar{a}_i^{out}$ were statistically significant.

Furthermore, Table 4 shows crash severity statistics by road types and installation of speed humps. The statistics show that as well as crash occurrence, speed humps are also effective in reducing crash severity, especially by preventing fatalities. The fatal crashes near speed humps on major roads decreased from 6.07% to 2.07% and from 1.97% to 1.01% on local roads. To control for other exogenous factors such as the age of drivers and victims, and the types of vehicles and roadways, statistical analyses were conducted, and the results are reported in the next section.

3.3. Effect of speed humps on crash severity

3.3.1. Ordered probit model

The level of severity of a traffic crash records the highest level of injury severity among the victims from the crash. In pedestrian crashes, it generally indicates the injury severity of pedestrians in traffic crashes and is categorized into discrete variables. These categories are usually ordered from the most severe case to the least severe one. There are four injury categories in traffic crash data: fatal, severe injury, moderate injury, and minor injury[2]. In the study, we combined the two lowest injury levels, moderate and minor injury, into one response variable because pedestrian-involved crashes usually resulted in at least minor injury.

The ordered probit model is widely-used for outcome variables of this type (i.e., ordinal and categorical responses) (Jang et al., 2013; Khattak et al., 2002, 2003; Kockelman & Kweon, 2002; Lee & Abdel-Aty, 2005; Quddus, Noland, & Chin, 2002; Rifaat & Chin, 2007; Tay & Rifaat, 2007). The general model specification is:

$$y_i^* = X_i\beta + \varepsilon_i$$

where

y_i^* =Latent and continuous variable measuring injury severity of the ith collision
X_i =Vector of independent variable describing environmental characteristics of ith collision
β =Vector of parameters to be estimated
ε_i =Random error term assumed to be a standard normal distribution

The latent and continuous variable y_i^*, is not directly observable; therefore, it is expressed using the observed variable y_i, a discrete level of injury severity, as follows:

$$y_i = \begin{cases} 1 & \text{if } -\infty < y_i^* \le \mu_1 \quad \text{Minorinjury} \\ 2 & \text{if } \mu_1 < y_i^* \le \mu_2 \quad \text{Severeinjury} \\ 3 & \text{if } \mu_2 < y_i^* \le \infty \quad \text{Fatalinjury} \end{cases}$$

where thresholds μ_k includes unknown coefficients for the threshold between categories k and $k+1$, which is estimated along with

[2] The Road Traffic Act in South Korea has four classifications of injury: fatal—Dies within 30 days from the crash date; major injury—Injuries requiring treatment for 3 weeks or more; moderate injury—Injuries requiring treatment for more than 5 days and less than 3 weeks; minor injury—Injuries requiring less than 5 days of treatment.

Table 3
Comparison of crash frequency inside and outside the influence of speed humps.

Road hierarchy	The number of crashes per kilometers		Number of grids	t-statistic	p-value
	$\overline{a}_i^{in}$	$\overline{a}_i^{out}$			
Local roads	1.81	2.14	7,272	5.36	<0.000
Major roads	2.58	3.57	5,054	7.95	<0.000

Table 4
Crash severity statistics in relation to the installation of speed humps and road types.

Hump	Road Type	Fatal crash percentage	Severe crash percentage	Minor crash percentage	Number of crash
Installed	Local	1.01	37.06	61.93	5,038
Non-installed	Local	1.97	40.70	57.32	20,561
Installed	Major	2.07	44.04	53.89	2,804
Non-installed	Major	6.07	51.66	42.28	34,370

the coefficients β, in the model. The conditional distribution of y_i is derived as:

$$P(y_i = k|X_i) = P(\mu_{k-1} < y_i^* \leq \mu_k|X_i) = P(\mu_{k-1} < X_i\beta + \varepsilon_i \leq \mu_k)$$
$$= \Phi(\mu_k - X_i\beta) - \Phi(\mu_{k-1} - X_i\beta)$$

where Φ is the cumulative distribution function of the standard normal distribution.

The maximum likelihood estimation was used to obtain estimated coefficients in the model. This procedure can be performed using statistical software, R, with "erer" package (Hothorn & Everitt, 2014). The full derivation of the model is given by McKelvey and Zavoina (1975).

3.3.2. Model outcomes

The exponentiated coefficient indicates the changes in odds ratio, compared with the reference group (because all the explanatory variables are categorical), while holding other variables constant. If the exponentiated coefficient is greater than 1, the variable is likely to increases the level of severity – increase the probability of fatal injury while decreasing the probability of minor injury. However, because the response variable in our study has three ordinal responses, it is difficult to interpret how the variable affects the response in the middle (i.e., severe injury). In view of this in more detail, marginal effects were computed along with the exponentiated coefficient. The marginal effect presents the change in probability of each response if the variable is 1; i.e., the subject falls into the corresponding category.

In this section, we focus our interpretation on the coefficients related to speed humps and road types, noted in bold in Table 5. Compared with the pedestrian crashes outside the zones of influence of speed humps, crashes inside the influence zones had a lower risk of severe and fatal injury, as the marginal effects of hump variable had negative signs for both severe and fatal injury responses. Risk of severe injury was higher on major roads. This outcome is intuitively reasonable because the vehicle speed is gen-

Table 5
Ordered probit estimates and marginal effects.

Base case: Minor injury	Categories	Coefficient	p-value	Marginal effect		
Variables				Minor	Severe	Fatal
Time of the day	0: Day, 1: Night	1.075***	0.00	−0.071	0.059	0.012
Car type (Ref: Passenger car)	Van	1.042**	0.03	−0.016	0.013	0.003
	Freight	1.277***	0.00	−0.097	0.077	0.020
	Other	0.919***	0.09	0.034	−0.028	−0.005
Weather (Ref: Dry)	Cloudy	1.173***	0.00	−0.063	0.051	0.012
	Rain	1.075***	0.00	−0.029	0.024	0.005
	Fog	2.666***	0.00	−0.333	0.180	0.153
	Snow	1.131*	0.00	−0.049	0.039	0.009
	Other	1.040	0.57	−0.016	0.013	0.003
Location (Ref: Sidewalk)	Shoulder	0.886***	0.00	0.048	−0.041	−0.007
	Traffic lane	1.102***	0.10	−0.039	0.032	0.007
	Crosswalk	1.161***	0.00	−0.059	0.050	0.010
	Other	0.965	0.23	0.014	−0.012	−0.002
Road Segment (Ref: Other)	Intersection	1.029***	0.01	−0.011	0.009	0.002
	Link Crosswalk	1.074***	0.00	−0.029	0.023	0.005
Gender (Ref: Male)	Female	0.967***	0.01	0.013	−0.011	−0.002
Age (Ref: Younger than 65)	Older than 65	1.011	0.51	−0.004	0.004	0.001
Victim Age (Ref: 14 < AGE < 65)	Younger than 14	0.881***	0.00	0.051	−0.043	−0.008
	Older than 65	1.987***	0.00	−0.263	0.197	0.066
Road type	**0: Local, 1: Major**	**1.415*****	**0.00**	**−0.138**	**0.116**	**0.022**
Hump	**0: Outside, 1: Inside**	**0.919*****	**0.00**	**0.034**	**−0.028**	**−0.005**
Hump * Road type		**0.837*****	**0.00**	**0.071**	**−0.061**	**−0.010**

*p < 0.1.
**p < 0.05.
***p < 0.01.

erally higher on major roads than on local roads. On the other hand, it is noteworthy that the interaction term of a hump and a road type has a value smaller than one, signifying that the impact of the humps in reducing the level of crash severity on major roads is greater than on local roads. The change in the marginal effect of the interaction term also indicates that speed humps installed on major roads will lower the likelihood of both fatal and severe injury compared to speed humps installed on local roads.

4. Conclusions

In this paper, we evaluate the effects of speed humps on vehicle speeds and pedestrian safety. The speed data were collected in the first analysis while controlling for other influential factors on a roadway section with three speed humps. The analysis of data revealed that drivers started to diminish vehicle speeds about 30 m ahead of speed humps, reached their lowest speeds at the humps, and recovered to their original speeds 30 m after passing the humps. The speed reductions that were induced by the speed humps were influential ±30 m from the humps.

To validate the distance of these zones of influence, we hypothesized the distance inside the influence of speed humps as ±30 m (i.e., 60 m with the speed hump in the middle) and, then, measured the degree of speed reduction by comparing vehicle speeds inside and outside the zones of influence of speed humps with large-scale vehicle trajectories. The speed comparison showed that the average vehicle speed within ±30 m from the speed humps was lower than the vehicle speed farther than 30 m from the speed humps. The speed reduction was 18.4% (from 24.71 km/h to 20.17 km/h) on local roads, and 24.0% (from 38.43 km/h to 29.2 km/h) on major roads. The speed reduction due to speed humps was reproducible and significant. We also examined the effect of speed humps on pedestrian safety using two measures—frequency and severity. The pedestrian crash occurrences were compared between inside and outside the zones of influence of speed humps separately on local and major roads. The comparison showed that there was a significant speed reduction under the influence of speed humps (15.4% in local and 27.7% in major roads) and that the reduction was more pronounced on major roads. The level of crash injury severity was analyzed using an ordered probit model. The outcomes indicate that crash severity under the influence of speed humps was lower (i.e., minor injury rather than severe or fatal injury). For the severity analysis, the effect of speed humps was again more pronounced on major roads.

On the other hand, the speed reductions near the speed humps could be abrupt to the following vehicles which occurred where automated speed enforcement cameras were installed (De Pauw, Daniels, Brijs, Hermans, & Wets, 2014; Shim, Park, Chung, & Jang, 2015), and unintentionally to the emergency manuevers. Although this phenomenon was not observed in this study, speed reductions near the speed humps, if abrupt, could negatively affect vehicle safety outside the zones of influence of speed humps. These potential side effects should be noted for the guidelines of speed hump installation.

This study revealed quantitatively the significant effects of speed humps for reducing vehicle speeds and enhancing pedestrian safety in roadways with different functional classifications—major and local roads. In many countries, speed humps have been deployed mostly on local streets where vehicle speeds are low (Barbosa et al., 2000; Johansson et al., 2011; Moreno & García, 2013; Moreno et al., 2011). The findings, however, suggest that the speed humps would likely be more effective when installed in higher speed environments (i.e., major roads). Meanwhile, the influence of speed humps is limited to ±30 m. Considering that the size of a typical block is far greater than ±30 m, speed humps should be deployed close to crosswalks or pedestrian crash hotspots (i.e., within 30 m).

Acknowledgement

This research was supported by the National Research Foundation of Korea grant funded by the Korea government (MSIP) (NRF-2014R1A2A1A11052725).

References

Afukaar, F. K., & Damsere-Derry, J. (2010). Evaluation of speed humps on pedestrian injuries in Ghana. *Injury Prevention, 16*(Suppl 1), A205–A206.
Antić, B., Pešić, D., Vujanić, M., & Lipovac, K. (2013). The influence of speed bumps heights to the decrease of the vehicle speed – Belgrade experience. *Safety Science, 57*, 303–312.
Barbosa, H. M. (1995). *Impacts of traffic calming measures on speeds on urban roads (Doctoral dissertation)*. University of Leeds.
Barbosa, H. M., Tight, M. R., & May, A. D. (2000). A model of speed profiles for traffic calmed roads. *Transportation Research Part A: Policy and Practice, 34*(2), 103–123.
Chen, L. i., Chen, C., Ewing, R., McKnight, C. E., Srinivasan, R., & Roe, M. (2013). Safety countermeasures and crash reduction in New York City—Experience and lessons learned. *Accident Analysis & Prevention, 50*, 312–322.
Clarke, K. A. (2005). The Phantom Menace: Omitted Variable Bias in Econometric Research. *Conflict Management and Peace Science, 22*(4), 341–352.
Cottrell, W. D., Kim, N., Martin, P. T., & Perrin, H. J. Jr., (2006). Effectiveness of traffic management in Salt Lake City, Utah. *Journal of Safety Research, 37*(1), 27–41.
De Pauw, E., Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2014). An evaluation of the traffic safety effect of fixed speed cameras. *Safety Science, 62*, 168–174.
Digital Tachograph Analysis System (eTAS). 2019. Available at https://etas.ts2020.kr/. (Assessed on August 5, 2019).
Engel, U., & Thomsen, L. K. (1992). Safety effects of speed reducing measures in Danish residential areas. *Accident Analysis & Prevention, 24*(1), 17–28.
Ewing, R. (1999). *Traffic calming state of the practice slide seminar*. Institute of Transportation Engineers. Federal Highway Administration September.
Ewing, R., & Dumbaugh, E. (2009). The built environment and traffic safety: A review of empirical evidence. *Journal of Planning Literature, 23*(4), 347–367.
Gårder, P. E. (2004). The impact of speed and other variables on pedestrian safety in Maine. *Accident Analysis & Prevention, 36*(4), 533–542.
Hothorn, T., & Everitt, B. S. (2014). *A handbook of statistical analyses using R*. Chapman and Hall/CRC.
Jang, K., Park, S. H., Kang, S., Song, K. H., Kang, S., & Chung, S. (2013). Evaluation of pedestrian safety: Pedestrian crash hot spots and risk factors for injury severity. *Transportation Research Record, 2393*(1), 104–116.
Johansson, C., Rosander, P., & Leden, L. (2011). Distance between speed humps and pedestrian crossings: Does it matter? *Accident Analysis & Prevention, 43*(5), 1846–1851.
Jordahl, K. (2014). GeoPandas: Python tools for geographic data. Available at https://github.com/geopandas/geopandas. (Assessed at August 5, 2019).
Khattak, A. J., Pawlovich, M. D., Souleyrette, R. R., & Hallmark, S. L. (2002). Factors related to more severe older driver traffic crash injuries. *Journal of Transportation Engineering, 128*(3), 243–249.
Khattak, A. J., Schneider, R. J., & Targa, F. (2003). Risk factors in large truck rollovers and injury severity: Analysis of single-vehicle collisions. *Transportation Research Record, 40*.
Kockelman, K. M., & Kweon, Y.-J. (2002). Driver injury severity: An application of ordered probit models. *Accident Analysis & Prevention, 34*(3), 313–321.
Korea road traffic authority (KoROAD). Traffic Crash Analysis System. 2019. Available at http://taas.koroad.or.kr/index.jsp.
Lee, C., & Abdel-Aty, M. (2005). Comprehensive analysis of vehicle–pedestrian crashes at intersections in Florida. *Accident Analysis & Prevention, 37*(4), 775–786.
Liu, X. J., Yang, J. K., Lövsund, P., Liu, X. J., Yang, J. K., & Lövsund, P. (2002). A study of influences of vehicle speed and front structure on pedestrian impact responses using mathematical models. *Traffic Injury Prevention, 3*(1), 31–42.
Marek, J. C., & Walgren, S. (1998). Mid-block speed control: Chicanes and speed humps. *Compendium of papers for the 68th annual meeting of institute for transportation engineers*. Toronto, Canada: Institute of Transportation Engineers. November.
McKelvey, R. D., & Zavoina, W. (1975). A statistical model for the analysis of ordinal level dependent variables. *The Journal of Mathematical Sociology, 4*(1), 103–120.
Ministry of the Interior and Safety (MOIS). (2019). Street map information. Available at https://www.juso.go.kr/addrlink/devLayerRequestWrite.do. (Accessed July 2019).
Moreno, A. T., & García, A. (2013). Use of speed profile as surrogate measure: Effect of traffic calming devices on crosstown road safety performance. *Accident Analysis & Prevention, 61*, 23–32.
Moreno, A. T., García, A., & Romero, M. A. (2011). Speed table evaluation and speed modeling for low-volume crosstown roads. *Transportation Research Record, 2203*(1), 85–93.
Otte, D. (1999). Severity and mechanism of head impacts in car to pedestrian accidents. In *Proc. IRCOBI Conf* (pp. 329–341). September.

Pau, M., & Angius, S. (2001). Do speed bumps really decrease traffic speed? An Italian experience. *Accident Analysis & Prevention, 33*(5), 585–597.
Quddus, M. A., Noland, R. B., & Chin, H. C. (2002). An analysis of motorcycle injury and vehicle damage severity using ordered probit models. *Journal of Safety Research, 33*(4), 445–462.
Rifaat, S. M., & Chin, H. C. (2007). Accident severity analysis using ordered probit model. *ATR, 41*(1), 91–114.
Sandhu, J., & Chandrasekhar, T. (2006). *ArcGIS network analyst tutorial*. Redlands, Calif: ESRI.
Shim, J., Park, S. H., Chung, S., & Jang, K. (2015). Enforcement avoidance behavior near automated speed enforcement areas in Korean expressways. *Accident Analysis & Prevention, 80*, 57–66.
Smith, D. J. (2002). *Temporary speed hump impact evaluation (Doctoral dissertation)*. Iowa State University.
Smith, D. J., Knapp, K., & Hallmark, S. (2002). *Speed impacts of temporary speed humps in small Iowa cities*. Ames: Centre for Transportation Research and Education, Iowa State University.
Tay, R., & Rifaat, S. M. (2007). Factors contributing to the severity of intersection crashes. *Journal of Advanced Transportation, 41*(3), 245–265.
Tester, J. M., Rutherford, G. W., Wald, Z., & Rutherford, M. W. (2004). A matched case–control study evaluating the effectiveness of speed humps in reducing child pedestrian injuries. *American Journal of Public Health, 94*(4), 646–650.

Jiho Yeo is a Ph.D. Student in the Cho Chun Shik graduate school of green transportation at KAIST. He received his B.S. urban planning from Hanyang University, Republic of Korea, in 2010, and the M.S. degrees in transportation engineering from KAIST, Republic of Korea, in 2015. His research interests include traffic safety, transportation network and analysis of transportation big data and human mobility.

Jooyoung Lee is a Ph.D. Student in the Cho Chun Shik graduate school of green transportation with a specialization in transportation engineering at Korea Advanced Institute of Science and Technology. He is interested in transportation bigdata and transportation safety. More specifically, his work examines driver's behavior affected in driving safety using large scale driving records.

Junhan Cho is a Senior Researcher with the Samsung Traffic Safety Research Institute. He received his Ph.D. in Transportation Engineering at Hanyang University in 2009. He had served as a Researcher with Geukdong Engineering, Research Professor and Affiliate Professor at Hanyang University, and Senior Researcher with the Korea Transportation Safety Authority. His major research areas include traffic safety, road designing, traffic signal operation, intelligent transport systems, and transportation statistics.

Dong-Kyu Kim is an associate professor in Civil and Environmental Engineering at Seoul National University. He received his B.S., M.S., and Ph.D. degrees in transportation engineering from Seoul National University, Republic of Korea, in 1999, 2001, and 2006, respectively. His research interests include transportation safety, transportation planning, and network optimization.

Kitae Jang is an associate professor of the Cho Chun Shik graduate school of green transportation at KAIST, leading the Transportation Operation and Planning for Sustainability (TOPS) Lab. He received the B.S. degree in civil engineering from Hanyang University, Seoul, Republic of Korea, in 2003, and the M.S. and Ph.D. degrees in civil and environmental engineering from the University of California, Berkeley, U.S., in 2006 and 2011, respectively. His minors are economics and public health. Then, he joined KAIST as an assistant professor in 2012 and was appointed as an associate professor in 2017. His research interests include traffic flow theory, transport economics, and transport system operation and planning.