Evaluation of Direct and Indirect Safety Effects of Speed-Limit Reduction on Urban Networks

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Abstract: This study develops a set of crash modification factors (CMFs) to evaluate the effects of lowering urban-road speed limits on vehicle and pedestrian safety. Cross-sectional methods and observation before–after methods are used to develop CMFs. In general, a CMF estimates the expected change in the frequency of crashes after specific countermeasures are applied on the road. In this study, the safety improvement effect in the section adjacent to the applied section as well as the section for which the policy to lower the speed limit was applied were evaluated. The results indicate that lowering the speed limit is effective in reducing the number of crashes. In particular, the CMFs for crashes involving serious injury and death are 0.6656–0.7804 in the application sections and 0.7979–0.8273 in the adjacent sections. This means that lowering the speed limit can reduce not only the number of crashes but also the occurrence of serious crashes. This study can be used to promote safety by analyzing the effect of the policy to lower the speed limits in the future and can be applied to the evaluation of the effectiveness of various safety policies in cities. **DOI: 10.1061/JTEPBS.0000724.**

Author keywords: Lowering the speed limit; Crash modification factors (CMFs); Safety performance functions (SPFs); Urban arterials.

Introduction

According to the Korea Transportation Safety Authority, 71.9% of traffic crashes in Korea occurred on roads in cities from 2011 to 2016 (TAAS 2021). In addition, 48.6% of all traffic crash deaths in Korea occurred on roads in urban areas. In Korea, various traffic safety policies have been implemented to solve the problems of traffic crashes in cities. Fortunately, the overall number of crashes is decreasing, but the proportion of pedestrians among urban traffic crash deaths has not fallen below 40%.

According to previous studies, speeding is the main cause of pedestrian traffic crashes and high crash severity in cities. Vehicle speed is one of the most important factors in traffic safety, and it is known that high vehicle speed increases the probability of crashes regardless of regional distinctions, such as urban or rural areas. According to a pedestrian collision test conducted by the Korea Transportation Safety Authority in 2018, 9 out of 10 pedestrians die if a vehicle collides with a pedestrian at 60 km/h, but only 5 out of 10 pedestrians die if the speed is lowered to 50 km/h. If a vehicle collides with a pedestrian at 60 km/h, the pedestrian is very likely to die (92.6%), while the likelihood of serious injuries when a pedestrian is hit by a vehicle approaching at 50 km/h is reduced to 72.7%. If the vehicle speed is lowered to 30 km/h, the likelihood of serious injury is significantly lowered to 15.4%.

Because the speed-dependent risk of crashes is documented by various studies, a policy to lower the speed limit in cities to 50 km/h is being implemented in Korea. To expand the policy, various promotional campaigns have been carried out in the cities, and speeding cameras are being installed at the same time. The policy to lower the speed limit in Korea has been implemented as a pilot project since 2018 and is currently expanding nationwide. However, some road user groups suggest that increased road traffic becomes inconvenient when policies lower the driving speed limit. Their opinion is that the improvement in urban operation by the policy of lowering the speed limit is not greater than the inconvenience experienced by users. In the field, because of these inconveniences, it is difficult to improve the speed-limit compliance rate and effectively introduce new policies. Therefore, quantitative and statistical effect analyses are needed to provide clear evidence that administrative policies improve safety. In this study, the improvement effect in terms of safety brought about by the policy to lower the speed limit was quantitatively analyzed and presented.

In addition, to analyze the macroscopic effect of the policy, the effect was analyzed not only in the target sections for which the speed limit was lowered, but also in the section adjacent to the application section. Alhomaidat et al. (2020) analyzed the tendency of the driver to drive at a higher speed in the section after leaving the speed-limit section (spillover effect) (Alhomaidat et al. 2020). Therefore, it was judged that it was necessary to analyze whether the implementation of the policy to lower the speed limit had a significant effect in terms of crash statistics even in the section adjacent to the section to which the policy was applied.

In this study, the safety improvement effect of the policy of lowering the speed limit to reduce the possibility of traffic crashes and high crash severity was evaluated. It is meaningful to quantify the

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Note. This manuscript was submitted on December 30, 2021; approved on May 12, 2022; published online on July 18, 2022. Discussion period open until December 18, 2022; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Transportation Engineering, Part A: Systems***, © ASCE, ISSN 2473-2907.

impact of the speed-limit lowering policy on adjacent sections by including the indirect treatment sections that have not been considered in previous studies as a spatial research scope. In addition, not only the before–after study suggested by the *Highway Safety Manual* (HSM) (AASHTO 2010), but also the cross-sectional method for the latest section to which the policy is applied were used to differentiate it from similar existing studies. In the next section, the latest utilization plan for this study was designed by considering the existing research on the crash modification factor presented by the HSM, and the difference between this approach and existing research is derived and presented.

Background

Crash Modification Factors

The HSM presents a crash modification factor (CMF), an indicator for quantitatively evaluating the effect of certain safety treatments implemented in a segment or intersection. In many previous studies, the CMF has been utilized to evaluate the safety effects of certain treatments (Carter et al. 2012; Gross et al. 2010; Sacchi et al. 2014). In general, the CMF can be calculated by the observational before–after method and the cross-sectional (CS) method (Alamry and Hassan 2020; Elvik 2009, 2011, 2013a, b; Kim et al. 2021; Lee et al. 2015; Park and Abdel-Aty 2015, 2021; Park et al. 2014, 2015; Srinivasan et al. 2010).

Safety Effect of Speed-Limit Reduction Policy on Urban Networks

In most countries belonging to the Organisation for Economic Co-operation and Development (OECD 2021), the speed limit for roads in cities is set to less than 50 km/h. Recently, in Korea, policies are being implemented to set speed limits consistent with this trend. However, the effect of this policy on safety has not yet been clearly proven at this early stage of policy introduction. In this section, studies related to the policy of lowering the speed limit conducted overseas are considered. The effects of policies derived from previously conducted studies were summarized, and their methodologies that could help this study were derived.

First, the existing literature that studied speed limits and safety in a non-CMF method was reviewed. Aarts and Van Schagen (2006) reviewed various studies related to driving speed and the risk of road crashes. Most of the studies considered and analyzed the effect of the absolute speed on the risk of crashes at the level of an indivisible vehicle or road section. In particular, the larger the speed difference between vehicles, the higher the crash rate. Park et al. (2021) investigated the relation between speed and safety on urban roads. For this, related variables and speed measurements were used. The results of the study indicated that there is a relationship between speed variability and crash occurrence. Pei et al. (2012) evaluated the relationship between speed and crash risk in Hong Kong. A point probability model based on a full Bayesian method was used to model crash occurrence and crash severity. The results showed that speed was positively related to the severity of crashes. Imprialou et al. (2016) proposed an aggregate unit that can explain the situation just before the crash, not the traditional aggregate method of the link unit. The full Bayesian method was used, and, as a result of modeling, it was found that speeding had a significant effect on the increase in the frequency of crashes. In this study, the results were compared using a link-based model, a traditional method. As a result of link-based model analysis, the fact that the frequency of crashes decreases as the speed decreases was suggested as an important implication. Siuhi et al. (2021) verified the signal of the posted differential speed limits (DSLs) on traffic safety and operation. Siuhi et al. (2021) defines DSL as the difference between the posted limits for different types of vehicles. As a result of the analysis, it was found that the safety of the road with a low minimum speed, that is, the road with a large difference from the maximum speed, was poor. In addition, it provided that further research is needed to quantify the effectiveness of posting a minimum speed limit. Quddus (2013) developed two geographic information system (GIS)–based advanced statistical models to investigate the relationship between average speeds, speed variations, and accrual rates. The results were not related to the average speed and crash rate, but speed variation was found to be statistically related to the crash rate. As a representative argument to determine the relationship between the crash severity and the probability of a crash, there is a conclusion that there is insufficient time to respond to the risk at high speeds because the response time and braking distance increase as the speed increases (Hauer 2009).

The following is a review of existing literature that studied speed limit and safety using the HSM methods (before–after study, the CMFs). Jaarsma et al. (2011) evaluated the effect of reducing the speed limit on rural roads in the Netherlands using the before–after with comparison group (CG) method. When the speed limit was reduced from 80 to 60 km/h, the crash reduction effect was found to be about 14%–24%. Islam and El-Basyouny (2015) evaluated the safety effect of lowering the speed limit for urban residential areas in Canada. Full Bayesian method and empirical Bayes (EB) method were used, and the reduction effect was found to be up to about 18%–50%. Son et al. (2019) analyzed the safety improvement effect by applying EB and CG method to Korean urban roads. It was analyzed that there was a reduction effect of about 16% in the KABCO (K is a fatal injury, A is a incapacitating injury, B is a non-incapacitating injury, C is a possible injury, and O is an only property damage) crashes. As such, the methods proposed by HSM are used to evaluate the safety improvement effect of lowering the speed limit. It is used not only to lower the speed limit but also to evaluate the effectiveness of other safety measures. In this study, the HSM methods were referenced based on existing research cases to analyze the effect of lowering the speed limit and optimal methods were applied under given conditions.

Summarizing past studies, the effect of speed change on urban traffic safety varies depending on the analysis method and environment. Therefore, accurate variables and sample settings that can quantitatively define the target road are important, and other policies and treatments that may negatively affect the analysis results should be controlled for. In addition, it is important to design an analysis method considering statistical significance. Finally, for safety analysis from the perspective of urban networks, it is necessary not only to apply a policy to lower the speed limit, but also to analyze the policy effect considering the spillover effect in the section adjacent to the target section.

The main purpose of this study is to evaluate the safety effects of policies that lower speed limits to prevent high-speed crashes, which are known to have a significant impact on the risk of urban traffic crashes. In Korea, a policy to lower the speed limit was implemented, and more than 2 years of data were accumulated. Therefore, it is suitable for conducting a case analysis to evaluate the safety effect of the policy to lower the speed limit. In this study, the policy effectiveness of not only the directly applied section but also the indirectly applied adjacent section was evaluated in depth. This content was not covered in previous studies, and it is the main unique contribution of this study. The next section describes the methodology used in the study. In the fourth section, the data used in the study are described, followed by results and discussions. The last section is the conclusion. In the conclusion, the implications, limitations, and plans for future research are presented.

Methodology

Safety Performance Functions

A safety performance function (SPF) is generally known as a model for predicting the frequency of crashes using independent variables, such as traffic volume and geometrical characteristics. The negative binomial [negative binomial (NB)] model (Poisson-gamma) is most commonly used in the development of SPFs because it can describe overdispersion. The SPF can be classified into a simple SPF and full SPF according to the independent variable used. The HSM presents a CMF calculated based only on simple SPF. However, the number of predicted crashes from the simple SPF is too simple because it is not only affected by annual average daily traffic (AADT). Therefore, in this study, not only the AADT but also the full SPF, which sets road geometry characteristics as variables, were used with the EB method to calculate the CMF. The functional form of the SPF (i.e., crash prediction model; NB regression model) is shown in Eq. (1)

$$N_{\text{predicted},i} = \exp(\beta_0 + \beta_1(\text{AADT}_i) + \beta_2(L_i) + \cdots + \beta_k(X_{ki})) \tag{1}$$

where $N_{\text{predicted},i}$ = predicted crash frequency on segment i; β_k = coefficients for the variable k; AADT_i = annual average daily traffic of segment i (vehicles/day); L_i = length of segment i; and X_{ki} = linear predictor k of segment i.

Cross-Sectional Method

The cross-sectional method is used to estimate the safety effect of a treatment or policy applied to a particular type of interval (Park et al. 2014). In particular, it is useful for the CMF estimation when there is no information regarding the time when a specific treatment is applied to the section. The HSM explains that the CMF can be estimated from cross-section studies if the date of treatment is unknown and data from the period before treatment are not available. It may be estimated by taking the ratio of the average frequency of crashes between the section to which the treatment is applied and the section not applied (Carter et al. 2012). The CMF is an index of coefficients when the shape of the model is log-linear, and can be calculated as the coefficient of variables related to processing (Lord and Bonneson 2007). The CMF and standard error (SE) equation calculated through the CS method are as follows Eqs. (2) and (3):

$$\text{CMF} = \exp(\beta_k \times (x_{kt} - x_{kb})) \tag{2}$$

$$\text{SE} = \frac{\exp(\beta_k + \text{SE}_{\beta_k}) - \exp(\beta_k - \text{SE}_{\beta_k})}{2} \tag{3}$$

where x_{kt} = linear predictor k of treated sites; x_{kb} = linear predictor k of untreated sites; and SE = standard error of the CMF.

Observational Before–After Study

According to the HSM, an observational before–after study is largely divided into three categories: (1) the naive before–after method, (2) CG, and (3) EB. In this study, the following two methodologies were used in consideration of the availability of data collection: the naive before–after method and the EB method. A comparison group method requires a procedure for selecting a section similar to the section to which treatment is applied. However, in this study, it was not used because a comparative group sample that can be judged to be significant was not secured.

Naive Before–After Method

This is known as the simplest methodology to compare before–after safety. This method is used to assume there are not many variables affecting safety during the before–after period. However, for this reason it is impossible to consider the reduction over time and the reduction effect of other unexplained variables, so there is a problem with regression-to-mean (RTM) bias. Nevertheless, it is used in most research reports and papers. The reason is that the calculation method is simple. This method is widely used as a primary analysis tool using basic data. The CMF equation calculated through this methodology is as follows in Eq. (4):

$$\text{CMF} = \frac{N_{T,A}}{N_{T,B}} \tag{4}$$

where $N_{T,A}$ = observed crash frequency of treated sites in after period; and $N_{T,B}$ = observed crash frequency of treated sites in before period.

Empirical Bayes Method

The before–after EB method is a representative method known to have excellent performance in safety evaluation. It has the advantage of being able to solve the RTM bias problem by using the crash prediction model presented previously. The before–after with EB method presented in the study of Hauer et al. (2002) measures the safety effect through a comparison between the observed number of crashes and the expected number of crashes. The expected number of crashes may be calculated as shown in the following Eqs. (5)–(7), where w is a weight factor estimated using the overdispersion parameter (k) calculated from the SPF and the expected number of crashes in the before period. This weight factor is shown in Eq. (6):

$$N_{\text{expected},B} = w(N_{\text{predicted},B}) + (1-w)(N_{\text{observed},B}) \tag{5}$$

$$w = \frac{1}{1 + k(\sum N_{\text{expected},B})} \tag{6}$$

$$N_{\text{expected},A} = N_{\text{expected},B} \times \left(\frac{N_{\text{predicted},A}}{N_{\text{predicted},B}}\right) \tag{7}$$

where $N_{\text{expected},B}$ = expected crash frequency of treated sites in the before period; $N_{\text{predicted},B}$ = predicted crash frequency of treated sites in the before period; $N_{\text{observed},B}$ = observed crash frequency of treated sites in the before period; $N_{\text{expected},A}$ = expected crash frequency of treated sites in the after period; and $N_{\text{predicted},A}$ = predicted crash frequency of treated sites in the after period.

The CMF can be calculated using the observed crash frequency collected during the treatment before–after period and the expected crash frequency calculated through the SPF. The calculation equations are as follows in Eqs. (8)–(10) (Gross et al. 2010; Park et al. 2014):

$$\text{CMF} = \frac{\frac{N_{\text{observed},A}}{N_{\text{expected},A}}}{1 + \frac{\text{var}(N_{\text{expected},A})}{(N_{\text{expected},A})^2}} \tag{8}$$

$$\text{var}(N_{\text{expected},A}) = N_{\text{expected},A} \times \frac{N_{\text{predicted},A}}{N_{\text{predicted},B}} \times (1-w) \tag{9}$$

$$\text{var}(\text{CMF}) = \frac{\text{CMF}^2\left[\left(\frac{1}{N_{\text{observed},A}}\right) + \left(\frac{\text{var}(N_{\text{expected},A})}{N_{\text{expected},B^2}}\right)\right]}{\left[1 + \frac{\text{var}(N_{\text{expected},A})}{(N_{\text{expected},A})^2}\right]^2} \tag{10}$$

Table 1. Descriptive statistics of the crash frequency for the before–after method

Period	Severity level	Mean	SD	Min	Max	Total
Crash frequency in the direct treatment group						
Before period	KABC	53.444	62.452	3	269	962
(2 years)	KA	18.056	23.891	1	107	325
After period	KABC	43.611	48.068	4	184	785
(2 years)	KA	12.056	11.669	1	46	217
Crash frequency in the indirect treatment group						
Before period	KABC	55.194	50.224	1	246	1,987
(2 years)	KA	18.667	15.630	1	76	672
After period	KABC	49.806	46.398	3	193	1,793
(2 years)	KA	14.917	12.976	1	58	537

The variance of CMF is calculated using Eq. (10), and the standard error of the safety effect is calculated by taking the square root of $\mathrm{var}(\mathrm{CMF})$.

Data Collection and Preparation

In this study, data were used that were collected on roads in Korean cities where the policy to lower the speed limit was applied. Three data sets were collected: crash data, geometry data, and traffic volume data. First, crash data were collected from the Traffic Accident Analysis System (TAAS) in Korea. The accident data provided by TAAS include location information and crash characteristics information. Therefore, the data set was constructed by separately collecting only crashes that occurred in the section where the policy was implemented. Second, the geometric and operational data of the section were collected from the Kakao map and the Google map. Data were collected using satellite images and road-view functions of roads accessible from the perspective of general road managers. It is expected that this approach can be used not only by researchers from specialized transportation institutions but also by general institutions. In the study, a total of two continuous variables were considered input: natural logarithm of AADT (vehicles/day) and segment length (km). A category variable was considered: number of lanes. In addition, three variables were considered binary indicators: speed limit of segment, presence of speed camera, and presence of bus-only lane. Finally, section traffic data were collected from the ViewT 3.0 site operated by the Korea Transportation Research Institute. The collected data here were preprocessed into a data set for SPF development and used for modeling. Only variables identified as significant in the analysis process were selectively used for model development, and the variables used in this study are presented together in the model development results of the following section. Data were collected around the implementation date of the policy, and before–after methods were used for this sample. However, in the cases of sections whose implementation date is unknown, data from comparative sections that were not implemented at the same time were collected for the application of the cross-sectional method.

In summary, based on methodology, there are largely two types of data sets used in this study. The first was collected for sections where data could be collected during the period before and after implementation. This data set was used in the before–after study by applying the naive method and the EB method. The speed-down policy was implemented on a different date for each detailed section from the beginning of 2017 to the end of 2018, and data for 2 years before and after the implementation were collected in each section unit. The second data set was relatively recent and collected for sections where data could not be collected after implementation. Only the cross-sectional method was applied to this data set. Data for 2 years from 2019 to 2020 were collected by section.

Tables 1–4 give the descriptive statistics of variables for the data sets. As a result of comparing crash frequency during the before–after period, it was found that the average crash frequency decreased in all crashes (KABC) and serious injuries and deaths crashes (KA). This may mean that implementing a policy to lower the speed limit is effective in reducing crashes. In this study, statistical methods were applied to prove the comparison results of these descriptive statistics and the analysis results are presented in the next section.

The direct treatment section and indirect treatment section targeted in this study can be expressed as Fig. 1. Here, the indirect

Table 2. Descriptive statistics of the traffic and geometry variables for the before–after method

Variable	Mean	SD	Min	Max
Natural logarithm of AADT (vehicles/day)	9.997	0.891	7.053	10.989
Number of lanes	5.593	1.447	3.000	10.000
Segment length (km)	1.146	0.634	0.260	2.850
Presence of speed camera (1 = speed camera, 0 = no speed camera)	1 = 21 sites, 0 = 33 sites			
Speed limit of segment	30 km/h = 5 sites, 40 km/h = 3 sites, 50 km/h = 14 sites, 60 km/h = 27 sites, 70 km/h = 4 sites, 80 km/h = 1 site			

Table 3. Descriptive statistics of crash frequency for the cross-sectional method

Speed limit	Severity level	Mean	SD	Min	Max	Total
50 km/h	KABC	53.444	62.452	3	269	962
	KA	18.056	23.891	1	107	325
60 km/h	KABC	43.611	48.068	4	184	785
	KA	12.056	11.669	1	46	217

Table 4. Descriptive statistics of the traffic and geometry variables for the cross-sectional method

Variable	Mean	SD	Min	Max
Natural logarithm of AADT (vehicles/day)	10.871	0.374	9.769	11.529
Segment length (km)	1.082	0.668	0.430	4.700
Presence of bus-only lane	1 = 22 sites, 0 = 54 sites			
Speed limit of segment	50 km/h = 42 sites, 60 km/h = 34 sites			

Note: 1 = bus-only lane presence; and 0 = no bus-only lane.

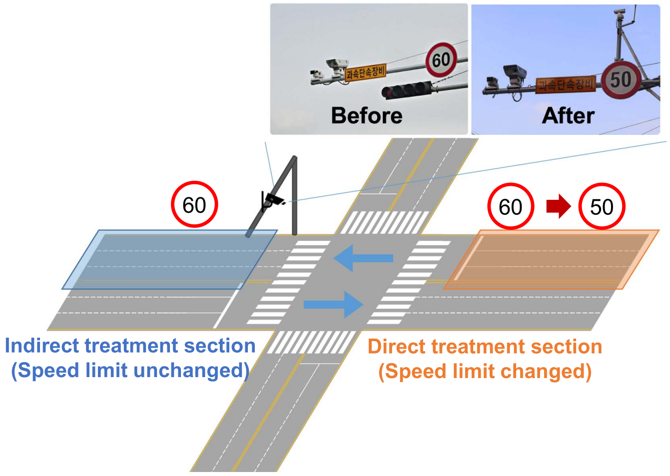

Fig. 1. Treatment sections.

treatment section refers to a section adjacent to the direct treatment section with a traffic characteristic change point such as an intersection. The indirect section is a section where the speed-limit lowering policy is not applied, but it is expected to be applied indirectly because of the change in speed limit at the direct treatment section, which is a key analysis target of this study.

Results and Discussion

In this study, safety evaluation was performed using two data sets: (1) direct treatment sections for which the policy was directly implemented; and (2) indirect treatment sections, which are adjacent to the direct treatment sections. The CMF of the policy to lower the speed limit was calculated using the naive before–after method, the EB method, and the CS method. First, for the data set of direct treatment sections, all three methods were used to calculate the CMF. The data set of indirect treatment sections was utilized only by the naive before–after method and the EB method. The NB-based crash prediction models (SPFs) developed for the application of the EB method and CS method applied in the study are presented in Tables 5 and 6.

Table 5. Full safety performance functions by severity level for the EB method

Independent variable	KABC Coefficient	KABC p-value	KA Coefficient	KA p-value
Intercept	−3.5752	0.0042	−3.5744	0.0033
ln(AADT)	0.5827	<0.0001	0.5040	<0.0001
Number of lanes	−0.3784	0.0928	−0.4626	0.0200
Segment length	0.6382	<0.0001	0.5987	<0.0001
Speed cameras	0.3724	0.0454	0.5041	0.0021
Speed limit (30 km/h) (1 = 30 km/h, 0 = others)	0.8385	0.0181	Not significant	
Speed limit (50 km/h) (1 = 50 km/h, 0 = others)	1.1504	<0.0001	0.9394	<0.0001
Speed limit (60 km/h) (1 = 60 km/h, 0 = others)	0.8842	0.0013	0.6577	0.0040
Dispersion (k)	0.2887		0.1822	
Deviance	57.9662		55.5835	
AIC	500.5215		375.7986	

Note: AIC = Akaike information criterion.

Table 6. Full safety performance functions by severity level for the CS method

Independent variable	KABC Coefficient	KABC p-value	KA Coefficient	KA p-value
Intercept	−3.9066	0.0233	−4.8782	0.0269
ln(AADT)	0.5225	0.0002	0.5129	0.004
Segment length	0.1833	0.0165	0.2174	0.0221
Presence of bus-only lane	0.3204	0.0075	0.2961	0.0522
Speed limit (50 km/h)	0.0295	0.0089	0.0248	0.0895
Dispersion (k)	0.1587		0.1961	
Deviance	78.1291		76.5976	
AIC	649.4348		481.1696	

Note: AIC = Akaike information criterion.

In general, the four SPF results indicate that the number of crashes is high in sections with higher traffic volume (AADT) and longer segment length. The installation of speed cameras can also be interpreted as having a significant effect on the increase in the number of crashes. However, the higher the number of lanes, the lower the number of crashes. According to the sample of the study, the number of crashes is the highest in the segment with three lanes. In this study, the number of lanes in the reference group used to develop the SPFs for the EB method is 3–10. Therefore, it is impossible to interpret it as a section in which the number of lanes is less than three lanes or more than 10 lanes.

Full SPFs for the EB method were developed for reference sites by dividing the data into the KABC and KA types according to the crash severity level. The total length of direct treatment sections used in the analysis is 22.58 km (mean = 1.254 km), with a total of 18 road sections. The total length of the direct treatment sections is 39.33 km (mean = 1.093 km), with a total of 36 sections. All variables used in the development of the crash prediction model are significant at the 90% confidence level.

Direct Treatment Sections

The CMFs were estimated using the naive method, EB method, and CS method according to the severity level for the sections where the policy was implemented (direct treatment sections) (Table 7). Here, when calculating the CMFs using the EB method, full SPFs were developed and utilized. The coefficients of all variables of the NB-based full SPFs are listed in Table 5. The CMF using the CS method was estimated by applying the coefficient of the variable speed limit (50 km/h). In general, the results of the

Table 7. Evaluated CMFs of speed-limit reduction by the naive before–after method, empirical Bayes method, and cross-sectional method on the direct treatment group

Method	Dependent variable	CMF	SE	Confidence interval (CI)
Naive before–after method	KABC	0.8152	0.0392	0.7384–0.8919*
	KA	0.6656	0.0582	0.5516–0.7797*
Empirical Bayes method	KABC	0.8560	0.0410	0.7756–0.9363*
	KA	0.6993	0.0607	0.5802–0.8183*
Cross-sectional method	KABC	0.7445	0.0116	0.7217–0.7673*
	KA	0.7804	0.0150	0.7510–0.8097*

Note: $*p < 0.05$.

naive, EB, and CS methods all showed that the value of the CMF was less than 1. This means the safety effect of the policy to lower the speed limit is positive. In particular, the results of the naive method showed that the CMF (KABC) was 0.8152 [confidence interval $(\mathrm{CI}) = 0.7384 - 0.8919$], which was larger than the CMF (KA) of 0.6656 (CI = 0.5516–0.7797), indicating a greater impact on the reduction of serious crashes. The results of the EB method showed similar results that the CMF (KABC) of 0.8560 (CI = 0.7756–0.9363) was larger than the CMF (KA) of 0.6993 (CI = 0.5802–0.8183). However, the results of the CS method showed that the CMF (KA) was larger than the CMF (KABC), contrary to the results of the previous two methods. The implementation of the policy to lower the speed limit has a positive effect on crash reduction in all crash severity categories. Here, it is judged that the result of the EB method is lower than the value of the naive method because there is some RTM. Therefore, it can be seen that the result of the EB method is better than the result of the naive method.

Indirect Treatment Sections

Beecause there was a difference in data collection conditions in the indirect treatment sections, the CMFs were estimated for KABC and KA crashes only for the naive and the EB method, except for the CS method (Table 8). The CMFs were found to be significant at the 95% and 85% confidence levels. However, the significant CMFs at an 85% confidence level can cause systematic Type I errors (Park et al. 2015). Therefore, it is recommended to use highly significant 90% and 95% confidence levels for the CMFs. This approach is recommended to confirm the general effect of treatment on the CMFs, which is significant at the 85% confidence level. To compare the statistical differences between the CMFs, the confidence interval of each CMF was also presented according to the significance level.

According to the analysis results, the effects of the policy to lower the speed limit were also positive for crash reduction in the indirect treatment sections. As a result of estimating the CMFs for indirect treatment sections, both the results of the naive and the EB method showed that the CMF (KA) was lower than CMF (KABC). However, compared to the results of the direct treatment sections, the overall effect was found to have decreased slightly. This can be interpreted as showing the crash reduction effect only by the indirect influence of the policy to lower the speed limit.

Conclusions and Recommendations

The main purpose of this study was to quantitatively evaluate the effectiveness of the policy project for lowering the speed limit applied to roads in Korean city. The analysis sections were divided into direct treatment sections and indirect treatment sections. In Korea, because the policy to lower the speed limit is being implemented throughout the city, Korean city was divided into two categories to evaluate the indirect impact of the policy on non-enforcement sections.

The CMFs were estimated in three ways: the naive method, the before–after EB method, and the cross-sectional method. Full SPFs were developed for roads in Korean cities for the application of the EB method and CS method. The main results of this study are summarized as follows. As a result of estimating the CMFs using the naive method, EB method, and CS method for direct treatment sections, all were found to be less than 1. Both the severity classifications of KABC and KA showed that the CMFs were less than 1, indicating the safety improvement effect was positive in direct treatment sections. In particular, the results of the naive method and the EB method showed that the CMF (KA) was smaller than the CMF (KABC), indicating that the reduction effect of KA crashes was significant. On the other hand, in the CS method, the CMF (KA) was found to be greater than the CMF (KABC), indicating that the reduction effect of overall crashes was greater.

For the indirect treatment sections, the CMFs were estimated using the naive method and the EB method, excluding the CS method. Like the direct treatment section, the effect of the project to lower the speed limit was found to be positive. However, the overall reduction effect was found to be relatively small. This indicates that the implementation of a policy to lower the speed limit applied to a specific section can have a significant positive effect on adjacent roads.

Based on the results of this study, the safety improvement effect of the project to lower the speed limit is effective. In addition, to analyze the indirect impact of the policy, the safety effect was analyzed for indirect treatment sections, which was also found to be significant and positive. However, because only Korean data were used in this study, the effect may vary depending on the independent variable and situation in other regions abroad. In addition, the characteristics of roads in Korea may not have been clearly reflected in that the CMF proposed by the HSM was recommended to be applied to US conditions (AASHTO 2010). The CMF results derived from this study were compared with the CMF results of previous studies (Al-Marafi et al. 2021; Elvik 2013a; Gayah et al. 2018; Islam and El-Basyouny 2015; Jaarsma et al. 2011; Vadeby and Forsman 2018) (Table 9). According to the CMF of the lower speed limit shown in existing studies, it was found that there was generally a crash reduction effect (from 0.50 to 0.86). However, in some countries crashes have increased significantly on roads that have excessively reduced speed limits compared to engineering design speeds (Gayah et al. 2018; Vadeby and Forsman 2018). These research results mean it is not unconditionally good to lower the speed limit, but it is important to interpret the effect in consideration of the spatial background and characteristics. Therefore, it is necessary to interpret the effect in consideration of the spatial background and characteristics.

This study analyzed the direct and indirect safety improvement effects of the policy to lower the speed limit applied to roads in cities. However, additional work is required based on limitations, including various factors that have not been considered in the research process. First, the policy of lowering the speed limit may reduce the speed felt by road users and increase the vehicle travel time. Therefore, the subject implementing the policy needs to judge and selectively apply the complex improvement effect by sufficiently considering not only safety but also the operating efficiency of the road. An analysis of this effect was not considered in the study. Second, because research on the policy of lowering the speed limit has been conducted in various countries, it is recommended to consider changes in CMFs using meta-analysis methodologies. If the characteristics of various regions are reflected as variables, the

Table 8. Evaluated CMFs of speed-limit reduction by the naive before–after method and empirical Bayes method on the indirect treatment group

Method	Dependent variable	Crash modification factor		
		CMF	SE	Confidence interval (CI)
Naive before–after method	KABC	0.9019	0.0294	0.8444–0.9595*
	KA	0.7979	0.0461	0.7075–0.8883*
Empirical Bayes method	KABC	0.9505	0.0308	0.9061–0.9949**
	KA	0.8273	0.0475	0.7342–0.9204*

Note: $*p < 0.05$; $**p < 0.15$.

Table 9. International research results of lowering the speed limit using the CMF

Authors (year)	Country	Speed limit (Before, km/h)	Speed limit (Before, km/h)	CMF (C.I)
Jaarsma et al. (2011)	Netherlands	80	60	0.76 ~ 0.86
Islam and El-Basyouny (2015)	Canada	50	40	0.50
Elvik (2013a)	Norway	80	60	0.64 ~ 0.78
Gayah et al. (2018)	United states	80	72	0.61
Gayah et al. (2018)	United states	83	57	1.45
Vadeby and Forsman (2018)	Sweden	90	80	0.59
Vadeby and Forsman (2018)	Sweden	90	70	1.02
Al-Marafi et al. (2021)	Australia	60	50	0.68

exact effect of lowering the speed limit can be estimated. Third, developing CMFunctions can be a good alternative to take into account the degree of reduction in speed limit and the effectiveness of policies over time (Park and Abdel-Aty 2017, 2021). It is difficult to design a policy that satisfies all road users, but it is important to analyze the effectiveness of policies in detail to provide safe and convenient road services to as many users as possible.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT, and Future Planning (2019R1G1A1010209).

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