Are school zones effective in reducing speeds and improving safety?

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ARE SCHOOL ZONES EFFECTIVE IN REDUCING SPEEDS AND IMPROVING SAFETY?

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ABSTRACT

This paper describes a study undertaken to assess the speed and safety effects of reducing speed limits from 50 to 30 km/h in school zones. Mean speeds and 85th percentile speeds were reduced by 12.2 and 11.6 km/h, respectively. Speed variation was also reduced, and the speed cumulative distributions shifted to the left, indicating further reductions for all speed ranges. The safety evaluation results revealed fatal/injury collisions were significantly reduced by 45.3% and injuries to vulnerable road users were reduced by 55.3%. In fact, for every 1 km/h reduction in mean speed, fatal/injury crashes were reduced by about 4%, which is consistent with findings from previous research. Neither spatial nor temporal collision migration/spillover effects were significant factors in the analysis. Consequently, the results of this study provide strong evidence that reducing speed limits to 30 km/h in school zones can bring significant safety benefits by reducing vehicular speeds and fatal/injury crashes.

Keywords

30 km/h School Zones, Before-and-After Evaluation, Full Bayes, Safety Effectiveness, Mean Speed, Speed Variation, Spatial Migration, Temporal Migration

1. INTRODUCTION

Road injuries continue to be a worldwide public health concern, exerting large social and economic burdens on our society. Approximately 1.25 million people are killed each year in traffic collisions worldwide, with an additional 20 to 50 million injured or disabled (World Health Organization, 2016). Nearly 400,000 individuals under the age of 25 are killed every year, with an average of 1,000 fatalities per day. Road crashes are becoming a leading cause of death among people aged 5-24 years, and the number is predicted to rise if adequate actions are not taken (Transport Canada 2011). Among the young lives lost, children are considered the most vulnerable road users (VRU) because they are at a higher risk of being involved as well as seriously injured in road collisions (Hazzard & Hildebrand 2015; Warsh et al. 2009). Potential reasons are attributed to a child's smaller body size, which is more vulnerable and less likely to be noticed by drivers. Moreover, children are more likely to behave unexpectedly and erratically, which increases their crash risk (Schwebel et al. 2012). Finally, children are unable to properly judge vehicular distances while crossing streets, which might also increase their risks of being involved in a collision (Dewar et al. 2007).

To improve children's safety around schools, the introduction of school zones is typically considered by many road authorities as a potential countermeasure to children's increased crash risk (Tay 2009; Zhao et al. 2015). Those zones include the roads around the school property, which many children use during their trips to and from school. Such streets are often congested during regular school hours, with parents dropping off and picking up their children, which means children crossing streets may be less visible to drivers due to the increased vehicle activity. Thus, school zones are a focus when considering ways to improve children's safety.

Such improvements could result in more children using active modes of transportation and fewer vehicles around schools (D'Amours Ouellet & Cloutier 2014).

Previous research has shown that high speeds are associated with an increase in collision frequency and the degree of crash severity (Christensen & Amundsen 2005; Nilsson 2004). When pedestrians are struck by vehicles, the seriousness of the injury increases with vehicular speed (Gårder 2004). At impact speeds of 45 km/h, pedestrians have a 60% chance of being killed, which is six times higher than at an impact speed of 37 km/h (Anderson et al. 1997). Thus, reducing the speed limit in school zones has been considered by many jurisdictions as a policy countermeasure to improve safety.

Marking school zones with reduced speed limit signs has been evaluated by many researchers around the world, but the findings have been inconsistent from one city to another. In the United Kingdom, Switzerland, Denmark and Australia, this measure was effective in reducing collisions, especially for pedestrian- and motorcyclist-related injuries (Engel & Thomsen 1992; Graham & Sparkes 2010; Grundy et al. 2009; Lindenmann 2005). Studies in Calgary, Saskatoon and the Netherlands reported that speed was reduced significantly after the speed limit was reduced to 30 km/h (Lazic 2003; Tay 2009; Vis et al. 1992). Some studies conducted in the United States and China suggested that a larger impact on speed can be achieved by changing the road geometry instead of only marking school zones (Strawderman et al. 2015; Young & Dixon 2003; Zhao et al. 2015). Limitations with previous research, such as the use of a small sample size to explore safety effects, as well as the lack of studies that concurrently conduct both a speed and safety evaluation for the same locations and time periods, were the motivation to conduct this study.

The objective of this paper is to present an evaluation of the speed and safety impacts of introducing a 30 km/h speed limit within a city-wide group of 216 school zones. The analysis was conducted using data from the City of Edmonton, which, in September 2014, reduced the speed limit from 50 to 30 km/h around all elementary schools, with clear traffic signage. Before-and-after collision and speed evaluations were carried out to examine the change in safety as well as speed and its variation, respectively. An analysis was also conducted to investigate if there were any spatial or temporal collision spillover (positive effect) or migration (negative effect) on nearby streets.

2. PREVIOUS WORK

Results of previous research on the impacts of school zones with reduced speed limits are mixed. Some studies found that school zones had no significant impacts on improving safety, since the compliance rate at these locations was typically low, while other evidence seemed to suggest that school zone safety was improved through reductions in speeds and collisions.

Young and Dixon analyzed data around four schools in Atlanta and found that the signage of school zones appeared to have no impact on reducing speeds (Young & Dixon 2003). They suggested that the largest impact on speeds could be achieved by changing the road geometry, as opposed to simply designating an area as a school zone. A study conducted by Zhao et al. investigated 20 school zones in Beijing and studied driving behaviour through a simulator experiment using 30 drivers. The authors argued that the effectiveness of school zone signs/markings depended highly on the road geometric conditions and could vary significantly from one site to another (Zhao et al. 2015). In another study of four schools in Mississippi, Strawderman et al. concluded that marking school zones with a reduced speed limit was

1 ineffective by itself in improving safety; they found that the right balance of signage was
2 important, with a high saturation of signage having the best effect (Strawderman et al. 2015).

3 Other studies provided strong evidence to support the effectiveness of reduced speed
4 limits in school zones. A study commissioned by the City of Saskatoon in 2003 reported that the
5 average 85th percentile speed of 15 selected school zones was reduced by 10 km/h, which was
6 assumed to indicate an improvement in safety (Lazic 2003). In 2009, a similar study in Calgary
7 found that the mean speed at school zones with a 30 km/h speed limit was significantly lower
8 than on residential streets with 50 km/h speed limits (Tay 2009). In a study conducted in the
9 Netherlands, Vis et al. demonstrated that the introduction of 30 km/h zones in 15 areas led to a
10 reduction in speed and traffic volume, which showed an overall positive effect on road safety
11 with high levels of support from local residents (Vis et al., 1992).

12 As for the impacts on collisions, a study in Switzerland by Lindenmann found that
13 collisions were reduced significantly on the 30 selected 30 km/h residential zones (Lindenmann
14 2005). Similar conclusions were found by Engel et al., where a study on 44 streets with reduced
15 speed limits was introduced in Denmark, leading to a reduction of 72% in road casualties (Engel
16 & Thomsen 1992). In 2009, a collision analysis by Grundy et al. examined the effectiveness of
17 introducing 20 mph (32.2 km/h) zones by examining 20 years of data on road casualties in
18 London, England; the results showed that fatal and injury collisions had declined significantly,
19 especially among young children (Grundy et al. 2009). Li and Graham (2016) used the same data
20 to further quantify the effects of 20 mph (32.2 km/h) zones on road safety using a doubly robust
21 methodology. They found that slight injuries were reduced by 10% and serious casualties were
22 significantly reduced by 24% (Li & Graham 2016). In Canada, Hazzard and Hildebrand
23 compared collisions in 31 urban and 24 rural school zones/areas to comparable roads outside

1 school areas and found that delineated school zones were statistically safer. However, the school
2 zones settings were not consistent and only part of them adopted reduced speed limits. A study in
3 New South Wales also confirmed the results of previous research, suggesting that recorded
4 crashes, especially pedestrian casualties, were reduced significantly in school zones with reduced
5 speed limits (Graham & Sparkes 2010). However, they also argued that lowering the speed limits
6 was not the sole reason for the reduction in collisions, since speed cameras and flashing lights
7 might have contributed to the reduction.

8 Tables 1 and 2 summarize the key findings from the aforementioned studies on the
9 effectiveness of school zones. They also highlight the main research gaps of those studies in
10 general.

11 Most previous studies evaluated the impacts of school zones on speed or collisions
12 independently, but not the corresponding changes between speed and collisions for the same
13 locations during the same before-after time periods. A joint analysis can provide better insights
14 on how school zones with a reduced speed limit can increase safety. The majority of existing
15 studies also used a relatively small sample size with few selected sites, so were not able to
16 account for the regression-to-the-mean effect, which could be a possible source of bias. The
17 results of these studies were often mixed and inconsistent, which prompts a need for further
18 analysis. As for quantifying the collision effects of reducing the speed limit, most previous
19 studies were conducted on residential streets instead of school zones, which makes the school
20 zones policy still unclear on the benefits it brings to the children's safety. Another important
21 issue that was never investigated in the literature was the effects of spatial or temporal spillover
22 or migration. School zones are in effect during certain times of the day, and their effects (either
23 positive or negative) outside school hours are unknown. It would be beneficial to understand the

1 impact on collisions outside school hours. Also, the impacts on nearby locations as a result of the
2 introduction of school zones was never explored in the literature. Both issues are investigated in
3 this study.

4 Using a large sample size of 216 school zones in Edmonton, a longitudinal collision
5 analysis was conducted to explore the impacts on collisions as well as the temporal and spatial
6 migration/spillover effects due to the introduction of 30 km/h school zones. To account for the
7 statistical uncertainty that may exists in the collision data, a Full Bayes approach used 622
8 comparison sites to address external confounding factors that might change over time. Since the
9 implementation of 30 km/h school zones was a citywide program and analyzed sites were not
10 selected because of their high collision frequency, the regression-to-the-mean effect was not
11 expected to have a significant effect; nevertheless, it was accounted for in the proposed
12 methodology. A speed analysis of 43 school zones was also conducted during the same time
13 period.

15 3. DATASET

16 The study area is located in the city of Edmonton, Alberta, Canada. Edmonton reduced speed
17 limits to 30 km/h in school zones in September 2014. The school zones are defined as the streets
18 surrounding each school and are clearly marked by traffic signs both at the beginning and end of
19 the zones. The reduced speed limit is in effect from 8:00 a.m. to 4:30 p.m. during school days.

20 A total of 216 school zones, comprising 432 streets, were selected as the treatment group
21 for the collision analysis (Figure 1). A comparison group of surrounding locations was
22 assembled by collecting additional data at 622 streets having a speed limit of 50 km/h. Those
23 streets were carefully selected from the second-order neighbouring streets with similar road

1 characteristics to the school zone streets: second-order neighbouring streets are those in the
2 second-nearest blocks on the same passage as the relative school zone streets.

3 The longitudinal analysis made use of historical collision records based on police reports,
4 spanning 2011 to 2016, within which no other significant changes were made upon treatment and
5 comparison sites except the speed limit reduction. The before period started on 1 September
6 2011 and ended on 31 August 2014 whereas the after period commenced on 1 September 2014 to
7 31 August 2016. The collision database included detailed information for each collision, such as
8 time of day, crash location, crash severity and crash-related objects. Only collisions occurring
9 during the school operation time (based on hour of day, day of week, and month of year) were
10 selected for both school zones and comparison sites. The focus of the safety evaluation was to
11 investigate the change in fatal and injury collisions, and how those collisions related to VRU
12 (pedestrians, cyclists and motorcyclists).

13 It is important to note that speed limit reduction in school zones were introduced to
14 improve the safety of children. The city is also planning to extend the speed limit reduction to
15 other areas – particularly to the areas that cater to vulnerable road users, such as at parks,
16 playgrounds, residential roads, etc. Consequently, the focus was to investigate the impacts on
17 injury and fatal collisions (while excluding Property-Damage-only (PDO) collisions) because
18 they are commonly considered as the greatest challenge in improving safety specifically for
19 vulnerable road users. More so, the goal of reducing injury and fatal collisions is also in line with
20 Vision Zero which has been recently adopted by the City of Edmonton.

21 The exclusion of PDO collisions was therefore meaningful given the focus of the paper;
22 however, there were other reasons. Typically, the data on PDO collisions is unreliable since it is
23 based on the judgement of the individuals involved in the collision. In Edmonton, PDO crashes

are only reported if the damage exceeds \$2000. The decision to report or not to report is made entirely by the affected individuals, whereas injury and fatal collisions must be reported to the police. A descriptive statistical summary of the collision data is provided in Table 3.

Before-after speed data were collected within 43 school zones (Figure 1), using a Vaisala Nu-Metrics Portable Traffic Analyzer NC200 at the midblock of each street. These devices have built-in sensors through which they detect, count and classify vehicles, and measure their speeds, although they might have problems counting or measuring the speed of motorcycles or other smaller vehicles. Speed surveys were typically conducted for a couple of days to a week, during which the devices were placed at a certain mid-block location and data were collected for 24 hours. To ensure that the time periods of the speed analysis corresponds with that of the crash analysis, the before-after speed data were collected in the early spring months from 2012 to 2016. The speed data were further filtered to include only those during regular school operation times. To exclude the influence of adverse weather on speed, only the speed data collected during clear weather conditions was selected in this study. Moreover, vehicles with a headway less than 5 seconds were excluded from the evaluation to ensure that only free-flow speed data were included in the analysis and that the effects of congestion were minimized (Gargoum & El-Basyouny 2016; Hassan & Sarhan 2011). Consequently, the speed of 338,490 vehicles was recorded and included in the analysis. A descriptive statistics summary of the speed data is presented in Table 4. In addition to the speeds, the compliance rates to the speed limit of the vehicles at different locations were also calculated and are discussed in Section 4.2.

4. METHODOLOGY

4.1. Collision Analysis: Full Bayes Before-After Study

The application of a Full Bayes (FB) approach in before-after studies has been proposed by several researchers (Aul & Davis 2006; Carriquiry & Pawlovich 2004; Lan et al. 2009; Li et al. 2008; Park et al. 2010; Pawlovich et al. 2006). The FB approach is generally appealing for several reasons. It i) requires less data; ii) accounts for all uncertainty in the data (including model parameters); iii) provides more detailed inference (credible intervals and parameter distributions); iv) adds more flexibility in selecting collision distributions (Poisson-Gamma, Poisson-Lognormal); and v) efficiently integrates the estimation of the safety performance function (SPF) and treatment effects in a single step, whereas these are separate tasks in the Empirical Bayes method.

A Poisson-Lognormal (PLN) regression model with covariates representing the time, treatment (intervention) and interaction effects (reflecting the cross product between the time and treatment effects) was used. The model was expanded by adding random parameters to allow for comparison-treatment pairs incorporated to deal with the between-pair variation. The model first aggregated the data over time and then by zone in a before-after design involving matched yoked comparison groups.

Let $N_z = 216$ denotes the number of school zones and let Y_i and t_i denote the number of collisions and the observation period, $i = 1, 2, \dots, n$, where $n = 4 \times N_z$ denotes the total number of observations. The PLN model was used to address over-dispersion for unobserved or unmeasured heterogeneity.

Since the matched comparison sites were chosen to be as similar to treatment sites as possible, this may induce a correlation in collision frequency between sites within comparison-

treatment pairs (El-Basyouny & Sayed 2010; El-Basyouny & Sayed 2011; El-Basyouny & Sayed 2012a; El-Basyouny & Sayed 2012b; Li et al. 2008). To account for this correlation, suppose that the i^{th} observation belongs to zone $z(i) \in \{1, 2, \dots, N_z\}$.

According to this model, it is assumed that

$$Y_i | \theta_i \sim \text{Poisson}(t_i \times \theta_i), \quad (1)$$

$$\theta_i = \mu_i \exp(u_i), \quad (2)$$

$$\ln(\mu_i) = \beta_{z(i),0} + \beta_{z(i),1} X_{i1} + \beta_{z(i),2} X_{i2} + \beta_{z(i),3} X_{i3}, \quad (3)$$

$$u_i \sim N(0, \sigma_u^2),$$

$$(4)$$

$$\beta_{z(i),j} \sim N(\beta_j, \sigma_j^2), \quad j = 0, 1, 2, 3. \quad (5)$$

where, $X_{i1} = 1$, in the after period; $X_{i1} = 0$, in the before period; $X_{i2} = 1$, for treated sites; $X_{i2} = 0$, for comparison sites; and σ_u^2 denotes the extra Poisson variance. It should be noted that each pair involves observations from treated and comparison sites before and after the intervention. Thus, X_{i1} is a time indicator, X_{i2} is a treatment indicator, and X_{i3} is a two-way interaction term allowing different treatment effects across time. A diffused normal distribution (with zero mean and large variance) was used for the regression parameters β_j and a $\text{Gamma}(\varepsilon, \varepsilon)$ was used for σ_u^{-2} and σ_j^{-2} where ε is a small number, e.g., 0.01 or 0.001.

Under the above model, it is easily shown that the odds ratio was given by

$$OR = \exp(\beta_3). \quad (6)$$

One of the advantages of using Hierarchical Bayes methods combined with random-effect models is its ability to model zero-inflated collision data (Lord et al. 2005). In this study, a Full Bayesian approach is used to analyze the treatment effect using intervention models. The

Bayesian approach allows the use of “indirect” estimators that “borrow strength” by using values from related areas and/or time periods to increase the “effective” sample size of interest by combining the information from the treatment and comparison groups.

The posterior distributions needed in the full Bayes approach are obtained using Markov Chain Monte Carlo (MCMC) sampling available in the statistical software WinBUGS (Lunn et al. 2000). MCMC methods are used to repeatedly sample from the joint posterior distribution. The techniques generate sequences (chains) of random points, whose distributions converge to the target posterior distributions. A sub-sample is used to monitor convergence and then excluded as a burn-in sample. The remaining iterations are used for parameter estimation, performance evaluation and inference.

Monitoring convergence is important because it ensures that the posterior distribution has been found, which also indicates when parameter sampling should begin. To check convergence, two or more parallel chains with diverse starting values are tracked to ensure full coverage of the sample space. Convergence of multiple chains is assessed using the Brooks-Gelman-Rubin (BGR) statistic (Brooks & Gelman 1998), in which a value under 1.2 indicates convergence. Convergence is also assessed by visual inspection of the MCMC trace plots for the model parameters as well as by monitoring the ratios of the Monte Carlo errors relative to the respective standard deviations of the estimates; as a rule of thumb these ratios should be less than 0.05. All of the above checks were previously used in similar evaluation studies (El-Basyouny & Sayed 2010; El-Basyouny & Sayed 2011; El-Basyouny & Sayed 2012a; El-Basyouny & Sayed 2012b; Li et al. 2008).

4.2. Speed Analysis

The school zones with available speed data were further classified into three (3) equal-size groups according to their initial compliance rates during the before time period. The compliance rate was calculated as the percentage of vehicles that were driving at speeds equal to or below the 50-km/h initial speed limit, as follows: high (86% and above), medium (74-86%) and low (below 74%). Such grouping allows the comparison that the speed limit reduction might have on changing behaviour in locations that had an excellent compliance history and contrast these effects against the locations that had a poor compliance record. The mean and 85th percentile speeds of each compliance group and for all sites were calculated and compared before and after the introduction of the school zones. Since speed was assumed to follow a normal distribution, the statistical significance for the change in mean speed was conducted using a two-sample *t*-test with pooled variance. The null hypothesis is that there is no difference between the mean speeds before and after the reduced speed limit, while the alternative hypothesis is that there is a reduction in mean speeds after the implementation of school zones.

Previous research has shown that an increase in speed variation has also been shown to be associated with an increase in collision occurrence (Dell'Acqua 2011). It is possible that although the mean speed is reduced, the speed variation could increase, which is considered to have a negative impact on safety. Thus, an *F*-test was conducted to test the change in speed variance (Dell'Acqua 2011; Islam & El-Basyouny 2013). The null hypothesis is that the speed variance has not been reduced by the treatment, while the alternative hypothesis is that the variance has been reduced.

Plots showing speed percentiles were constructed for all locations and for locations with different compliance rates. The plots were depicted using a cumulative speed distribution at

different speed ranges. Such a depiction allows the comparison of speed distributions graphically and provides good visualization on the change in speeds.

5. RESULTS AND DISCUSSION

5.1. Collision Analysis

5.1.1. *Full Bayes Before-and-after Study*

Given the advantages of Full Bayesian inference, the changes in collisions were evaluated using a FB before-after intervention model. The posterior summaries in Table 5 were obtained via WinBUGS using two chains with 100,000 iterations each, 20,000 of which were excluded as a burn-in sample. Examination of the BGR statistics, ratios of the Monte Carlo errors relative to the standard deviations of the estimates and trace plots for all model parameters indicated convergence. Table 5 summarizes the parameter estimates and their credible intervals for the developed model.

By accounting for the comparison-treatment pairing, the interaction effect β_3 was negative and significant at the 95% and 90% credible interval for fatal/injury and VRU collisions, respectively. The result implied a statistically significant reduction in expected collision frequency of 45.3% and 55.3% in fatal/injury and VRU fatal/injury collisions, respectively. The estimates of σ_u^2 were significant, thereby demonstrating the presence of over-dispersion in the data.

5.1.2. *Spatial and Temporal Collision Migration/Spillover Effects*

Since the comparison group was selected based on its spatial proximity to the school zones, collision migration or spillover might bias the results of the analysis. For example, collision migration might occur on nearby roads as drivers might end up speeding on these facilities to

1 make up for any time losses due to driving 30 km/h in the school zones. This might increase the
2 collisions on these nearby roads and hence bias the results of the analysis. Conversely, driving at
3 30 km/h in school zones might cause drivers to be more vigilant of the speed limits within an
4 area, leading to improvements in speed compliance on nearby roads. Subsequently, this would
5 result in a safety spillover leading to reductions in collisions on neighbouring roads. Again, this
6 might bias the results of the analysis.

7 The above discussion is meant to highlight the spatial effects of collision
8 migration/spillover on the analysis. In the same light, one might ask if the migration or spillover
9 effects might exist on times and days when school zones are not in effect. Was there any
10 improvement or deterioration in safety outside of school zone hours or during weekends or
11 statutory holidays? This will be referred to as a temporal collision migration/spillover analysis.
12 Both phenomena were investigated in this study by repeating the above analysis using different
13 data sets.

14 To address the spatial migration/spillover effects, the above analysis was repeated except
15 this time a new comparison group was used. The new comparison group was selected to be close
16 and similar to the initial comparison group, which were the 3rd-order neighbouring streets to
17 school zone streets with similar road characteristics. A total of 529 sites were finally selected in
18 the new group. Both groups (2nd and 3rd -order neighbouring) consisted of roads with 50 km/h
19 speed limits. In this analysis, the initial comparison group was assumed to be the treated
20 locations (even though there were no changes) and the OR was calculated using the data from the
21 new comparison group. The estimate and 90% credible interval of the OR for fatal/injury
22 collisions was 1.67 and (0.920, 2.443), respectively. The estimate and 90% credible interval of
23 the OR for VRU collisions was 0.687 and (0.0875, 1.763), respectively. Since both ORs are

bounded by 1 (with 1 covered in the confidence interval), this indicates a statistically insignificant effect. These results show that there were no changes in collisions before and after the introduction of school zones on the comparison group. Hence, it could be deduced that collision migration or spillover was not a factor in this study.

To address the temporal migration/spillover effects, an analysis method similar to that presented in section 4.2 was repeated except this time collisions occurring outside of school hours were used in the analysis for both the school zones and comparison sites. Note that the speed limit outside of school hours reverts to 50 km/h. Similar results were found to those observed in the spatial migration analysis. The estimate and 90% credible interval of the OR for fatal/injury collisions was 0.952 and (0.636, 1.336), respectively. Also, the estimate and 90% credible interval of the OR for VRU fatal/injury collisions was 0.940 and (0.157, 2.084), respectively. Again, both ORs are bounded by 1, indicating a statistically insignificant effect. The results show that there were no changes in collisions outside of school hours demonstrating that there were no temporal migrations or spillover. In this study, a 95% credible interval was consistently used except for cases where it did not produce significant results and, therefore, a 90% credible interval was used.

5.2. Speed Analysis

As described previously, the 43 school zones were clustered into three groups based on their compliance to the 50 km/h in the before time period. For each compliance group and for all sites, the mean speed and 85th percentile speed was compared before and after the introduction of the 30 km/h speed limit. A two-sample *t*-test was conducted to determine the statistical significance

1 in the change in mean speed, and an F -test was conducted to test the impact on speed variation.
2 Table 6 shows the results of the speed analysis.

3 The mean speed was found to be significantly reduced, with the largest reduction
4 recorded for the low-compliance group of 15.3 km/h. A 10.3 km/h and 5.6 km/h reduction in the
5 medium- and high-compliance groups were also found, respectively. There was also a reduction
6 in the 85th percentile for all speed groups. Overall, a 12.2 km/h reduction in mean speed and
7 11.6 km/h reduction in 85th percentile speeds were found. All reductions in mean speeds were
8 statistically significant at the 99% confidence level. Although Table 4 shows that the compliance
9 rate to the speed limit in the after period dropped, overall the average and 85th percentile speeds
10 were lower, indicating a positive effect. It is important to emphasize the fact that the reported
11 speeds in the after period were close to 30 km/h with an average of approximately 34 km/h.
12 Despite the fact this value is slightly higher than the speed limit, the results from the speed
13 cumulative distribution showed that the entire speed profile shifted to the left, indicating a
14 general speed decrease. The biggest change occurred at the mid-speed range (close to the speed
15 limit) as shown later in Figure 2. The results provided sufficient evidence to show that driver
16 behaviour has changed at the school zone locations.

17 When comparing the speed reductions to the above collision reductions, it could be
18 concluded that for each 1 km/h reduction in speed, a 4% reduction in fatal and injury collisions
19 was observed. These results are consistent with previous findings by Nilsson (Nilsson 2004).
20 Moreover, the speed variance was significantly reduced in all groups except for the low-
21 compliance group. Overall, the speed variance was significantly reduced when all sites were
22 combined. Since the reductions in mean speed and speed variation are considered to be
23 associated with positive safety effects (Christensen & Amundsen 2005; Dell'Acqua 2011;

1 Nilsson 2004), this study confirms that the implementation of a 30 km/h speed limit in school
2 zones has significant positive safety impacts by reducing severe and VRU collisions and driving
3 speeds.

4 To further explore the change in speed ranges, cumulative percentile speed distribution
5 plots were constructed for all locations as well as for locations with different initial compliance
6 rates. The results are depicted in Figure 2, which shows that the cumulative speed distribution
7 shifted to the left after the introduction of school zones. This shift was more prominent in the
8 low-compliance locations and for vehicles traveling at higher speeds.

10 **5.3. Discussion of Results**

11 The collision analysis demonstrated statistically significant reductions in both fatal and injury
12 collisions in school zones after speed limit reductions. Neither spatial nor temporal collision
13 migration/spillover effects were observed. Secondly, the recorded mean and 85th percentile
14 driver speeds were observed to experience large, statistically significant reductions at 12.2 and
15 11.6 km/h, respectively. The speed variance in school zones was observed to have decreased
16 after the speed limit reductions, which typically implies an improvement in traffic safety.

17 These results are generally consistent with the previously documented and reported
18 findings of other urban speed reduction studies in Section 2, summarized in Tables 1 and 2. The
19 drop in collisions resulting from a speed limit reduction is consistent with all five studies listed in
20 Table 2. However, the literature on the efficacy of speed limit reductions in reducing speeds is
21 mixed as per Table 1. The first three studies reported no statistically significant driver speed
22 reductions, while the last three did. Of interest is the fact that the two studies showing
23 statistically significant speed reductions in school zones were from Canada. It should also be

1 noted that the first three studies used very small sample sizes while this study examined the
2 results from 43 school zones within the city of Edmonton. The efficacy of speed limit reductions
3 likely varies from one school zone to the next; however, the results of this study demonstrate that
4 when they are assessed on a city-wide level, overall, speeds are seen to decrease. In addition,
5 there is likely to be more consistency in roadway geometry, signage saturation and other design
6 factors within Canada compared with other countries.

8 **5.4. Implications of Results for Vulnerable Road User Protection Policies**

9 The results of this study may support further considerations for speed limit reduction policies
10 within an urban setting. The overall city-wide efficacy of school zone speed limit reductions
11 within Edmonton suggests that speed limit reductions may be considered for other areas –
12 particularly those that specifically cater to, and attract, vulnerable road users. In fact, Edmonton
13 is currently moving forward with 30 km/h speed limits around all playgrounds (Neufeld 2017).
14 In addition, the city has piloted neighbourhood speed limit reduction programs that have
15 demonstrated benefits in particular neighbourhoods and therefore been adopted permanently
16 (City of Edmonton 2017). The success of speed limit reductions to these other areas may result
17 in an even more wide-spread adoption of reduced speed limits to high pedestrian zones and areas
18 with high density of elderly and other vulnerable populations.

19 Edmonton, like many other cities in the world, has been making significant investments
20 in promoting active transportation through education and infrastructure in order address urban
21 transportation sustainability by reducing vehicular traffic volumes and their negative externalities
22 (congestion, emissions, noise pollution, and, of course, collisions), and promoting healthier
23 lifestyles. Walking and cycling infrastructure is specifically designed to encourage greater usage

1 by providing more pleasant and safer travel experiences. It is well-accepted today that separated
2 facilities (for cyclists and pedestrians) provide the safest means of transport for these travelers
3 (Hull & O'Holleran 2014; Pucher & Dijkstra 2003). The literature documents many
4 interventions (speed reductions, education, vehicle design) in addition to streetscape design that
5 promotes urban traffic safety. Speed reductions not only improve road safety for these users, but
6 also the perception of safety, which further encourages active transport.

7 With cities promoting healthier lifestyles and vibrant communities by encouraging active
8 transportation and other outdoor activities, it is commonly agreed that "VRU traffic injuries are
9 the greatest challenge of today's worldwide road safety" (Constant & Lagarde 2010). As
10 Edmonton was the first city in Canada to adopt Vision Zero (Johansson 2009), this seems a
11 particularly important challenge to address through the interventions available to policy-makers.
12 However, before policies to reduce speeds on various facilities within a city, or within the entire
13 city itself, are implemented, scientific evidence of their benefits is necessary.

14 As discussed above, it would be valuable to specifically study the before-and-after effects
15 of trial speed reductions in many other urban settings and facilities, including adjacent to bike
16 lanes, major pedestrian areas, near hospitals and medical facilities, and others. Such studies,
17 combined with this one, could provide evidence and justification for cities like Edmonton to
18 consider larger speed reduction policies to protect vulnerable citizens in many types of
19 neighbourhoods and streetscapes. More fundamentally, speed reductions, combined with other
20 interventions mentioned above, address larger issues of urban sustainability and livability;
21 holistic policy frameworks that include targeted speed reduction policies (such as one that would
22 be supported by this research) can help to modify the standards by which motor vehicles are
23 operated in urban areas.

6. CONCLUSION AND FUTURE WORK

This paper conducted before-and-after speed and safety evaluations to study the effects of reducing the speed limit from 50 to 30 km/h in school zones across the city of Edmonton. A total of 216 school zones as well as 622 comparison sites were selected for the collision analysis, and 43 school zones were further evaluated for changes in vehicular speeds. A series of statistical tests were used to test the significance of changes in collisions, speeds and speed variation.

To account for statistical uncertainty, a Full Bayes approach was developed for the before-and-after evaluation; the results showed that fatal and injury collisions were reduced by 45%. More so, vulnerable road user injury collisions were reduced by 55% using Full Bayesian intervention models. All reductions were found to be statistically significant. To further investigate the temporal and spatial collision migration or spillover effects that may exist, the full Bayes evaluation was repeated twice by first considering the collisions outside school times (to investigate the temporal effects) and by using a new comparison group of sites (to investigate the spatial effects). Consequently, results from these two analyses showed that neither spatial nor temporal collision migration/spillover effects were a significant factor in this study.

Significant reductions were also observed for mean speeds and 85th percentile speeds; these reductions were 12.2 km/h and 11.6 km/h, respectively. Speed variations were smaller in the after period for locations with high and medium initial compliance rates and for all locations as a whole. The reduction in speed variance is typically associated with positive safety implications. Speed distribution plots were depicted to compare the speed before and after the speed limit change. The plots show that speed was successfully reduced for the whole range of speeds, especially for high-speed locations.

1 It can be concluded from this study that 30 km/h school zones were significantly effective
2 in improving safety near schools. From a Vision Zero perspective, this type of program can assist
3 in achieving the long-term goals set up by transportation agencies worldwide. More broadly,
4 speed limit reduction policies in other areas with VRU (for instance, in residential
5 neighbourhoods, and around playgrounds and major pedestrian areas) can support the city of
6 Edmonton's goals of increasing its overall sustainability and livability. Studies like this one, in
7 combination with speed reduction studies in other urban settings, and other interventions
8 (roadway design, intervention, vehicle technology) should be part of a larger holistic package of
9 scientific evidence that speaks to more powerful policies that can promote modern active
10 transportation. This study only grouped and evaluated the school zones by different compliance
11 rates, without including further road characteristics. Future work may examine the influences of
12 different road environments on the effectiveness of 30 km/h school zones, such as the number of
13 lanes (2- vs. 4-lane roads), volume and presence of children at the school zones, length of the
14 speed zone and types of schools, and others. Future work could also explore the potential novelty
15 effects that may cause either a degradation or improvement of compliance to the new speed
16 limits over time.

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FIGURE 1 Map of school zones and traffic districts

FIGURE 2 Cumulative speed distribution profiles

TABLE 1 Literature Summary of School Zones’ Effects on Vehicular Speed

Study	Country	Data Sample	Result Summary*
Young & Dixon (2003)	US	4 school zones	School zone signage had no general impact on reducing vehicular speed.
Zhao et al. (2015)	China	20 school zones	Effectiveness of school zones in changing speed varied greatly depending on road geometric conditions.
Stawderman et al. (2015)	US.	4 school zones	Marking school zones was ineffective in improving safety, while a high saturation of signage had a more positive effect in changing driver behavior
Vis et al. (1992)	Netherlands	15 areas with 30 km/h zones	30 km/h zones led to a significant reduction in traffic volumes and speeds, receiving support from residents.
Lazic (2003)	Canada	15 school zones	85th percentile speed was reduced by 10 km/h, after reducing speed limit from 50 to 30 km/h in school zones.
Tay (2009)	Canada	20 spots around schools and playgrounds	Mean speed and 85th percentile speed at 30 km/h school zones were significantly lower than on other 50 km/h streets.

*Remarks: 1) Mixed findings on the effectiveness on speed reduction. 2) A relatively small sample size was used in most previous studies.

TABLE 2 Literature Summary of School Zones' Effects on Road Collisions

Study	Country	Data Sample	Result Summary*
Engel et al. (1992)	Denmark	44 experimental streets	Road casualties were reduced by 72% by reducing speed limits.
Lindenmann (2005)	Switzerland	30 residential zones	Collisions were reduced significantly on 30 km/h residential zones.
Grundy et al. (2009)	UK	20 mph zones around London	20 mph zones are effective in reducing road casualties, particularly for young children.
Graham & Sparkes (2010)	Australia	820 school zones	Crashes, especially pedestrian casualties, were significantly reduced by implementing 40 km/h school zones
Hazzard and Hildebrand (2015)	Canada	31 urban and 24 rural school zones	Delineated school zones are statistically safer than comparable streets outside school areas
Li et al (2016)	UK	20 mph zones around London	Minor road injuries were reduced by 10% and serious road casualties were reduced by 24% in 20 mph zones

*Remarks: 1) Most studies used a simplistic study design. 2) Most studies were conducted on residential streets, with limited studies being carried out in school zones, where children are the predominant vulnerable road users.

TABLE 3 Descriptive Statistics Summary of Collision Data

Collision Counts	School Zones (216 zones)		Comparison Sites (622 sites)	
	Before (3yrs)	After (2yrs)	Before (3yrs)	After (2yrs)
	2011.09-2014.08	2014.09-2016.08	2011.09-2014.08	2014.09-2016.08
Injury & Fatal	50	23	122	93
VRU Injury	20	6	32	20

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TABLE 4 Descriptive Statistics Summary of Speed Data

Speed Metrics	Before	After
Mean Speed (43 school zones overall)	45.8 km/h	33.6 km/h
85th Percentile Speed (43 school zones overall)	52.9 km/h	41.3 km/h
Standard Deviation (mean speed)	12.1 km/h	12.0 km/h
Maximum Zone Mean Speed (1 zone)	55.6 km/h	39.7 km/h
Minimum Zone Mean Speed (1 zone)	31.7 km/h	27.3 km/h
Compliance Rate to Speed Limit +0 km/h	76%	45%
Compliance Rate to Speed Limit +5 km/h	86%	67%
Compliance Rate to Speed Limit +10 km/h	92%	81%
Compliance Rate to Speed Limit +15 km/h	95%	89%

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TABLE 5 Parameter estimates and credible intervals

	Severe Collisions*	VRU Collisions**
β_0 Intercept	-2.435 (-2.788, -2.115)	-3.595 (-4.108, -3.117)
β_1 Time Indicator	0.0851 (-0.281, 0.392)	-0.862 (-1.985, -0.0556)
β_2 Treatment Indicator	-1.110 (-1.653, -0.656)	-0.723 (-1.522, -0.116)
β_3 Two-way Interaction Term	-0.658 (-1.280, -0.0336)	-1.100 (-2.656, -0.0117)
σ_u^2 Extra Poisson Variance	0.126 (0.00840, 0.471)	0.512 (0.0178, 1.606)
σ_0	1.230 (0.967, 1.524)	0.785 (0.209, 1.261)
σ_1	0.295 (0.0812, 0.724)	1.123 (0.263, 2.088)
σ_2	0.872 (0.195, 1.494)	0.603 (0.110, 1.432)
σ_3	0.353 (0.0724, 1.123)	0.854 (0.131, 2.324)
Odds Ratio (OR)	0.547 (0.278, 0.967)	0.447 (0.0702, 0.988)
Deviance Information Criteria (DIC)	1073	482.1

* 95% credible intervals

** 90% credible intervals

TABLE 6 Before-After Evaluation Results—Speed Statistical Analysis

		Overall	Compliance Group		
			Low	Medium	High
Mean Speed	Before	45.8	50.4	42.5	37.6
(km/h)	After	33.6	35.1	32.2	32.0
	Speed Reduction	-12.2	-15.2	-10.3	-5.6
85 th Percentile Speed	Before	52.8	59.7	50.2	47.1
(km/h)	After	41.3	44.1	40.8	39.4
Variance	Before	145.7	138.3	154.5	152.1
	After	144.2	146.7	139.9	144.3
Observations	Before	234,185	120,778	77,291	36,116
	After	104,305	49,897	30,449	23,959
Two Sample <i>t</i> -Test	<i>t</i> -value	-272.9	-241.4	-123.8	-55.1
(statistical test of mean speed change)	<i>p</i> -value	<0.01	<0.01	<0.01	<0.01
<i>F</i> -test	<i>F</i> -value	1.011	0.942	1.105	1.054
(statistical test of speed variance change)	<i>p</i> -value	<0.05	1	<0.01	<0.01