BEFORE-AND-AFTER EMPIRICAL BAYES EVALUATION OF ACHIEVING BARE PAVEMENT USING ANTI-ICING ON URBAN ROADS

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EXECUTIVE SUMMARY

Worldwide, reports on traffic collision statistics and research studies show a dramatic increase in collisions during winter months in regions with adverse winter weather conditions. In Canada, the yearly cost associated with injury and property-damage collisions caused by adverse weather conditions is estimated at $1 billion annually. Not only does adverse weather impact road safety at a considerable cost to the economy, it also significantly reduces traffic mobility. As such, Winter Road Maintenance (WRM) operations are performed to improve traffic safety and mobility. WRM is a costly snow and ice control operation that involves extensive use of both material and manpower as it targets restoring pavement to a safe condition, thereby reducing traffic collisions.

Canadian municipalities are increasingly choosing to implement achieving bare pavement (BP) for snow and ice control during fall/winter seasons. One strategy, when a snowstorm event is forecasted, is to apply anti-icing chemicals to the pavement surface to prevent the snow and ice from forming a bond with the road surface prior to snow fall. Such an approach facilitates a more efficient plowing operation and reduces the amount of deicing chemicals needed to achieve BP compared to traditional reactive WRM. As such, it reduces the cost of WRM operations. In 2017, the City of Edmonton (CoE), with the intention of improving its WRM operations and after a review of current practices in major Canadian cities, expanded a pilot project to test the benefits of achieving bare pavement using anti-icing.

The use of anti-icing has its own limitations. Anti-icing chemicals are applied directly to the road surface compared to reactive deicing where the chemicals are applied to the snow and ice layer, which it penetrates as it melts. While in both approaches, the chemical comes in contact with the infrastructure surface, its direct application in anti-icing may have a stronger impact on the pavement's long-term performance. Another limitation is vehicle wear and tear due to the corrosive nature of the chemicals. However, the CoE has been combining their anti-icing agent with corrosion inhibitor to overcome this limitation.

Since there is limited research regarding the benefits of achieving bare pavement using anti-icing agents, there is debate as to whether or not adopting such a policy would be beneficial from a safety standpoint while also being economically feasible. This report investigates the safety performance of the CoE anti-icing pilot compared to the traditional reactive WRM approach on urban roads using a before-and-after Empirical Bayes (EB) approach, as outlined in the AASHTO Highway Safety Manual. Further, the corresponding changes in collisions were converted to monetary values, based on three different collision cost methods, to determine its economic feasibility.

The safety effectiveness and statistical significance of anti-icing, on 1,293 linear-km of urban roads, for different collision types, severities, and priority levels were determined. Results suggest that reaching BP significantly reduces all collision types and severities on midblocks

with a reduction value in the range of 13.7% to 19.7%. Reaching BP on intersections was found to be very effective in reducing injury collisions with an estimated reduction of 12.50%. When sites were grouped based on a WRM priority-basis, it is found that anti-icing is effective for reducing the majority of collision types and severities on the different priority levels with reductions ranging from 8.70% to 49.83% on midblocks and between 5.37% and 13.00% at intersections. All reductions were statistically significant. Table E1 shows a summary of the evaluation results. The monetary benefits of the reductions in PDO and nonfatal injury collisions were estimated at $20.4 million to $59.4 million using a 1.92% interest rate and a 2-year service life. These findings provide unequivocal evidence that achieving BP using anti-icing can lead to significant societal safety benefits that economically translate in huge collision cost savings.

Further research is required to evaluate the effects of achieving BP using anti-icing at a more disaggregate level, i.e., snowstorm event level. This could provide further insight into the relationship between safety improvements and several WRM variables. In addition, comparing the impact of different anti-icing technologies is recommended.

TABLE E1 Overall Before-and-After Evaluation Results

Collision Location/Type		**Severity**	**SE (%)**	***t*-ratio**
Midblocks Collisions	*All*	*TOT*	16.20	10.20*
		PDO	15.80	9.40*
		INJ	17.84	3.60*
	ILC	*TOT*	19.70	6.04*
	RE	*TOT*	13.73	4.80*
	SPEED	*TOT*	16.63	7.88*
		PDO	16.45	7.38*
		INJ	17.93	2.76*
Intersections Collisions	*All*	*TOT*	1.77	1.57
		PDO	-0.06	-0.05
		INJ	12.48	4.34*
	LTXP	*TOT*	12.38	4.38*
	FOTC	*TOT*	7.72	2.94*

*Statistically significant at the 99% confidence level; *SE* = safety effectiveness, positive implies reduction and negative implies increase; *TOT* = Total; *ILC* = Lane change improperly; *RE* = Rear-end; *LTXP* = Left turn cross path; *FOTC* = Failed to observe traffic control; *PDO* = Property-damage only; *INJ* = Non-fatal Injury.

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1 INTRODUCTION

Worldwide, reports on traffic collision statistics show a dramatic increase in collisions during winter months in regions with adverse weather (*1–5*). In fact, the majority of traffic collisions in Canadian cities occur during the fall and winter seasons, with percentage of collisions reaching as high as 50% of the yearly total (*3*, *4*, *6*). This is in addition to the number of studies that support these statistics (*7–11*). In Canada, the yearly cost associated with injury and property-damage collisions caused by adverse driving conditions is estimated at $1 billion (*12*). In the USA, more than 5.9 million vehicle collisions occur every year, 21% of these collisions are caused by severe weather, and on average, 418,000 people are injured and 5,000 are killed yearly in weather-related collisions (*5*). The cost of all reported weather-related collisions was estimated to be as high as $22 billion per year (*13*).

The main factor leading to increased collisions in winter is the deterioration of pavement surface condition (*2*, *5*, *11*). Wet as well as snow- and ice-covered pavement creates a slippery road surface, which inevitably leads to hazardous situations. The frequent spinning and sliding of vehicle tires on snow or ice polishes the snow layer surface and, as such, reduces traction, hindering the vehicle's performance in braking or stopping, significantly increasing the required braking distance (*14*). Not only does adverse weather impact road safety, it also significantly reduces traffic mobility (*5*, *15*). Weather events, including heavy snow as the severest condition, reduce traffic volumes by up to 44%, average speed by 40%, and capacity by 30%, while increasing travel time delays by up to 50% (*5*).

As such, Winter Road Maintenance (WRM) operations are performed to improve traffic safety and mobility (*1*, *2*, *11*, *15*). WRM is a costly snow and ice control procedure that comprises a sequence of proactive and/or reactive steps that aim to increase the pavement surface traction (*1*, *16*) and involves extensive use of material, equipment, and manpower as it targets restoring pavement to a safe condition, thereby reducing traffic collisions (*1*, *17*). In traditional reactive WRM operations, snow removal is performed after a predetermined amount of snow has accumulated on the road surface. Deicing chemicals are then applied to the road surface to break the bond between snow and ice and the pavement, and then the mix is pushed off the pavement in a process referred to as "plowing". A major drawback of the reactive approach is that the force of traffic leads to the formation of a compacted snow layer that is strongly bonded to the pavement surface. Consequently, a large amount of deicing material is needed to penetrate the snow layer and break that bond (*16*).

A proactive maintenance strategy, which is increasingly being implemented in Canadian cities to tackle the limitations of reactive WRM approaches, known as "Anti-icing", prevents or minimizes the bond between snow and ice and the pavement (*16*, *17*). When a snowstorm event is expected, anti-icing chemicals are applied to the road surface shortly before the storm to prevent the bond from forming. This allows snow and ice to be plowed off the road surface using less deicing chemicals during or after the snowstorm event (*16*, *18*, *19*). Proactive WRM strategies have several benefits over reactive approaches, such as decreased use of deicing materials, reducing both the negative environmental impacts and the costs associated with the WRM process (*20*). Proactive strategies, however, depend on the accurate forecasting of snowstorm events. Applying anti-icing chemicals too soon or too late before the storm can require the reapplication of chemicals or allow the formation of a tightly bonded snow and ice layer on the pavement surface. As such, inaccurate weather or snowstorm forecasting could result in a significant cost increase making the proactive approaches infeasible or cost-ineffective compared to reactive approaches (*16*).

Due to the high cost of WRM operations, optimizing the use of limited resources is essential. The annual cost of WRM in Ontario is in the range of $100 million, which represents 50% of the total annual highway maintenance budget, while the annual direct cost of WRM is $1 billion in Canada and over $2 billion in the United States (*15*, *21*). Not to mention the indirect environmental costs of using chemicals in WRM operations (*15*). Thus, high overheads and budget constraints make maintaining bare pavement (BP) conditions on all roads during the entire winter season impractical. Hence, maintaining BP conditions is only continuous on high priority corridors (e.g., freeways, bridges, bus routes, etc.), and snow removal operations are only initiated when a certain amount of snow has accumulated on the road surface. Therefore, cities are limited to adopting policies and WRM strategies that are within their budget constraints (*1*, *18*, *22*).

The successful implementation of an anti-icing snow and ice control program has the potential to improve safety and reduce WRM costs (*18*), however, it is not without its own limitations. Anti-icing chemicals are applied directly to the road surface compared to reactive deicing where the chemicals are applied to the snow and ice layer, which it penetrates as it melts. While in both approaches, the chemical comes in contact with the infrastructure surface, its direct application in anti-icing may have a stronger impact on the pavement's long-term performance (*23*). Another limitation is vehicle wear-and-tear due to the corrosive nature of the chemicals. However, the City of Edmonton has been combining their anti-icing agent with a corrosion inhibitor to overcome this limitation (*18*).

Since there is limited research regarding the benefits of achieving BP using anti-icing agents, there is debate as to whether or not adopting such a policy would be beneficial from a safety standpoint while also being economically feasible. In addition, every agency assesses the performance of its snow and ice control operations using different methodologies and techniques. As such, comparing results and practices among agencies is fraught with challenges as there is no single measure widely accepted or used (*17*).

In 2017, the City of Edmonton (CoE), with the intention of improving its WRM operations and after a review of current WRM practices in major Canadian cities, expanded a pilot project to test the benefits of achieving BP using anti-icing (*18*). This study investigates the safety performance of the CoE pilot on arterial and collector roads using a before-and-after Empirical Bayes (EB) approach, as outlined in the AASHTO Highway Safety Manual (*24*). Further, the corresponding changes in collisions were converted to monetary values, based on three different collision cost methods, to determine its economic feasibility (*25*). This study addresses a critical gap in previous research as it is the first study to assess anti-icing performance on urban roadways using the before-and-after EB technique, which accounts for critical analysis limitations in the literature, such as the regression-to the-mean (RTM) and other confounding effects (*26*).

2 LITERATURE REVIEW

Usman et al. (*2*) was the first study to model the relationship between collision frequency and road surface condition during snowstorm events using data from four freeways in Ontario, Canada, with a total route length of 89.6 km. The study utilized a Road Surface Index (RSI), which is a surrogate measure of pavement friction and descriptive Road Surface Conditions (RSC) recorded at Road Condition Weather Information Systems stations. As such, a range of RSI values could be estimated for different WRM strategies based on the RSC targeted by maintenance operations (e.g., maintaining BP). The results showed that RSC, represented as RSI, has a statistically significant relationship with collision frequency at all locations. The lower the RSI value (poorer pavement condition), the higher the expected number of collisions. An improvement of 1% in RSI would lead to a 2.28% reduction in the expected number of collisions. In addition, it was found that reducing the BP recovery time by one hour (from four to three hours after a four-hour snowstorm) could reduce the mean number of collisions by 9%.

Usman et al. (*11*), investigated the relationship between winter road collision occurrence and several factors such as the RSC, traffic exposure, temperature, precipitation, and visibility. Their dataset included 31 different highway routes across Ontario, Canada. Data observed over six winter seasons from 2000 to 2006 were used in the study with 13,775 recorded collisions. It was concluded that road surface condition not only has a significant relationship with road safety but is also the major contributing factor to collision occurrence during snowstorm events. Their model suggests that reducing the BP recovery time from eight hours to four hours would reduce collision frequency by over 50%.

A study by Mahoney et al. (*26*) investigated the safety benefits of the anti-icing WRM policies adopted by the Connecticut Department of Transportation (DOT) in the USA, focusing on the agency's switch from deicing to an anti-icing approach on state highways, during the 2006/07 winter season. It was observed that nonfatal injury collisions were reduced by a significant 19.2% during the winter season after converting to the anti-icing strategy, and nonfatal injury collisions, on snow, slush, and ice-covered pavement, dropped by 33.5% during anti-icing years compared to deicing years.

Qiu et al. (*8*) studied the effects of WRM operations on the frequency of collisions in Iowa, USA. The analysis used Road Weather Information Systems stations data, collision records, and traffic volume data recorded over four years. Snow plowing operations were found to reduce injury and property-damage only collisions by 24.2% and 23%, respectively.

A recent study by Zhang et al. (*27*) compiled traffic data, weather data, roadway surface conditions, and collision data from all interstate and major arterial routes within Iowa in the winter seasons between 2016-18. The authors were able to collect data on a higher granularity level than most WRM studies: data points on traffic and weather were collected for five-minute intervals compared to the traditional one-hour time intervals. The model indicates that the road condition, Vehicle Miles Travelled (VMT), and the amount of freezing rain and snow are significant variables when estimating collision frequency. It was concluded that improving road conditions during a snowstorm can significantly reduce the expected mean collision frequency.

Ye et al. (*28*) used artificial neural networks (ANNs) to model a safety performance function that captures the relationship between collision frequency and chemical use during WRM operations, Annual Average Daily Traffic (AADT), weather severity index (WSI), and segment length. Data from two highways in Idaho with a total length of 92.436 miles were used. WRM, represented as chemical usage, was found to reduce collisions by about 27% to 38%.

Further, the author estimated the benefit-cost ratio of WRM. With a reduction of 200 collisions and an average collision cost of $42,796, the total safety benefits of WRM operations were estimated at $8,559,200. The WRM expenditures accounted for the equipment cost, chemical cost, and labour cost. The benefit-cost ratios for the two studied highway segments were 5.54 and 7.43.

Hanson et al. (*29*) reviewed the deployment of Fixed Automated Spray Technology stations (FAST) in Ontario, Utah, and Pennsylvania. FAST stations can automatically apply anti-icing chemicals onto a road surface based on road weather and environment weather data. All surveyed agencies reported decreases in collision frequency on road segments that were upgraded with FAST stations. A lack of recorded data prevents an exact cost-benefit analysis for any of the surveyed transportation agencies. The study recommends that maintenance costs for FAST stations has to be considered to warrant the installation of a FAST system. Veneziano et al. (*30*) evaluated the safety effectiveness of 21 FAST stations on state highway bridges in Colorado, USA, and reported mixed results. Kuemmel et al. (*31*) compared the change in collision rates for different salting mixtures used on highways in Iowa, Minnesota, New York, and Pennsylvania in the winter seasons from 1992-1994. It was found that WRM significantly reduces collisions on Freeways.

The majority of previous studies focused on modelling the relationship between collision frequency, RSC (e.g., dry, wet, snowy), WRM operation parameters (e.g., time to restore BP condition and cost of chemicals), exposure measures (e.g., VMT), snowstorm event parameters (e.g., length), and weather (e.g., WSI). Several regression methods were used to develop the models, such as the GNB, the PLN, and ANNs. It was found that road surface condition not only has a significant relationship with collision frequency but is also the major contributing factor to collision occurrences during snowstorm events. WRM operations were found to reduce collision frequency by up to 50%, property-damage collisions by 23%, and injury collisions by 24.2%. Further, switching to a proactive anti-icing policy from a standard reactive approach could reduce injury collisions by 33.5% on rural roadways.

Only one study explicitly assessed the safety performance of anti-icing compared to the common reactive policies on rural roads (*26*). The study adopted a conventional analysis approach which has been known to lead to biased conclusions due to the method's inability to account for the regression-to-the-mean (RTM) effects and other confounding factors. The before-and-after Empirical Bayes (EB) approach used in this study can address all of the major limitations that are associated with the use of conventional safety analysis techniques (*32*, *33*). In addition, the monetary value of the expected change in frequency of collisions is estimated, which may help in assessing the economic feasibility of anti-icing WRM and provide WRM agencies with useful information about the economic performance of achieving BP using anti-icing.

3 PROGRAM AND DATA DESCRIPTION

Historically**,** the City of Edmonton (CoE) has implemented a reactive WRM prioritized plan for snow clearing on approximately 11,500 lane-km (3,323 linear-km) (*1*). Table 2 shows Edmonton's WRM priority levels and their corresponding corridors and policies (*18*). On higher priority corridors, plowing starts after 3 cm of snow accumulation to maintain BP conditions while low priority routes are bladed to 5 cm of snowpack. For decades, a mix of sand and salt, prewetted with liquid calcium chloride (aka brine), was used as a de-icer to melt the snow and ice before removal and as an abrasive to improve traction (*34*), although the mix ratios change based on the pavement and air temperatures (*1*). In 2017, based on a review of state-of-the-art snow and ice control practices in major Canadian municipalities, the CoE expanded an anti-icing pilot project to test the effectiveness of adopting a proactive anti-icing policy (*18*).

TABLE 1 Priority Hierarchy of Winter Maintenance Operations for Edmonton's Transportation Network

Priority Level	Location	Policy
1	Freeways, arterial roads, business districts, protected bike lanes, priority bus routes, and multiuse trails	Maintain BP standard within 24-48 hours from the end of snowfall
2	Collector roads, bus routes, transit park and ride access roads	Maintain BP standard within 48 hours from the end of snowfall
3	Local industrial roadways	Maintain BP standard within 5 days from the end of snowfall
4	Residential streets, alleys and painted bike lanes	Blading starts in 48 hours from the end of snowfall and is completed in 5 days

A total of 100 maintenance routes on arterial and collector roads, with different priority levels based on corridor importance and traffic volume, were included in the project. Anti-icing was performed on 55 routes with a total distance of 1,293 linear-km (treatment routes) while the regular reactive approach was maintained on 45 routes with 1,068 linear-km (reference routes). When a snowstorm was forecasted, anti-icer brine, calcium chloride solution with an added molasses corrosion inhibitor, was applied to approximately 40% of Edmonton's arterial and collector roads. Figure 1 shows Edmonton's road network, anti-icing routes, and reference (regular WRM) routes for the pilot project. Figure 2 shows the study maintenance routes road classification (arterial and collector roads). The use of anti-icing reduced plowing operations and it was found that sand may not be applied to the road surface before plowing, saving WRM time, money, and resources (*18*).

The CoE provided both the AADT and traffic collision data. Recorded traffic collision data between October and March over seven fall/winter seasons between 2012 and 2019 were used in the analysis. The after period included the two seasons of 2017/2018 and 2018/2019, and the before period included the five seasons prior to 2017/2018. The CoE maintains a Motor Vehicle Collision Information System (MVCIS). It is a database with all reported collisions in Edmonton that involve at least one motor vehicle and result in an injury, fatality, or property damage of at least $2000 CAD. The collisions database includes several details about each collision, such as severity, date, location (intersection or midblock), coordinates, cause, etc.

Several collision types, identified based on the cause and severity, were used in the analysis. Table 2 summarizes all collision severities and types included in the study. It is worth mentioning that a population ratio was used to estimate missing AADT values for certain years and locations.

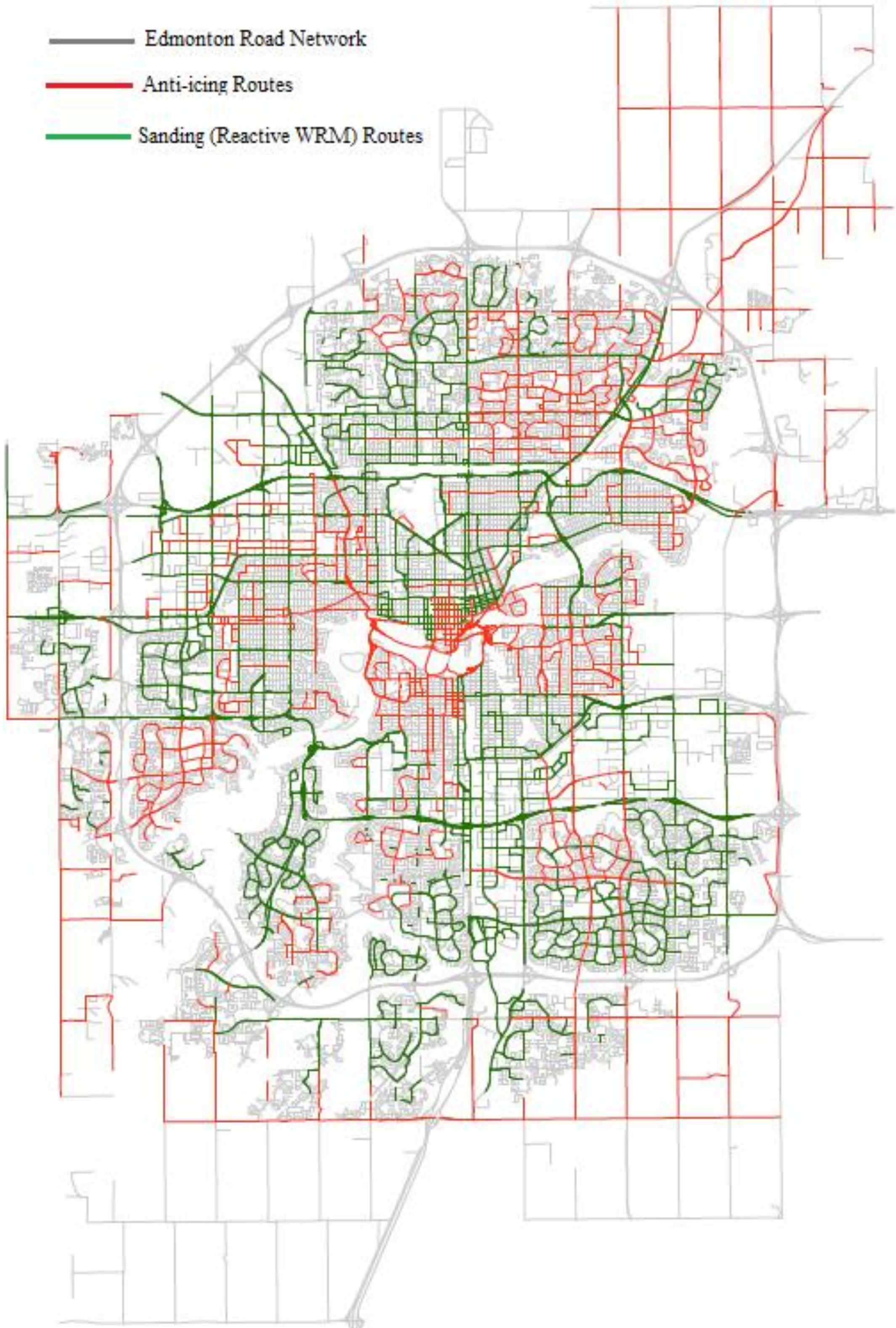

Figure 1 Pilot project WRM anti-icing and sanding (regular reactive) routes

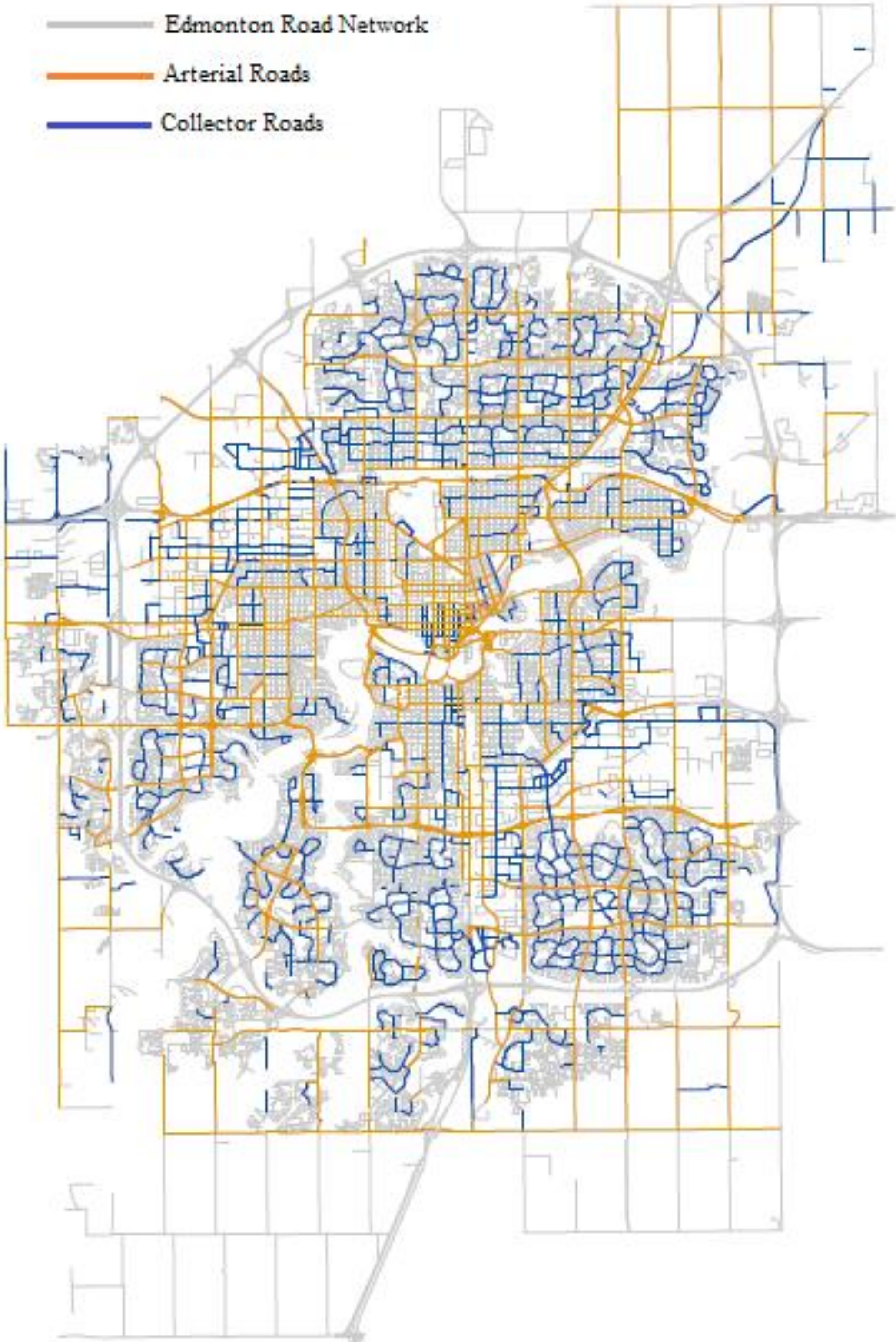

Figure 2 Pilot project arterial and collector routes

TABLE 2 Collision Classifications Description

Collision Classification	**Description**
Total (*TOT*)	Includes all collisions
Injury (*INJ*)	Includes all nonfatal injury collisions
Property damage only (*PDO*)	Includes collisions that resulted in property damage only
Rear-end (*RE*)	Includes collisions caused by vehicles following too closely to each other
Improperly lane changing (*ILC*)	Includes collisions caused by improper lane changing
Speed-related (*SPEED*)	Includes collisions where speed was identified as a contributing factor
Left turn cross path (*LTXP*)	Includes collisions caused between left turning vehicles and through movement at intersections
Failed to observe traffic control (*FOTC*)	Includes collisions caused by failure to observe or yield to traffic control devices

4 METHODOLOGY

4.1 Safety Performance Functions

Developing Safety performance functions (SPFs) is an essential step in the before-and-after evaluation. SPF are used to capture the relationship between collision frequency at certain locations, such as intersections or midblock road segments, and a set of explanatory variables (e.g., AADT, road segment length, etc.). A reference group is used to develop the SPFs for predicting collisions on the treated group, assuming no treatment has happened at these locations. Collision distribution is expressed using a negative binomial (NB) error structure, which is able to capture the over dispersion in collision data (*32*). The models' parameters are estimated using SAS GENMOD, which uses the maximum likelihood estimation (*35*). The models goodness-of-fit were assessed using Pearson x^2 and the scaled deviance (SD). SPFs were developed for several combinations of collision severities and types on midblock and intersection locations. **Equations 1** and **2** show the final model forms and significant variables used for midblock and intersection locations, respectively. A backward stepwise elimination process was performed to select model variables to retain.

$$\text{Collisions per year} = \text{AADT}_{average} * \beta_1 * \text{Length} * e^{\beta_0} \quad (1)$$

$$\text{Collisions per year} = (Length * \text{AADT}_{major}) * \beta_1 * \text{AADT}_{minor} * \beta_2 * e^{(\beta_0 + \beta_3 * ID)} \quad (2)$$

where $AADT_{average}$ is the average *AADT* on a route; *Length* is total route length; $\text{AADT}_{\text{major}}$ is the average *AADT* on major intersection approaches on a route; $AADT_{minor}$ is the average *AADT* on minor intersection approaches on a route; β_0, β_1, β_2 and β_3 = model parameters; and *ID* is the intersection density on a route which is equal to the number of intersections/route length.

The reference group and treatment group have similar routes in terms of maintenance priorities, road classes, and geometric features. This is essential to ensure the accurate estimation of the effects of the performed treatments.

4.2 Yearly Calibration Factors (YCF)

YCF is the ratio between the sum of the observed number of collisions and the sum of predicted number of collisions calculated by SPFs in the same season using the reference group data (**Equation 3**). Predicted SPFs number of collisions in the treatment group are adjusted by multiplying them with the corresponding YCFs. YCFs are used to account for confounding factors that are not captured in the variables of the SPFs (e.g., weather conditions, roadway improvements, etc.) (*36*). It is assumed that the effect of these confounding factors is similar on both the treatment and reference groups.

$$C_{ij} = \frac{\sum_{ref} N_i}{\sum_{ref} \mu_i} \quad (3)$$

where *C* is the yearly calibration factor; *N* is the observed number of collisions; μ is the predicted number of collisions; *i* is the collision type and severity; and *j* is the season.

4.3 Before-and-After Evaluation with EB Method

The before-and-after Empirical Bayes (EB) analysis technique is used to account for regression-to-the-mean (RTM) bias in collision frequencies (*37*). RTM reflects the random fluctuation in collision frequency without any effect from external factors. That is to say, RTM is the tendency of high collision frequencies to drop over time, and vice-versa, without any external effect or intervention. By incorporating information from a reference group into the collisions prediction, the RTM effect is accounted for, as proposed by Hauer et al. (*37*). Safety effectiveness using the EB approach is defined as the ratio between the observed number of collisions and the expected number of collisions.

The first step in the EB method is to calculate the expected number of collisions in the before period for each route in the treatment group. The expected number of collisions is a weighted average of the observed number of collisions and the predicted number of collisions using the SPFs adjusted by the YCFs. **Equations 4** and **5** show the calculation of the expected number of collisions on each route.

$$N_{Expected,B} = (w)N_{Predicted,B} + (1-w) * N_{Observed,B} \quad (4)$$

$$w = \frac{1}{1+\frac{N_{Predicted,B}}{k}} \quad (5)$$

where w is a weighted adjustment factor (between 0 and 1); $N_{Expected,B}$ is the expected number of collisions in the before period; $N_{predicted,B}$ is the predicted number of collisions in the before period; $N_{observed,B}$ is the observed number of collisions in the before period; and k is the overdispersion parameter estimated in SPF.

The second step is to calculate the expected number of collisions in the after period. In order to account for traffic volume and the differences in the before and after periods length, a multiplier, that equals the ratio between the predicted collisions in the after period and the predicted collisions in the before period, is developed. Then, this multiplier is applied to the expected number of collisions in the before period to calculate the expected number of collisions in the after period. The third step is the calculation of the overall odds ratio of collision reduction (θ) and its standard error (SE) (**Equations 6** to **8**).

$$\theta = \frac{\frac{\sum_{Allsites} N_{Observed,A}}{\sum_{Allsites} N_{Expected,A}}}{\left(1+Var\frac{(\sum_{Allsites} N_{Expected,A})}{\left(\sum_{Allsites} N_{Expected,A}\right)^2}\right)} \quad (6)$$

$$Var\left(\sum_{Allsites} N_{Expected,A}\right) = \left(\sum_{Allsites}\left(\left(\frac{\sum_{Allsites} N_{Predicted,A}}{\sum_{Allsites} N_{Predicted,B}}\right)^2 * N_{Expected,B} * (1-w)\right)\right) \quad (7)$$

$$SE(\theta) = \sqrt{\frac{\left(\frac{\sum_{Allsites} N_{Observed,A}}{\sum_{Allsites} N_{Expected,A}}\right)^2\left(\frac{1}{\sum_{Allsites} N_{Observed,A}}+Var\frac{(\sum_{Allsites} N_{Expected,A})}{\left(\sum_{Allsites} N_{Expected,A}\right)^2}\right)}{\left(1+Var\frac{(\sum_{Allsites} N_{Expected,A})}{\left(\sum_{Allsites} N_{Expected,A}\right)^2}\right)^2}} \quad (8)$$

where $N_{Expected,A}$ is the expected number of collisions in the after period; $N_{Predicted,A}$ is the predicted number of collisions in the after period; and $N_{Observed,A}$ is the observed number of collisions in the after period.

The safety effectiveness (SE) or percent reduction is then calculated using the odds ratio as in **Equation 9** and its SE is calculated using **Equation 10**.

Collision reduction (aka safety effectiveness) = $100 \times (1 - \theta)$ (9)

SE = $100 * SE(\theta)$ (10)

The last step is to assess the statistical significance of the estimated collision reduction percentage. The ratio between collision reduction estimate and its standard error is compared with the significance critical values. If the value of ratio is less than 1.645, then the treatment effect is not significant at the 90% confidence level. If ratio is more than or equal to 1.645, conclude that the treatment effect is statistically significant at the 90% confidence level. Finally, if ratio is more than or equal to 1.96, the treatment effect is significant at the 95% confidence level. The before-and-after EB evaluation was repeated for several collision types, severities and priority levels. It is worth noting that all routes included in the project were in either priority levels 1 or 2.

4.4 Collisions Costs Estimation

Using the safety effectiveness (**Equation 9**) and the expected number of collisions in the after period, the number of collisions reduced/increased due to countermeasures (A) is determined. Then, three different collision costs categories recommended by the Capital Region Intersection Safety Partnership (CRISP) are used to calculate the corresponding monetary values (B) (*25*).

CRISP is a partnership that conducts on-going research to reduce intersection collision frequencies in Alberta's capital region. Table 3 shows collision costs according to three different categories: direct costs, human capital costs, and willing-to-pay costs (*25*).

Direct costs are costs directly linked to the collision, such as property damage, emergency services, medical expenses, legal expenses, and travel delay costs. Human capital costs represent future net production lost to a society due to a collision. Willing-to-pay uses the costs the society is willing to pay to prevent a collision, that involves injury or death, from happening (*25*). Finally, the present worth of the monetary values (PWB) is determined using **Equations 11**, **12** and **13**. A 1.92% interest rate is used (i.e., this is the opportunity cost interest rate used by the City of Edmonton's procurement department). The number of years is the number of years in the after period (n = 2).

TABLE 3 Collision Costs by Different Methods as developed by Capital Regional Intersection Safety Partnership

Criterion	**PDO**	**Injuries**
Direct Costs	$14,065	$48,341
Human Capital	$14,065	$137,749
Willing-To-Pay	$14,065	$206,994

$$B = \frac{1}{n} * A * collision\ cost \quad (11)$$

$$PWB = B * \text{discount factor} \quad (12)$$

$$\text{Discount factor} = \left(\frac{(1+r)^n - 1}{r*(1+r)^n}\right) \quad (13)$$

where r = interest rate and n = number of years

5 RESULTS AND DISCUSSION

5.1 Developed SPF Models

SPF models were developed for different collision types and severities on intersections and at midblock locations. Tables 4 and 5 summarizes the developed models' goodness of fit and parameters estimation, respectively. The scaled deviance and Pearson x^2 values were used to test the model's goodness of fit. As shown in the table, all models are a good fit to all collision types and severities.

TABLE 4 SPF Models' Goodness of Fit Results

Collision Location/Type		**Severity**	**Goodness of fit**			
			Scaled Deviance	**Pearson x^2**	**df**	$x^2_{0.5}$
Midblocks	*All*	*TOT*	47.368	43.453	43	59.304
		PDO	47.450	46.315	43	59.304
		INJ	49.714	41.785	43	59.304
	ILC	*TOT*	50.241	54.090	43	59.304
	RE	*TOT*	50.191	46.427	43	59.304
	SPEED	*TOT*	47.994	43.330	43	59.304
Intersections	*All*	*TOT*	48.154	44.412	41	56.942
		PDO	48.262	45.162	41	56.942
		INJ	49.001	46.903	41	56.942
	LTXP	*TOT*	52.427	37.203	41	56.942
	FOTC	*TOT*	51.328	45.203	41	56.942

df = degrees of freedom; *TOT* = Total; *ILC* = Lane change improperly; *RE* = Rear-end; *LTXP* = Left turn cross path; *FOTC* = Failed to observe traffic control; *PDO* = Property-damage only; *INJ* = Non-fatal Injury.

Table 5 shows that all regression parameters were significant at the 99% confidence level and the signs of all parameters are intuitive. On midblocks, collision frequency increases with the increase in route length and average route AADT. At intersections, collisions increase with the AADT on major intersection approaches, AADT on minor intersection approaches, route length, and intersection density. Shape parameters were significant, validating the presence of overdispersion in the data.

Table 5 SPF Models' Parameters Estimates

Collision Location/Type		Severity	Parameters Estimates						
			Intercept	*Length*	$AADT_{avg}$	$AADT_{major} \times Length$	$AADT_{minor}$	*ID*	*Dispersion Parameter*
Midblocks	*All*	*TOT*	-8.043	1	0.953	-	-	-	0.366
		PDO	-7.953	1	0.930	-	-	-	0.383
		INJ	-11.939	1	1.107	-	-	-	0.380
	ILC	*TOT*	-16.368	1	1.679	-	-	-	0.584
	RE	*TOT*	-16.006	1	1.699	-	-	-	0.591
	SPEED	*TOT*	-8.351	1	0.934	-	-	-	0.434
Intersections	*All*	*TOT*	-14.374	-	-	0.949	0.699	0.253	0.384
		PDO	-14.814	-	-	0.974	0.700	0.249	0.393
		INJ	-15.496	-	-	0.834	0.742	0.294	0.315
	LTXP	*TOT*	-24.265	-	-	1.629	0.625	0.268	0.906
	FOTC	*TOT*	-13.981	-	-	0.943	0.421	0.391	0.348

All parameter estimates were statistically significant at the 99% significance level

TOT = Total; *ILC* = Lane change improperly; *RE* = Rear-end; *LTXP* = Left turn cross path; *FOTC* = Failed to observe traffic control; *PDO* = Property-damage only; *INJ* = Non-fatal Injury; $AADT_{avg}$ is the average *AADT* on a route; *Length* is total route length; $AADT_{major}$ is the average *AADT* on major intersection approaches on a route; $AADT_{minor}$ = average *AADT* on minor intersection approaches on a route; and *ID* is the intersection density on a route.

5.2 Overall Before-and-After Evaluation

Table 6 shows the overall collision reduction percentages and the corresponding *t*-ratios for the different collision types and severities on midblocks and intersections. For midblock locations, there is a statistically significant reduction in all collision types and severities at the 95% confidence level. Including all severities, there was a 16.20% reduction in total collisions, while *ILC*, *RE*, and *SPEED* collisions dropped by 19.70% (highest reduction), 13.73%, and 16.63%, respectively. *PDO* collisions dropped by 15.80% for all collisions and by *16.45%* for *SPEED* collisions. Finally, a reduction of 17.84% was observed for *INJ* collisions and a reduction of 17.93% was recorded for *SPEED INJ* collisions. For intersections, the changes were not statistically significant for all collision severities. Injury collisions dropped significantly by 12.48% but the changes in *TOT* and *PDO* collisions were not statistically significant. In addition, the reductions in *LTXP* and *FOTC* collisions are 12.38% and 7.72%, respectively. As evident from the results, anti-icing is effective in improving safety on both midblocks and intersections. However, it is more effective on midblocks compared to intersection locations.

TABLE 6 Overall Before-and-After Evaluation Results

Collision Location/Type		**Severity**	**SE (%)**	***t*-ratio**
Midblocks	*All*	*TOT*	16.20	10.20
		PDO	15.80	9.40
		INJ	17.84	3.60
	ILC	*TOT*	19.70	6.04
	RE	*TOT*	13.73	4.80
	SPEED	*TOT*	16.63	7.88
		PDO	16.45	7.38
		INJ	17.93	2.76
Intersections	*All*	*TOT*	1.77	1.57
		PDO	-0.06	-0.05
		INJ	12.48	4.34
	LTXP	*TOT*	12.38	4.38
	FOTC	*TOT*	7.72	2.94

SE = safety effectiveness, positive implies reduction and negative implies increase; *TOT* = Total; *ILC* = Lane change improperly; *RE* = Rear-end; *LTXP* = Left turn cross path; *FOTC* = Failed to observe traffic control; *PDO* = Property-damage only; *INJ* = Non-fatal Injury.

5.3 Priority-Based Before-and-After Evaluation

The before-and-after EB analysis was repeated for the different priority levels (1 and 2). Table 7 compares collision reduction percentages and the corresponding *t*-ratios for the different collision types and severities on midblocks and intersections for the different priority levels. For midblocks, all reductions were significant at the 95% significance level; expect for *INJ* and *RE* collisions on priority 2 routes. Reductions on priority 1 routes ranged from 14.00% for *RE* collisions and reached up to 18.90% for *ILC* collisions. Despite the insignificant changes mentioned for priority 2 routes, the highest safety effectiveness observed on the two priority levels was for priority 2 *ILC* collisions with a value of 49.83 %. All other priority 2 routes reductions are between 8.70% and 19.23%. For intersections, priority 1 *LTXP and INJ* experienced the highest drops estimated at 13.00% and 12.41%, respectively. Reduction in *FOTC* collisions was significant at the two priority levels (6.56% for priority 1 routes and 11.00% for priority 2 routes). The drop in all *TOT* was significant for priority 2 routes with a value of 5.37%. As such, anti-icing significantly reduces collisions on midblocks and intersections at the two priority levels.

TABLE 7 Priority-based Before-and-After Evaluation Results

Collision Location/Type		Severity	Priority			
			1		2	
			SE (%)	***t*-ratio**	**SE (%)**	***t*-ratio**
Midblocks	*All*	*TOT*	15.60	9.21	19.23	4.74
		PDO	15.60	8.48	19.02	4.52
		INJ	17.81	3.36	18.66	1.20
	ILC	*TOT*	18.90	5.62	49.83	4.19
	RE	*TOT*	14.00	4.80	8.70	0.62
	SPEED	*TOT*	17.00	7.4	15.6	2.92
Intersections	*All*	*TOT*	1.02	0.83	5.37	1.8
		PDO	-0.98	-0.734	4.635	1.44
		INJ	12.41	4.00	11.21	1.40
	LTXP	*TOT*	13.00	4.25	7.83	0.99
	FOTC	*TOT*	6.56	2.20	11.00	1.91

SE = safety effectiveness, positive implies reduction and negative implies increase; *TOT* = Total; *ILC* = Lane change improperly; *RE* = Rear-end; *LTXP* = Left turn cross path; *FOTC* = Failed to observe traffic control; *PDO* = Property-damage only; *INJ* = Non-fatal Injury.

5.4 Monetary Values of Changes in Collisions

Table 8 summarizes the values for the present worth of safety benefits at intersections and midblocks for various human cost categories. On midblocks, the total monetary benefits associated with anti-icing during the two seasons (October to March) on 1,293 linear-km, compared to reactive WRM, are at least $12,153,989.3 using the direct human costs, and goes up to $23,786,394.5 using the WTP collision cost. For intersections, the benefits are estimated at $8,258,350 for direct human cost and $35,654,918.4 for the WTP human cost. With a total amount of up to $59.4 million in safety benefits, achieving BP using anti-icing would lead to significant societal benefits and collisions cost savings.

TABLE 8 Monetary Benefits due to Collision Cost Savings

Location	**Cost Category**		
	Direct Costs	**Human Capital**	**Willing-To-Pay**
Midblocks	12,153,989.3	18,709,365.4	23,786,394.5
Intersections	8,258,349.6	23,697,530.8	35,654,918.4
Total	*20,412,338.90*	*42,406,896.20*	*59,441,312.90*

The explanation of cost categories is presented in section 4.4

6 CONCLUSIONS AND FUTURE WORK

The effectiveness of anti-icing WRM on 1,293 linear-km of urban roads was evaluated using the before-and-after with EB method. SPFs and YCFs were developed for different collision types, severities, and priority levels. The safety effectiveness and statistical significance of anti-icing were determined. It was found that anti-icing is more effective on midblocks compared to intersections.

Results suggest that anti-icing significantly reduces all collision types and severities on midblocks with a reduction value in the range of 13.73% to 19.7%. Furthermore, on intersections, it was found to be most effective for *INJ* collisions and the reduction is estimated at 12.50%. It also reduces *LTXP* and *FOTC* collisions by 12.38% and 7.72%, respectively, on intersections.

In general, the priority-based analysis suggests that anti-icing is effective for reducing the majority of collision types and severities on two different priority levels with reductions ranging from 8.70% to 49.83% on midblocks and between 5.37% and 13.00% on intersections.

The monetary benefits of the reductions in *PDO* and nonfatal injury collisions (using 2-years and 1.92% interest rate) are estimated at approximately $12 million to $24 million for midblocks and $8 million to $36 million for intersections for a combined net total of $20 million to $60 million. Results support that achieving BP through anti-icing, from a safety standpoint, is a better alternative to reactive WRM as it significantly reduces the majority of collision types and severities on both midblocks and intersections. In addition, the monetary benefits associated with anti-icing would result in huge cost savings and societal benefits.

Further research is required to evaluate the effects of achieving BP using anti-icing at a more disaggregate level, i.e., snowstorm event level. This could provide further insight into the relationship between safety improvements and several variables such as the WRM variables (e.g., time of anti-icing before a storm, amount and type of the anti-icing chemical used, etc.). In addition, comparing the impact of different anti-icing technologies at key locations (e.g., high collision locations) is recommended as different methods are used and automated methods (e.g., FAST system) are more accurate than conventional manned application of the chemical.

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